Attitude Control on the Pico Satellite Solar Cell Testbed-2

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Aerospace’s “PicoSat” History

OPAL PicoSats (2)
250 grams

MEPSI on STS-113 (Endeavour)
800 grams each

MEPSI on STS-116 (Discovery)
1.1 and 1.4 kilograms

AeroCube-3
1.1 kilograms

PSSC Testbed-2 on STS-135 (Atlantis)
3.7 kilograms

REBR2 (2)
4.5 kilograms with heat shield

1999
2001
2003
2005
2007
2009
2011
2013

First University CubeSat Launch

MightySat II.1 PicoSats (2)
250 grams

AeroCube-1
999 grams

AeroCube-2
998 grams

Failed to Reach orbit

PSSC Testbed on STS-126 (Endeavour)
6.4 kilograms

REBR (2)
4.5 kilograms with heat shield

AeroCube-4.0 (1)
AeroCube-4.5 (2)
1.3 kilograms

The Pico Satellite Solar Cell Testbed-2 was our 15th spacecraft and 13th small satellite.
It was our 4th ride on a U.S. Space Shuttle.
PSSCT-1 and PSSCT-2

**PSSCT-1 (paper SSC09-IV-5)**
- 5” x 5” x 10”, 6.4-kg mass
- Spin-stabilized
- 1st generation attitude sensors
- Single Z-axis reaction wheel
- Single communications transceiver
- No GPS receivers
- Four solid rocket thrusters (never fired)

**PSSCT-2 (paper SSC12-II-1)**
- 5” x 5” x 10”, 3.7-kg mass
- 3-axis-stabilized
- 2nd generation attitude sensors
- Three reaction wheels
- Two communications transceivers
- Two GPS receivers
- On-orbit reprogrammability
- Four redesigned solid rocket thrusters (1 fired)

The PSSCT-2 mission was proposed as a relight of PSSCT-1. We modified everything except for the external dimensions.
PSSCT-2 was ejected into a 365 x 380-km orbit by Atlantis on July 20, 2011 using an Aerospace-designed Picosatellite Orbital Deployer (POD).
Farewell Atlantis…….

PSSCT-2 was the last satellite deployed by a U.S. Space Shuttle. This image was taken 72-s after deployment, indicating that the initial rotation rates were low.
Sun Sensors

The sun sensors use a thin plate with a square aperture bonded onto a quad photodetector. Aperture alignment with the detector array within 1° was difficult to achieve.
Sun Sensor Errors: Lab Test Results

- Fairly linear over +/- 34° range
- Offset error in X and Y-axes
  - Aperture misalignment
  - Each sensor is different
  - Correctable using test data
- Errors after linear fitting:
  - +/- 0.5° over +/- 30° angular range
  - +/- 0.2° over +/- 5° angular range

Sun sensor is accurate to 0.5° over its operating angular range. Within 5° of the center, the error drops to 0.2°. This can be further improved using a second-order curve fit.
The Earth sensor array uses wide field-of-view infrared thermometers (Melexis MLX90615). Temperature differences between “Earth” and “Earth plus space” pairs yield angular offset in that direction.
Magnetic Sensors and IMU

• **Honeywell MHC6042 and HMC1041Z**
  - 0.15-milligauss sensitivity
  - Orthogonality determined by soldering
  - HMC1041Z easy to mount incorrectly
  - No factory calibration

• **Analog Devices ADIS16405BLM**
  - Accelerometers, rate gyros, and magnetometers in a single ~1-in³ package
  - All have same coordinate system!!!
  - Magnetometers factory calibrated
  - 0.5-milligauss sensitivity
  - 0.006°/s gyro accuracy 200-s after bias error cal.
  - 3-milli-g acceleration sensitivity
  - Good orthogonality (<0.05°)

*We had two different magnetic sensor triads.*
Attitude Actuators

- **Reaction wheel triad**
  - 60,000 rpm brushless DC motor
  - Mumetal shield around motor
  - Mumetal wheel with $\sim 10^{-2}$ N-m-s storage
  - One microcontroller per motor

- **Magnetic torque coil triad**
  - 0.3 A-m² magnetic moment
  - 9.5 x 7.9-cm area; 216 turns
  - $\sim 10^{-5}$ N-m torque per coil

*We built our own reaction wheels and torque coils.*
Prefight Attitude Control Testing

• Hung PSSCT-2 inside cubic Helmholtz coil
  - Verified torque coil operation
  - Verified magnetometer operation
  - Checked polarities

• Sensor and actuator coordinate systems varied
  - Each magnetic sensor triad had a different coordinate system (CS)
  - Torque coil triad CS was different
  - Each sun sensor had a different CS
  - Earth sensor array had a different CS
  - Reaction wheels had a left-handed CS

• Preliminary transformations were done in the ground station software
  - Easy to check in lab, but
  - CS Transformations were needed on-board for yet unwritten attitude control loops
  - Backing out correct CS’s for control loops was prone to errors.

*First on-orbit B-dot control loops didn’t work. We ran a series of tests to find the errors in sensor and actuator polarity.*
On-Orbit Nadir Tracking Loop

1. Detumble spacecraft
2. Find Earth
   - Rotate about X-axis while checking Earth nadir thermometer
   - Repeat about Y-axis if Earth hasn’t been found
3. Track Earth
   - Calculate angular offsets using multiple thermometer readings
   - Adjust X and Y reaction wheels to center the Earth

Initial nadir-tracking didn’t work well. We discovered that two of the infrared thermometers gave incorrect temperatures, probably due to loss of internal pressure. We chose two orthogonal sets of working thermometers to give good nadir tracking based on camera images. On-orbit reprogrammability enabled this option.
Nadir Tracking at Night: It Works!

Nadir-tracking was tested using the fisheye camera to periodically snap Earth images. We discovered that our camera could see cities and aurora at night, thus providing nadir tracking information during eclipse.
LVLH Tracking for GPS Radio Occultation

- +Z pointing at center of Earth using Earth nadir sensor
- +X pointing in anti-flight direction using magnetometer
  (rotation angle about Z determined using magnetometer)
- Rotation angles about Z uploaded as a time-tagged lookup table
- Rotation angles calculated using orbit trajectory and IGRF2011
- Needed B-dot detumbling every 2-minutes

We needed 10-s of B-dot detumbling every 2-minutes to prevent buildup of angular momentum. Current loops most likely cause of momentum buildup.
Firing of Rocket to Boost Apogee

- 40-N-s rockets on -Z face
- Start with LVLH tracking
- Rotate 90° about Y-axis
- Take picture to verify orientation
- Fire rocket
- Check orbital elements
- Modify B-dot detumbling timing to handle ~300°/s rotation rates
- Wait a few days to get satellite back under control

Although we carefully aligned each solid rocket to make their thrust vectors pass through the satellite center-of-mass, we still had offset thrusts that induced rotation. The spacecraft performed a 300° rotation during the 1.5-s of thrusting. Apogee boost was less than expected.
Pointing of Side Panels at the Sun

- Needed angular errors less than 5°
- We developed a semi-proportional motor control scheme to improve control stability; original Nadir-tracking used a bang-bang control scheme.
- We got better than 2° pointing accuracy over 2-minutes of operation.
- Longer-term stability would require periodic B-dot detumbling.

The reaction wheel controllers could not smoothly change rotation speeds, but we adapted by modifying the spacecraft control algorithms.
Lessons Learned

• On-orbit re-programmability of all systems is a great asset, but it can consume a good fraction of your flight operations.

• Allow sufficient ground-testing time to verify attitude control operation. It’s just faster on the ground.

• Cameras can provide crude, but effective, attitude information.

• Ground test your spacecraft using a realistic communications link.

• Know the complete moment-of-inertia matrix for your satellite.
  - Non-zero cross terms can cause problems.

• Spacecraft attitude control is a lot harder than it looks.
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Thank you!!!!!