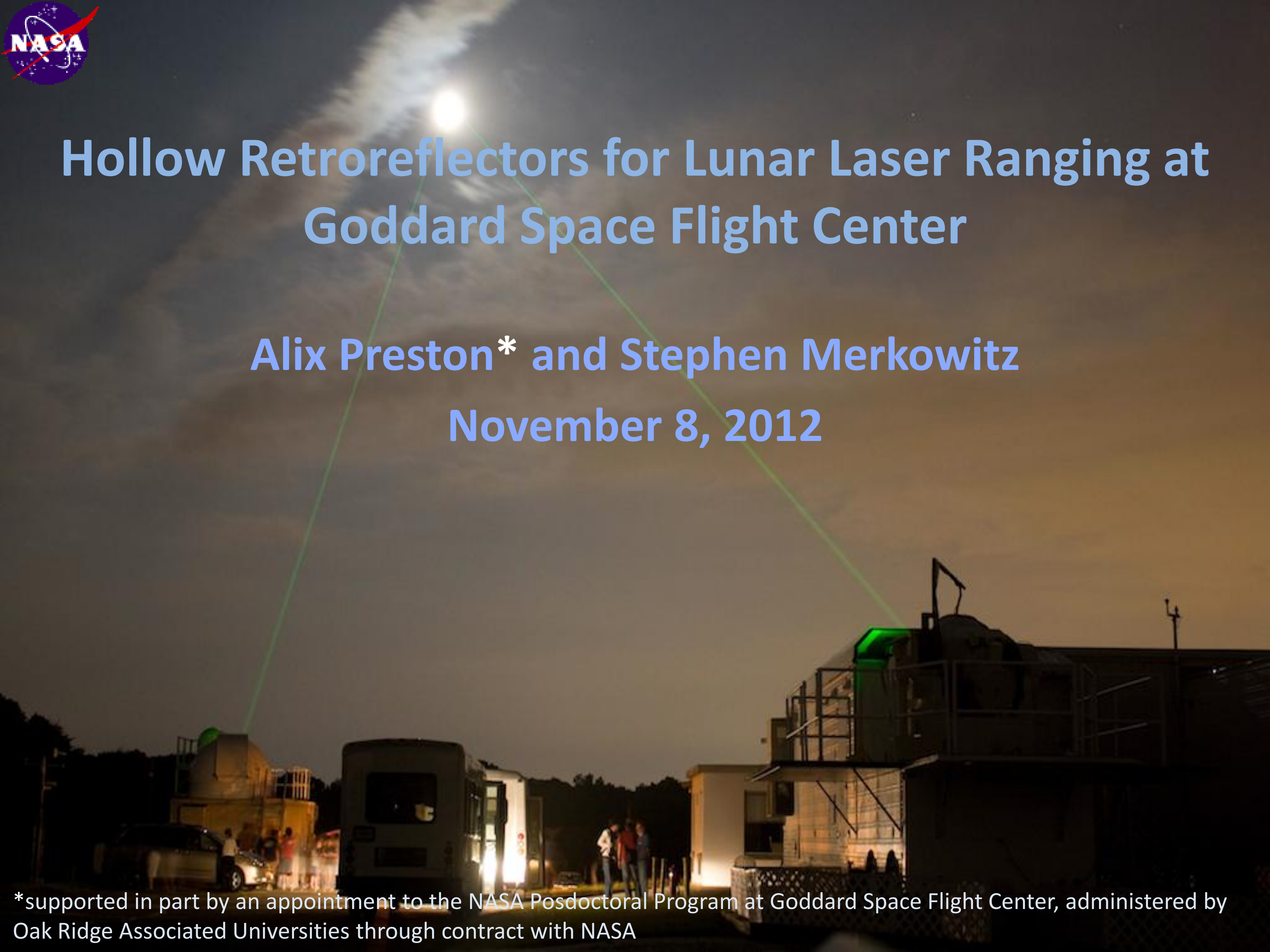

Hollow Retroreflectors for Lunar Laser Ranging at Goddard Space Flight Center

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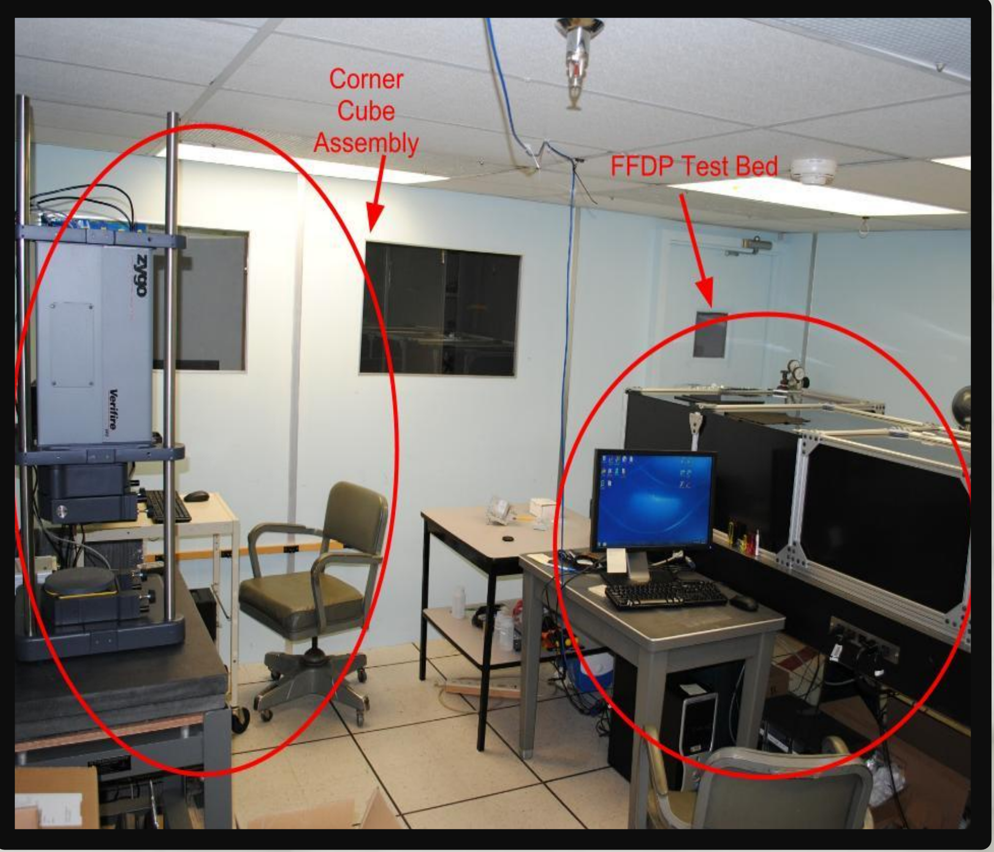
Goddard Facilities

- At Goddard, we've been working on developing next-generation hollow corner cubes for LLR
- Have the facilities to design, build, and test hollow corner cubes all in one place
- Located in the 48" telescope lab at GGAO



Why Large Cubes?

- APOLLO routinely ranges with millimeter-level precision
- Being limited by errors in the physical size of the array
- Solution is to distribute large cross-section single cubes
- Next-generation LLR will require single retroreflectors with large cross sections
    - 15 cm (~6”) coated hollow cube has a cross section similar to the Apollo 15 300 cube array

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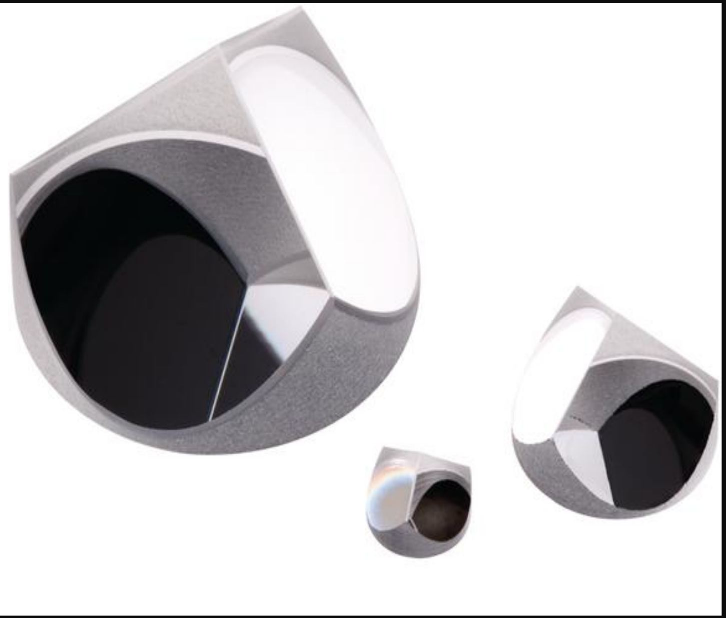
Why Hollow Cubes?

- Polishing large, solid cubes to high precision is very difficult
- Solid cubes are potentially heavier (depends on the fixture)
- Thermal gradients in solid cubes are a problem
- Somewhat limited by material (needs to be optically transparent, low CTE, excellent homogeneity, able to polish well, etc..)
- Other issues…



Hollow Cube Fabrication

- Using a Zygo interferometer to do the cube alignment
  - Can get dihedral angles, beam deviations, wavefront error, etc..

- Zygo mounted vertically on 4" granite table that sits on concrete to reduce vibrations

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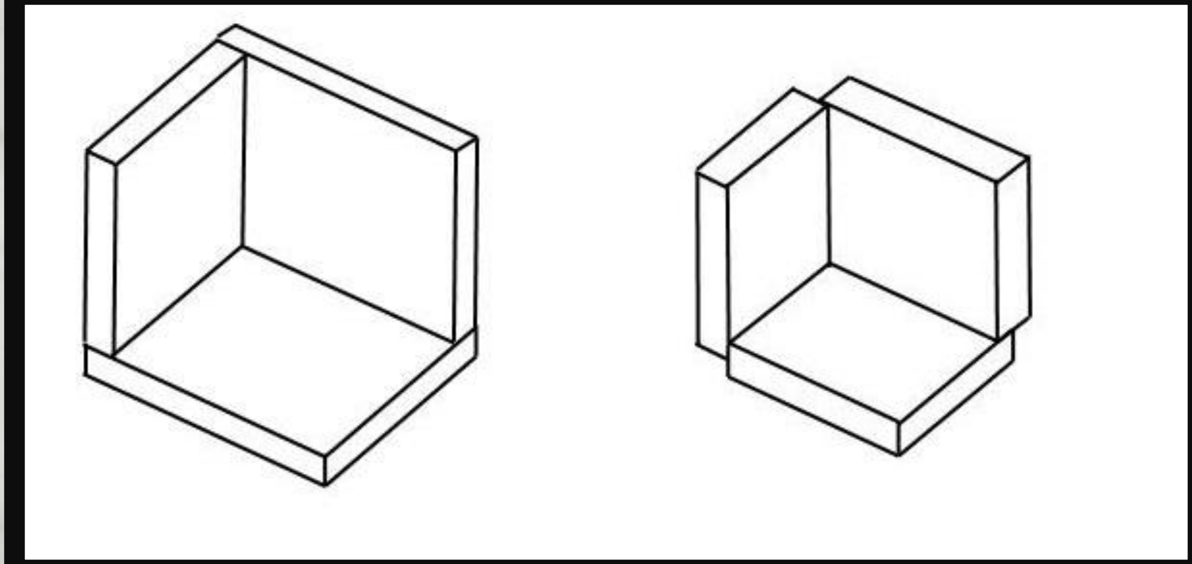
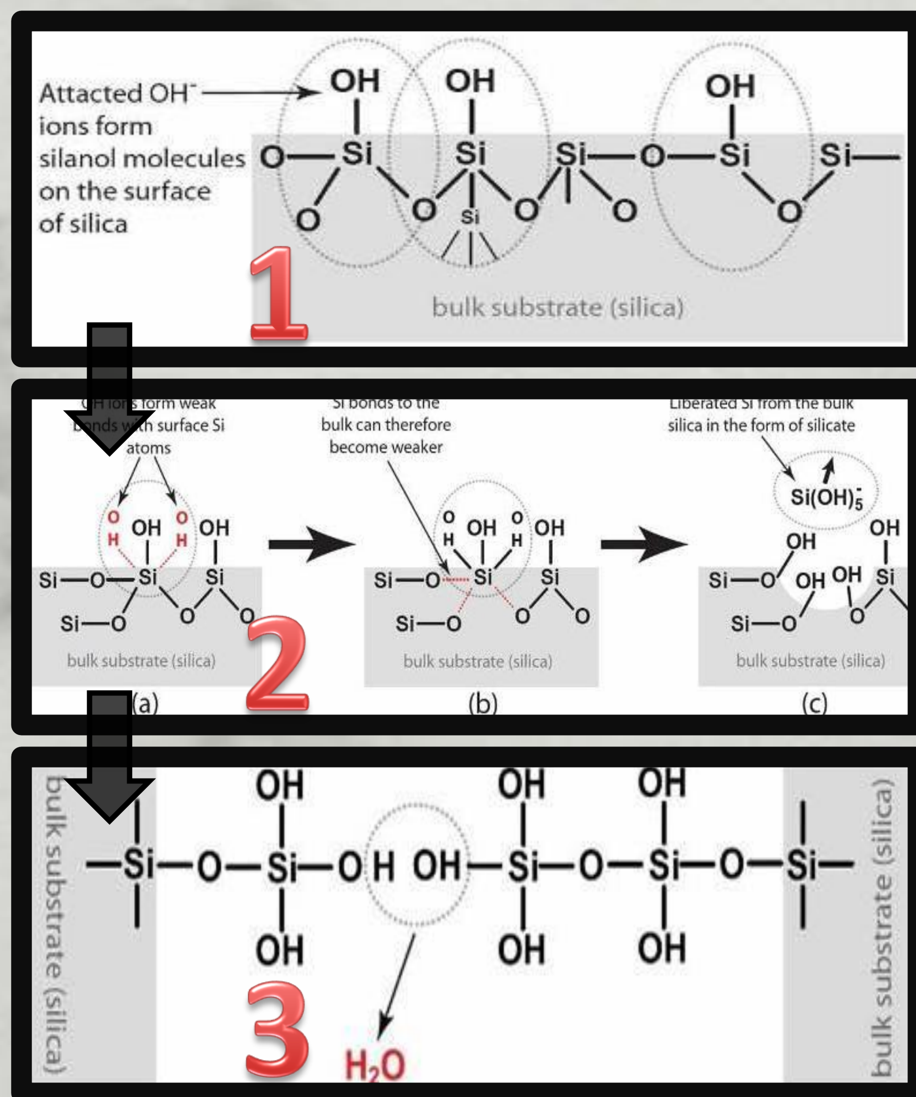
Cube Designs



- Have been testing 2 different designs, along with 2 reflective coatings
- Larger cubes have 3” aperture, smaller cubes are 2”
- Larger cubes have a high reflectivity dielectric coating at 532 nm, smaller cubes have aluminum coating
- Used hydroxide bonding and epoxy bonding on the small cubes, and hydroxide bonding only on the large cubes

Hydroxide Catalysis Bonding (HCB)

- Use a small amount of hydroxide solution (typically NaOH, KOH, or sodium silicate)
- Bonding occurs in 3 steps:
  1. Hydration
  2. Etching
  3. Polymerization
- Produces a thin, strong bond
- Bond material is basically glass -> lower CTE than epoxy
- Epoxy bonds change over time, HCB may not change as much



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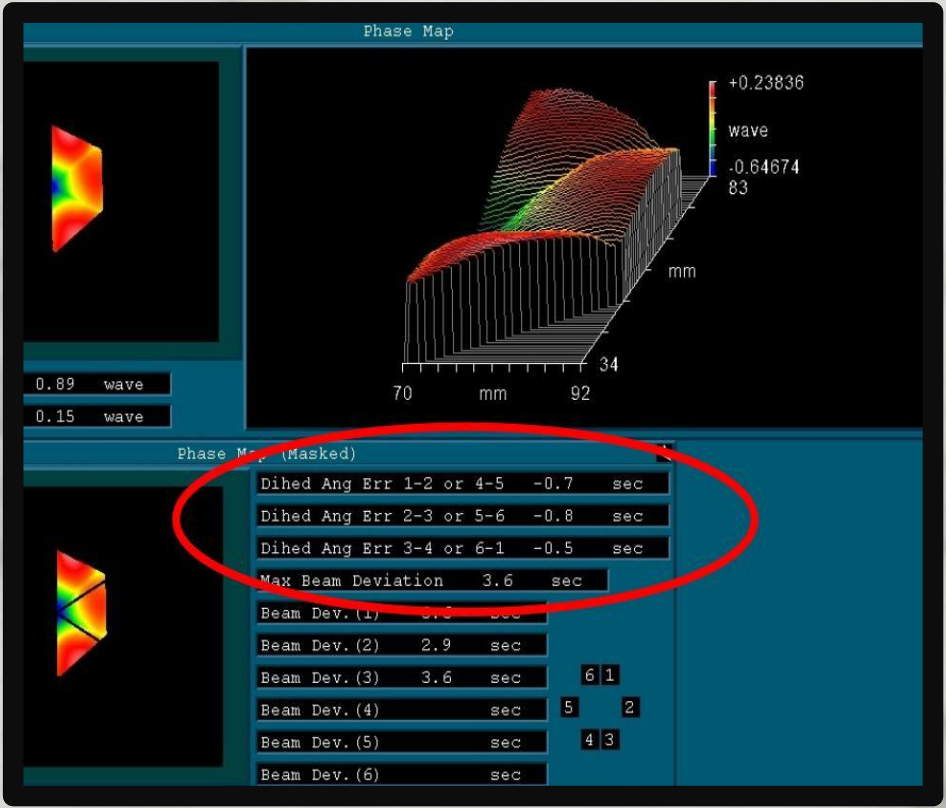
Epoxy Bonded Cubes

- Epon 828/Versamid 142 (50/50) epoxy was used
- Able to get sub-arcsec dihedral angle errors and <1λ wavefront flatness
- Beam deviations due to quality of the mirrors
- Need to get flatter mirrors to reduce beam deviations and wavefront flatness



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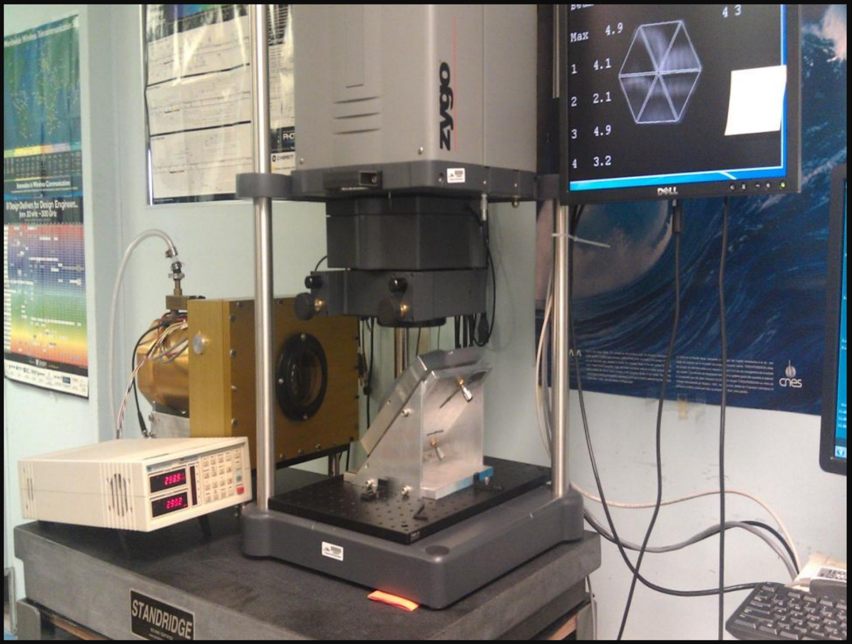
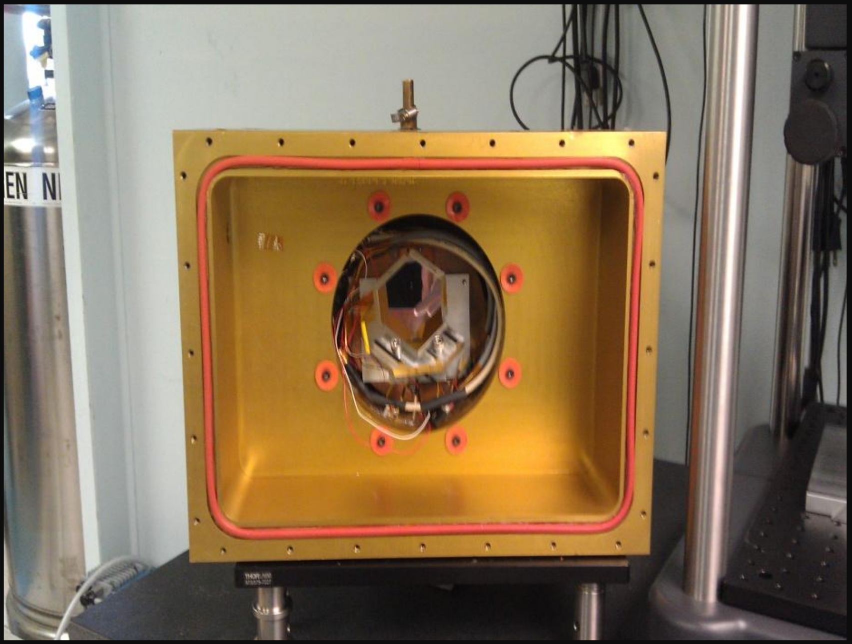
Epoxy Thermal Tests

- Used a small vacuum chamber and cooled reflectors down with liquid nitrogen
- Temp. sensors on cube and cold plate
- Wanted to cool down in an even manner by radiation to reduce thermal gradients
- Able to cool down the cubes, but not to the temps. we need and still have gradients
- Holder is currently being redesigned for -180 C to 120 C





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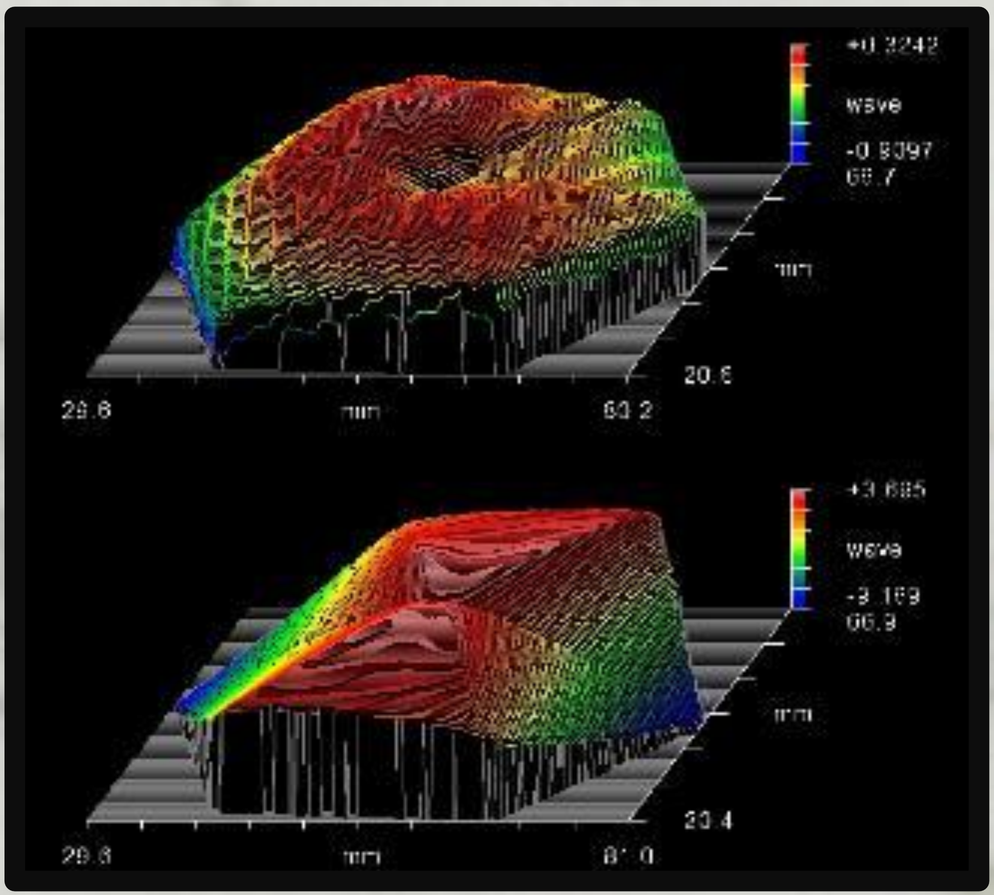
- Cooled the cube to ~250 K, not sure of the gradient
- After thermally cycling, the cube returned almost back to normal (only a few 0.10” off original dihedral angles)
- To make sure it wasn’t the cube, we rotated it and tested again -> same effect in same direction
- Not due to the cube, but a thermal gradient
- **Almost 12 waves of distortion and still returned to same shape!!**



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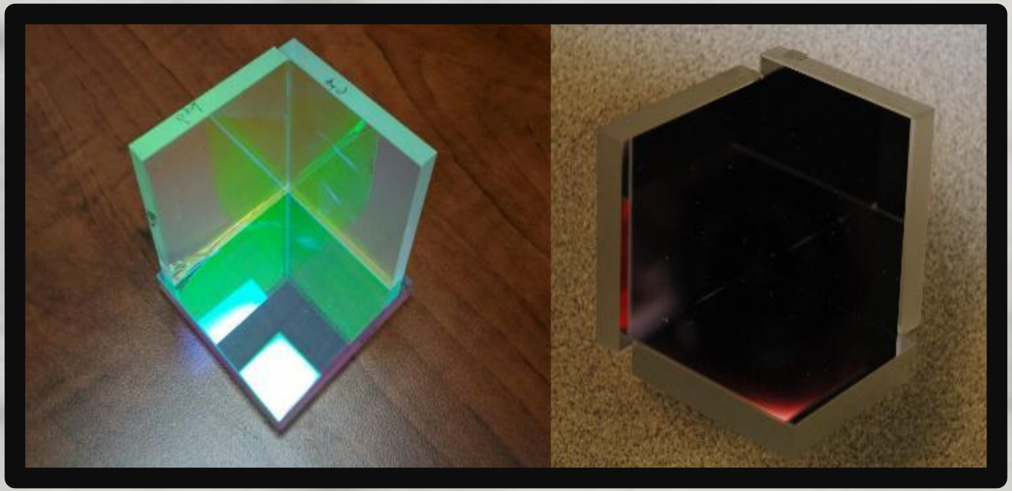
Hydroxide-Bonded Cubes

- Bonded both designs using HCB method
- The small cubes tended to “flower” out -> still able to get some usable cubes to test
- Much better results with the larger cubes
- Larger dihedral angles most likely due to the non-perpendicularity of the mirrors



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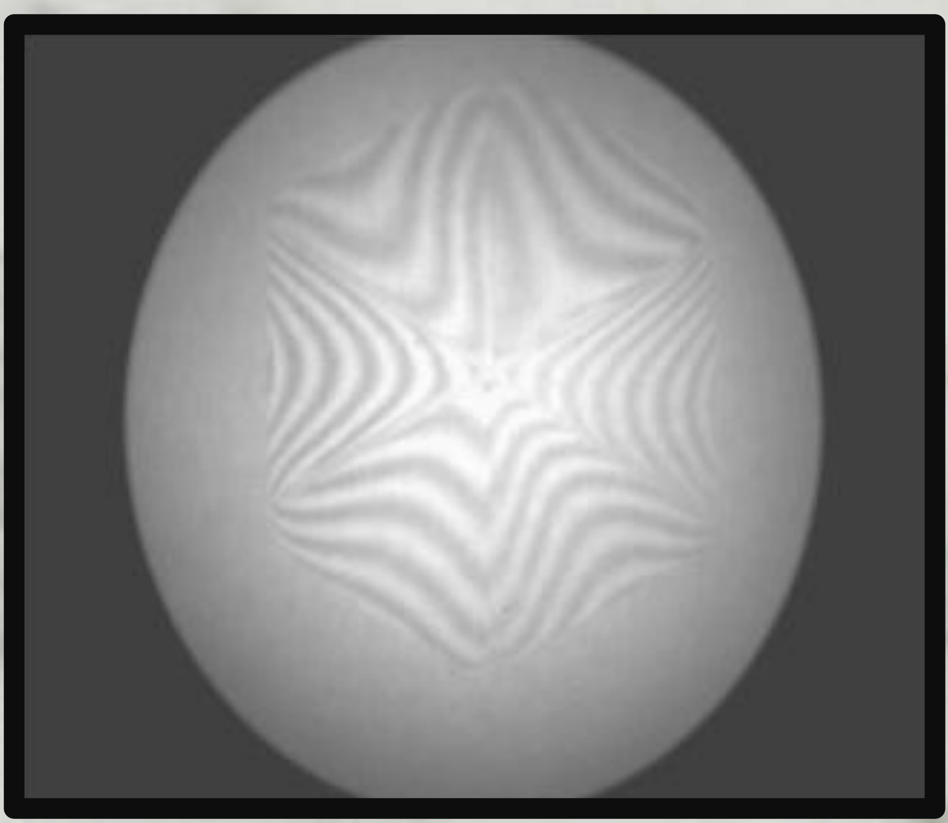
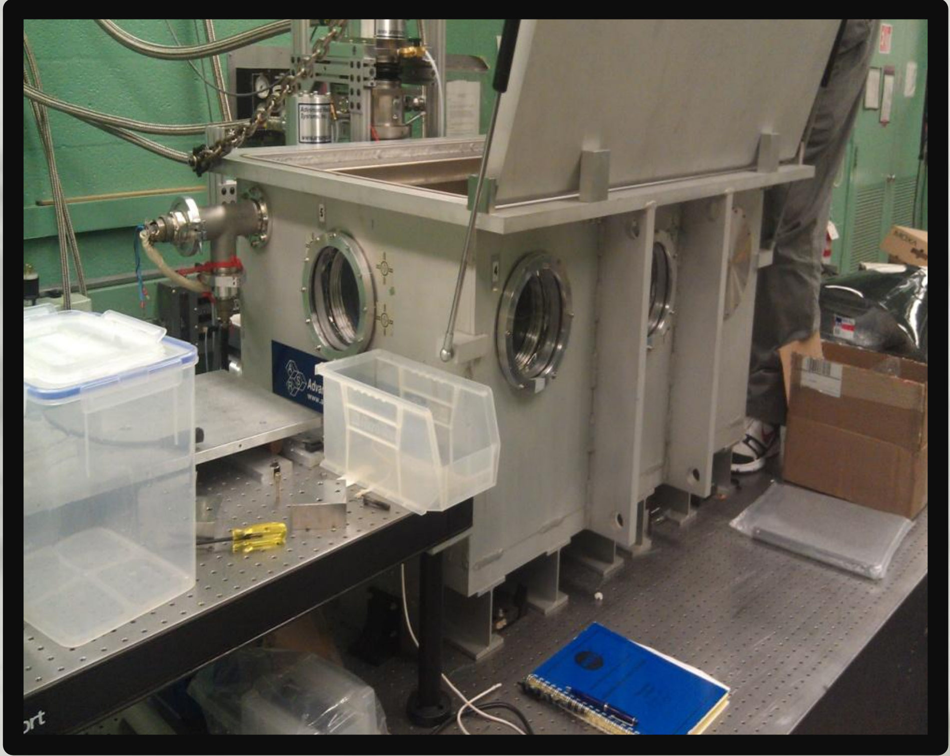
- When bonding the large cubes, usually better to only bond 2 seams
- When all 3 seams were bonded, large stresses were induced -> can be seen by the curvature in interferogram
- Possibly due to the bonding process itself, or the non-perpendicularity in the mirrors
- To HCB cubes, you need flat and perpendicular mirror panels



HCB Thermal Tests

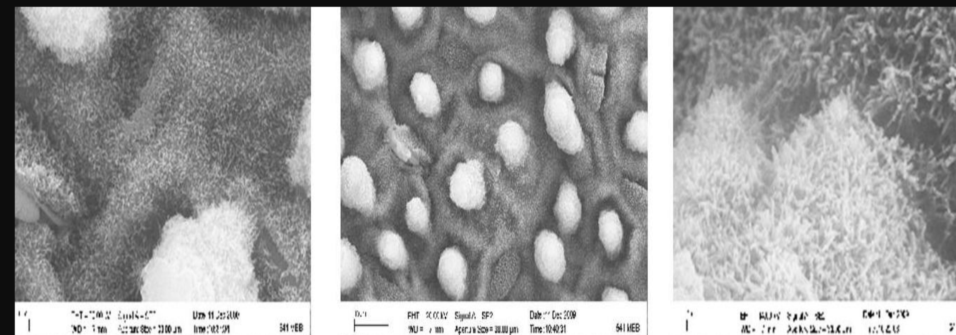
- One of the large cubes was cooled to ~70 K in a different chamber
- Worked in on another groups project at the last minute
- Cooled over 2 days
- Weren’t able to get an interferogram
- Not a large change in dihedral angles after cooling

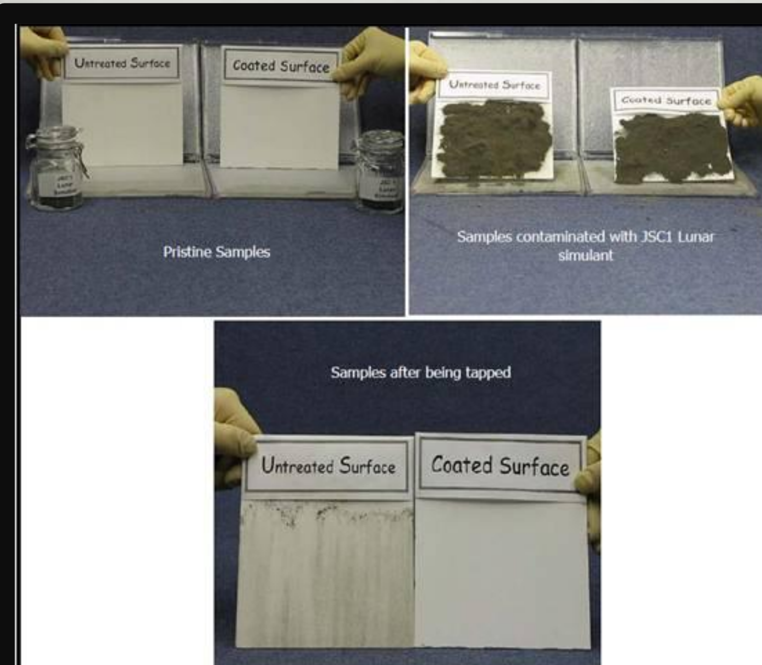


Dust Mitigation

LOTUS Coating:

•Developed at Goddard
•Primarily for Moon/Mars missions to reduce dust accumulation and biogens
•Modeled after the lotus leaf
•Extremely hydrophobic
•Able to apply coating at less than 100 C
•See how coating effects cubes (acts like a catchers mitt??)





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Conclusion & Future Work

- Made epoxy bonded cubes with sub-arcsec dihedral angles
    - Will get better mirrors to improve the wavefront flatness
    - Need to thermally cycle the cubes evenly to see how they behave
    - Able to withstand gradients and still return to original shape
- Able to use HCB to bond cubes
    - Larger and flatter bond areas seem to produce better results
    - Need to thermally cycle to see if HCB is better than epoxy
    - Have mirrors on the way that that are perpendicular to 3 arcsec
    - Most likely will need a hybrid design of the 2 designs already used
- A thermally shielded fixture is being made to thermally cycle the cubes so there isn't a temperature gradient when cooling
- Depending on the results, could scale up to 4"-6" soon
- Make cubes with the Lotus coating to see if it's a feasible coating