Novel Attitude Control Challenges for an Earth-Observing CubeSat

Matthew Sorgenfrei NASA Ames Research Center, Moffett Field, California, 94035, matthew.c.sorgenfrei@nasa.gov

Matthew Nehrenz NASA Ames Research Center, Moffett Field, California, 94035, <u>matthew.t.nehrenz@nasa.gov</u>

Abstract

This paper presents a novel attitude determination and control solution for a three cube nanosatellite performing science operations in low Earth orbit. The spacecraft is tasked with studying the water content of Earth's upper atmosphere by taking radiometer measurements along the 183 GHz absorption line. The radiometer must be calibrated against the cold of deep space, and this calibration necessitates spinning the spacecraft at approximately 5 RPM about the minor axis—an inherently unstable configuration. Along with this angular velocity requirement, the spacecraft must be able to resolve its attitude to approximately 1.5° about all axes in order to geo-locate the radiometer data, a relatively high level of accuracy for a CubeSat. This paper will describe in detail the Earth observation science mission as well as the development of the spacecraft attitude determination and control subsystem. A commercially available kit of parts was assembled to satisfy the attitude determination and control requirements, and the challenges of integrating this hardware into the power-limited spacecraft system in a relatively short period of time will also be discussed.

1. INTRODUCTION

This paper discusses the development of the attitude determination and control subsystem (ADCS) for a three cube CubeSat operating in low Earth orbit. This spacecraft, known as the CubeSat Hydrometric and Atmospheric Radiometry Mission (CHARM), levies a range of requirements on the spacecraft ADCS that results in a relatively unique subsystem design. The main science objective of CHARM (a joint mission between NASA Ames Research Center and the Jet Propulsion Laboratory) is to collect data about the water content of the upper atmosphere using a passive radiometer. The radiometer payload was allocated 1.5 cube units of volume, with the remaining volume set aside for the spacecraft bus and ADCS. This resulted in a very stringent mass, power, and volume budget for the ADCS, a major driver for the eventual subsystem design.

For the purposes of this paper, a CubeSat will be defined as any spacecraft which adheres to the CubeSat standard [1], whereby a 10cm x 10cm x 10cm cube of volume is designated as 1U. NASA Ames has launched an array of 3U CubeSats for scientific research over the past decade, including the recent PharmaSat and O/OREOS missions [2]. An important distinguishing feature of these past missions is that they have been passively stabilized using permanent magnets and hysteresis rods, as opposed to being actively controlled. While actively controlled CubeSats have flown in LEO [3], these missions have largely been technology demonstrators. In contrast, the CHARM spacecraft not only is tasked with undertaking a complex science objective, but must also be actively controlled in order to satisfy that objective.

The remainder of this paper is organized as follows. First, the science objectives of the CHARM mission and details of the science payload will be presented in Section 2. Next, the overall design of the spacecraft ADCS will be outlined in Section 3. A set of preliminary simulation results will be presented along with a discussion thereof in Section 4. Finally, some comments about the future challenges for the CHARM mission team will be offered in Section 5.

2. SCIENCE PAYLOAD

The objective of the CHARM mission is to learn more about the global water cycle of Earth by obtaining science measurements of both liquid water path (LWP) and precipitable water vapor (PWV) [4]. Such measurements can be used to generate both temperature and relative humidity profiles of the upper atmosphere, which in turn can help scientists understand how the global Earth climate system is currently changing. This is a high-level goal for the Earth Science Mission Directorate of NASA, which has been a central sponsor of early research in technologies supporting such measurements. Both LWP and PWV measurements are taken using a passive microwave radiometer which observes the 183 Ghz water absorption line through 4 separate channels. Such measurements have previously been gathered as a subset of data collected on much larger instruments, such as the Advanced Microwave Sounding Unit on NASA's Aqua spacecraft.

Miniaturization of the microwave radiometer to fit within the volume and power constraints of a 3U CubeSat is made possible by the development of new sensing technologies at the Jet Propulsion Laboratory (JPL). CHARM makes use of Indium Phosphide Monolithic Microwave Integrated Circuit (InP-MMIC) radiometer, which was built by JPL with an emphasis on creating low-noise amplifiers. As can be seen in Figure 1, the InP radiometer technology provides greatly improved measurement quality as compared to the current state of the art for this type of radiometer. The InP-MMIC technology has been demonstrated on high-altitude Global Hawk UAV missions, but demonstrating this technology on-orbit would greatly increase its readiness inclusion in future Earth observation missions.



Figure 1. A comparison between the data resolution available using a typical amplifier, (a) and the low-noise amplifier developed for the CHARM mission

In order to maintain the low noise characteristics that make the InP radiometer desirable for use in LEO it is necessary to continuously recalibrate the instrument. Calibration occurs by taking a measurement of the cold sky of space immediately prior to taking science data of the Earth itself. When this radiometer is integrated into a 3U CubeSat, the practical implication is that either the instrument itself or the entire spacecraft must spin fast enough for calibration to occur. At the orbit that was made available for this mission, the minimum spin rate for the instrument was calculated to be 5 RPM. This spin rate was one of two central drivers for the spacecraft ADCS design, along with the spacecraft knowledge accuracy requirement. The required level of knowledge accuracy derives from the need to geo-locate the data collected by the radiometer with known locations on the surface of the Earth. For the selected orbit the instrument has a footprint of approximately 15 km, which ultimately leads to an attitude knowledge accuracy requirement of 1.5° about the nadir direction.

3. ATTITUDE CONTROL SYSTEM DESIGN

The design of the CHARM ADCS represented a unique challenge due to the existence of relatively stringent attitude control requirements in the face of very strict mass, power, and volume budgets. CHARM was selected to reach orbit on a resupply mission to the International Space Station, which results in an orbit of approximately 325 km at an inclination of 51.6 degrees. This is a comparatively low altitude for LEO science missions, and eliminated the possibility of using deployable solar panels due to the prohibitive increase in drag. Simulations indicated that at 325 km a 3U spacecraft would likely de-orbit in roughly 60 days, which provides very little time for commissioning and science operations. The addition of deployable panels would only aggravate the short operating life and as such all subsystems--particularly the ADCS--had to operate under a very strict power budget. Along with this power budget the ADCS was allocated a maximum of 0.5U of volume since the remaining subsystems occupy 1U.

The basic concept of operations for CHARM envisions collecting cross-track science data that is perpendicular to the velocity vector of the spacecraft. As seen in Figure 2, the radiometer traces out a swath across the surface of the Earth as the spacecraft moves downrange, enabling data collection immediately after calibration has occurred. Attitude control will be undertaken by means of a single reaction wheel and three mutually orthogonal magnetic torque rods, while attitude determination is enabled using a threeaxis magnetometer, a static IR Earth horizon senor, and a three-axis MEMS gyro. Only one reaction wheel was allocated for attitude control because the pointing requirements for the mission are fairly coarse, and the majority of the dynamic motion occurs about a single axis. Sun sensors were omitted from the attitude determination design fairly early in the development cycle because it was determined that too much solar panel surface area would be lost by including these sensors. Additionally, it could not be guaranteed that enough sun sensors would be able to see the sun during science operations, which is exactly when the best attitude estimates are required. As such, a slightly unconventional suite of components was necessary, all of which are supplied by Maryland Aerospace, Inc.

A central challenge for the ADCS was to develop a control architecture which allowed the spacecraft to spin continuously at 5 RPM while also tracking the velocity vector, effectively precessing the momentum vector once per orbit at an altitude with comparatively large disturbance moments. The antenna of the radiometer looks out one of the 1U x 3U faces of the spacecraft, which means that CHARM must spin about its minor axis. In the presence of flexible motion or eddy current disturbances, minor axis spin is unstable, and any control law selected for use had to be able to guarantee stability. The "nominal" spin state, in which the spacecraft is spinning at 5 RPM about the minor axis (which points in the velocity direction), only occurs after the spacecraft has first detumbled using a traditional B-dot controller and the magnetic torque rods. After detumble, the spacecraft is first spun up to 1 RPM using only the torque rods in order to impart a certain amount of momentum bias. Once this spin rate is achieved, the reaction wheel provides the necessary torque to spin the spacecraft at 5 RPM or higher. In subsequent sections of this paper simulation results will be presented for all phases of ADCS operations, including detumble and the two-step approach to spin mode.





Figure 2. The theoretical ground coverage that can be obtained from cross-track passes of the radiometer when the spacecraft is spinning at 10 RPM

REFERENCES

[1] Chin, A., Coelho, R., Nugent, R., Munakata, R., and Puig-Suari, J., "The CubeSat: The Picosatellite Standard for Research and Education", Proc. of AIAA Space Conference and Exhibition, San Diego, CA 2008

[2] Diaz-Aguado, M., Ghassemeih, S., Beasely, C., and Schooley, A., "Small Class-D Spacecraft Thermal Design, Test, and Analysis—PharmaSat Biological Experiment", Proc. of IEEE Aerospace Conference, Piscataway, NJ, 2009

[3] Mauthe, S., Pranajaya, F., and Zee, R., "The Design and Test of a Compact Propulsion System for CanX Nanosatellite Formation Flying", Proc. of AIAA/USU Small Satellite Conference and Exhibit, Logan, UT, 2005

[4] Lim, B., Mauro, D., De Rosse, R., Sorgenfrei, M., and Vance, S., "CHARM: A CubeSat Water Vapor Radiometer for Earth Science", Proc. of IEEE International Geoscience and Remote Sensing Symposium, Munich, Germany, 2012