JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

CubeSat Signal Preprocessor Assessment and Test (CAT) Mission

Differential Drag Implementation and Lessons Learned

Dawn Moessner
CAT Mission Design and Navigation Lead
Dawn.Moessner@jhuapl.edu

Wen-Jong Shyong
CAT Mission Design Software Development
Wen-Jong.Shyong@jhuapl.edu

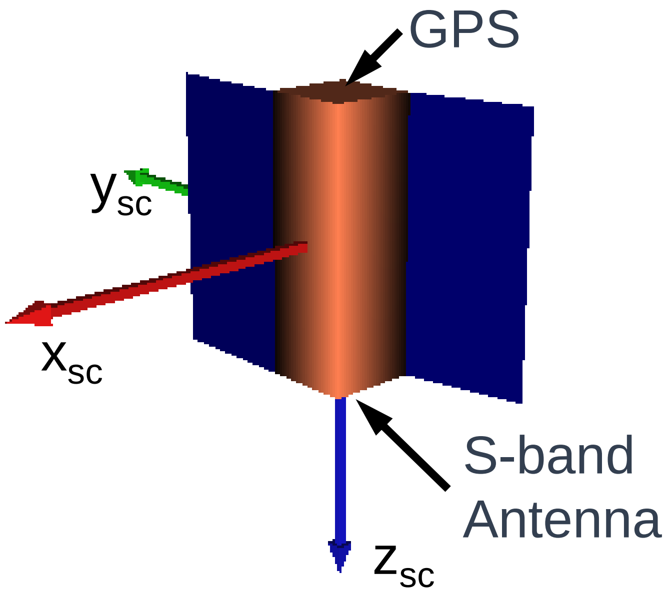
FLIGHT DEMONSTRATION MISSION
CAT

Outline

- CAT Mission Overview
- Differential Drag Attitude Modes
- Modeling
- Drag Maneuver Planning
- Deployment
- Formation Maintenance
- Updates to Drag Maneuver Process
- Conclusion

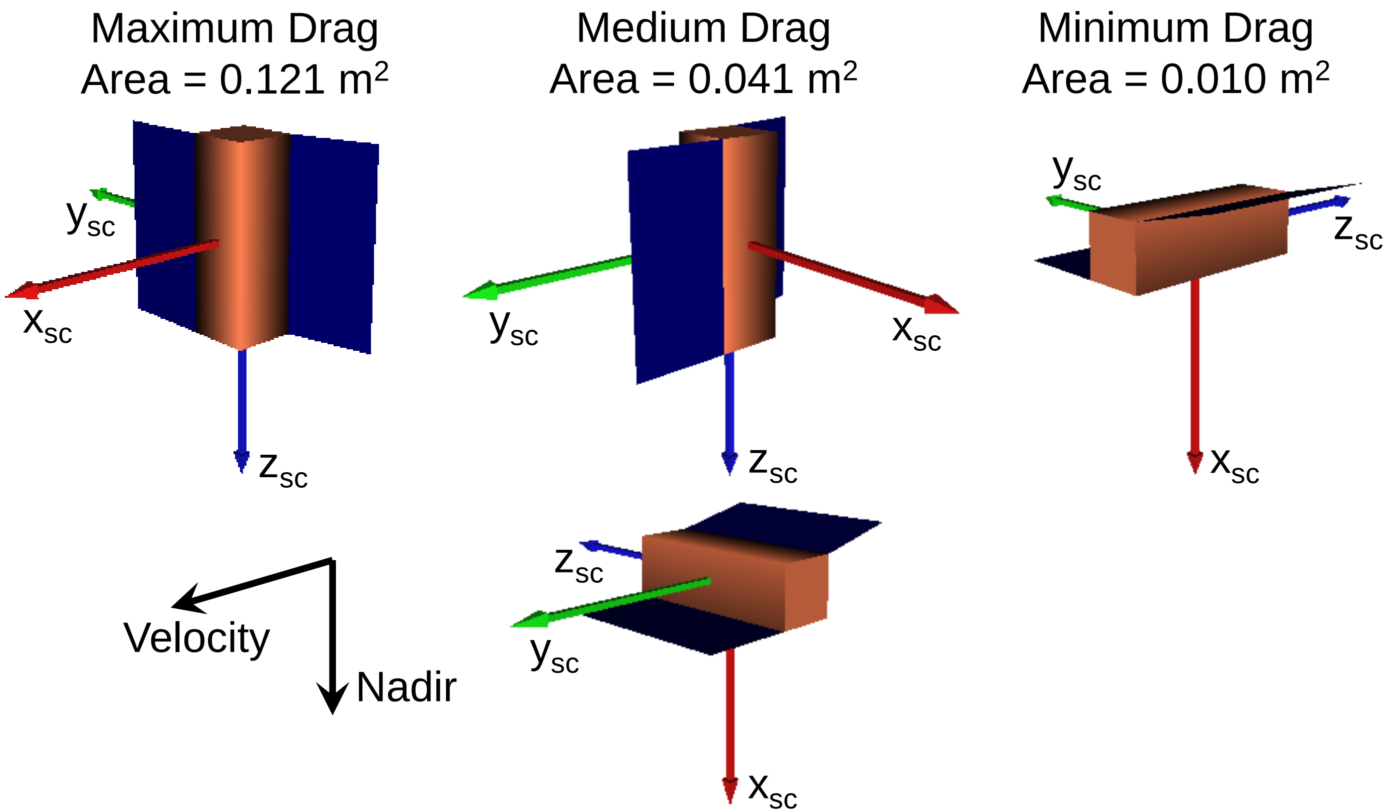
CAT Mission Overview

- Two identical 3U configuration CubeSats each with two deployed solar panels
- Each spacecraft carries an industry-provided RF payload
- Deployed from the International Space Station via Nanoracks on January 31, 2019
- Uses differential drag to maintain in-track separation distance between 10 and 150 km



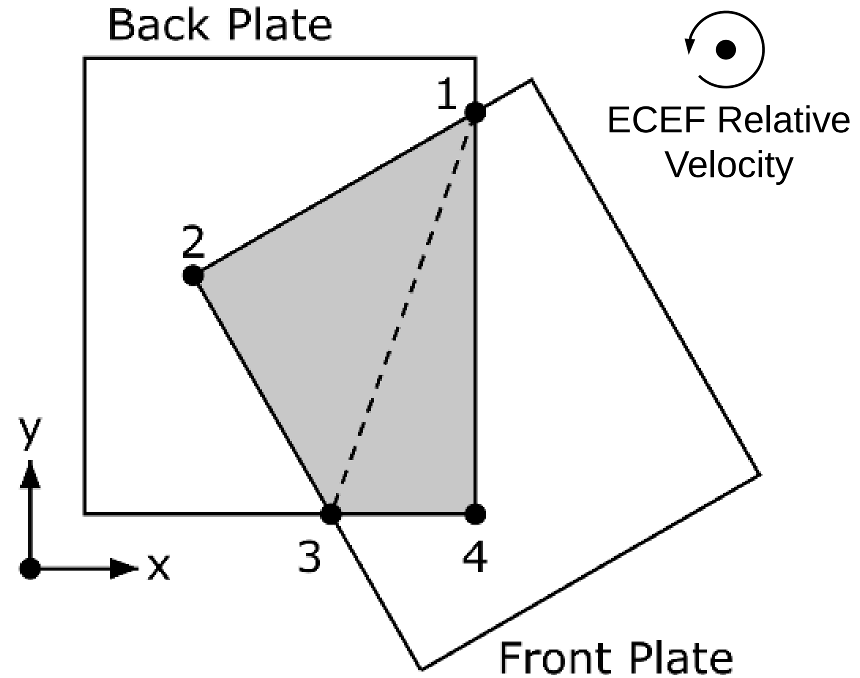
Differential Drag Attitude Modes

- CAT takes advantage of fixed, deployed solar panels to create drag differential
- Max to min drag area ratio is 12:1, max to med drag area ratio is 3:1
- Drag maneuvering occurs during eclipse so as not to interfere with power levels



Modeling

- ODTK would be used for orbit determination
  - Filtered GPS position, velocity, and time data available from spacecraft telemetry
  - Position and time converted to NAVSOL format and input as measurements to the Kalman filter
  - Cd estimated through OD process
- STK/Astrogator used for predicted trajectory propagation and differential drag maneuver targeting
- Plugins developed for both ODTK and STK to calculate drag cross-sectional area based on spacecraft attitude
  - Required a reconstructed attitude history and a predicted attitude
  - Utilized flat-plate model of spacecraft
  - Calculated projected area of each plate for which angle between plate normal and ECEF velocity direction was <90°
  - Accounted for possibility of one plate blocking all or part of another plate



Drag Maneuver Planning

- After deployment, spacecraft are separating with CAT-1 ahead of CAT-2
- Nominally spacecraft are Sun-pointed while in sunlight and in min drag mode during eclipses
- Initially, max drag maneuvers on CAT-2 will counteract deployment acceleration and bring spacecraft back below 150 km, then separation is to be maintained between 10 and 150 km
- Selected target separation distance of 75 ±25 km and target separation rate of 0±1 km/day
- Each week, latest spacecraft state propagated forward 5 weeks and drag maneuvers added
  - If the separation distance exceeded the target bounds
  - If separation distance was within target bounds, but separation rate exceeded the target rate bounds
- Drag maneuver times and quaternions input to CATApp, which coordinates and updates all spacecraft commanding, then outputs daily command loads

1) Spacecraft are too close and continuing to close. CAT-1 max drag maneuver

$s < 50$ km, $\dot{s} < 0$ km/day

2) Spacecraft reach target separation after 1-2 weeks and are still separating. CAT-2 max drag maneuver

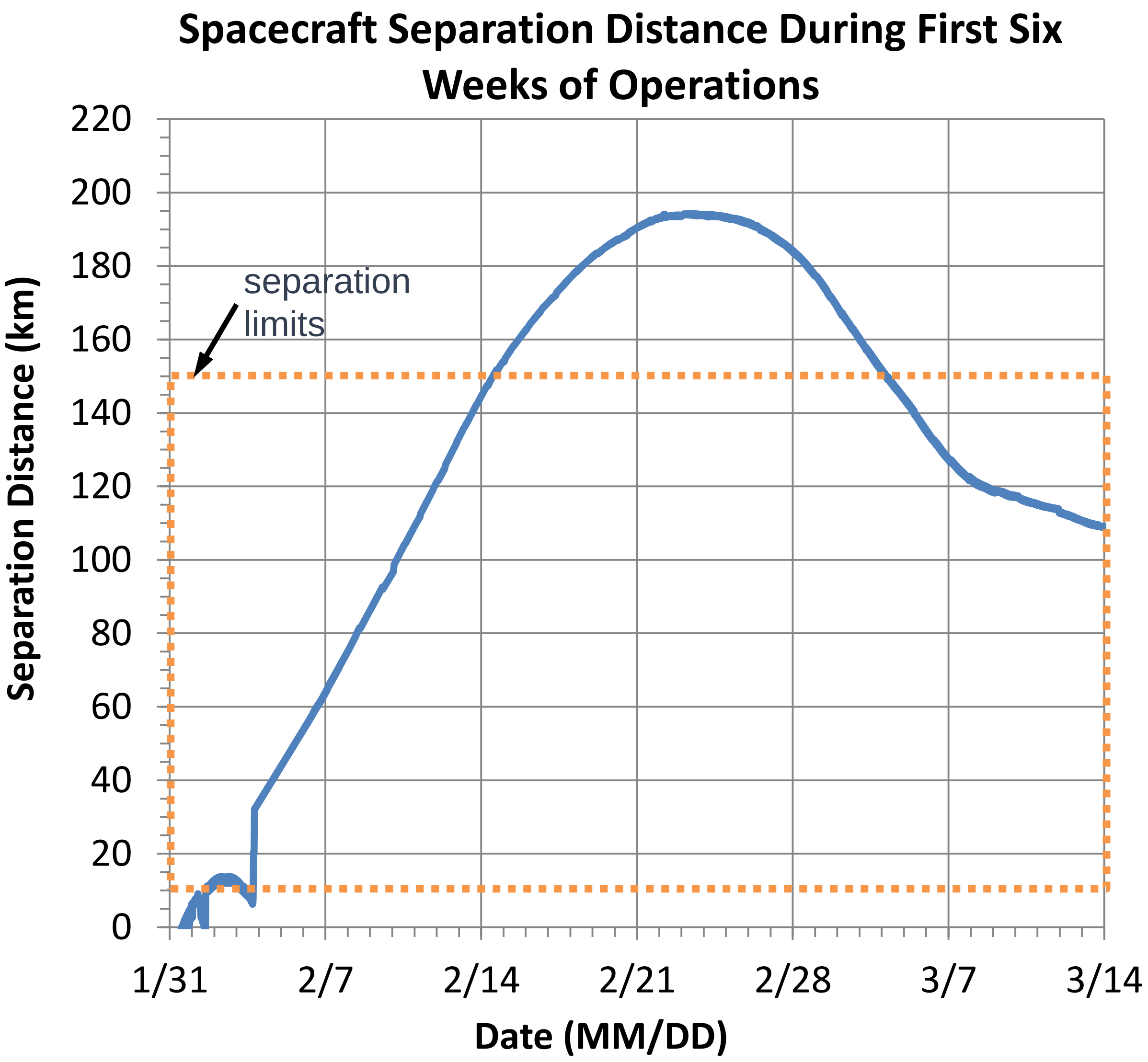
$s = 75$ km, $\dot{s} > 0$ km/day

3) Spacecraft are at target separation and target separation rate. Both CATs to nominal attitude

$s = 75$ km, $\dot{s} = 0$ km/day

Deployment

- January 31, 2019, 10:35 UTC
- At 18:34 UTC both spacecraft beacons detected during the first pass with the SCF
- Neither GPS was able to track enough satellites
  - Used JSPOC TLE states
  - Changed nominal eclipse attitude to point GPS to zenith
  - After 6 days, CAT-2 GPS provided valid solutions through July 2019. After July, TLE states used for OD
  - CAT-1 continues to use TLE states for OD
- Differential drag began on February 13th
  - Delay due to diagnosing attitude commanding error
  - In 10 days went from 11.6 km/day to 0 km/day, average acceleration -1.16 km/day^2
- On March 14th spacecraft check-out and payload commissioning completed
- On March 21st payload began primary operations

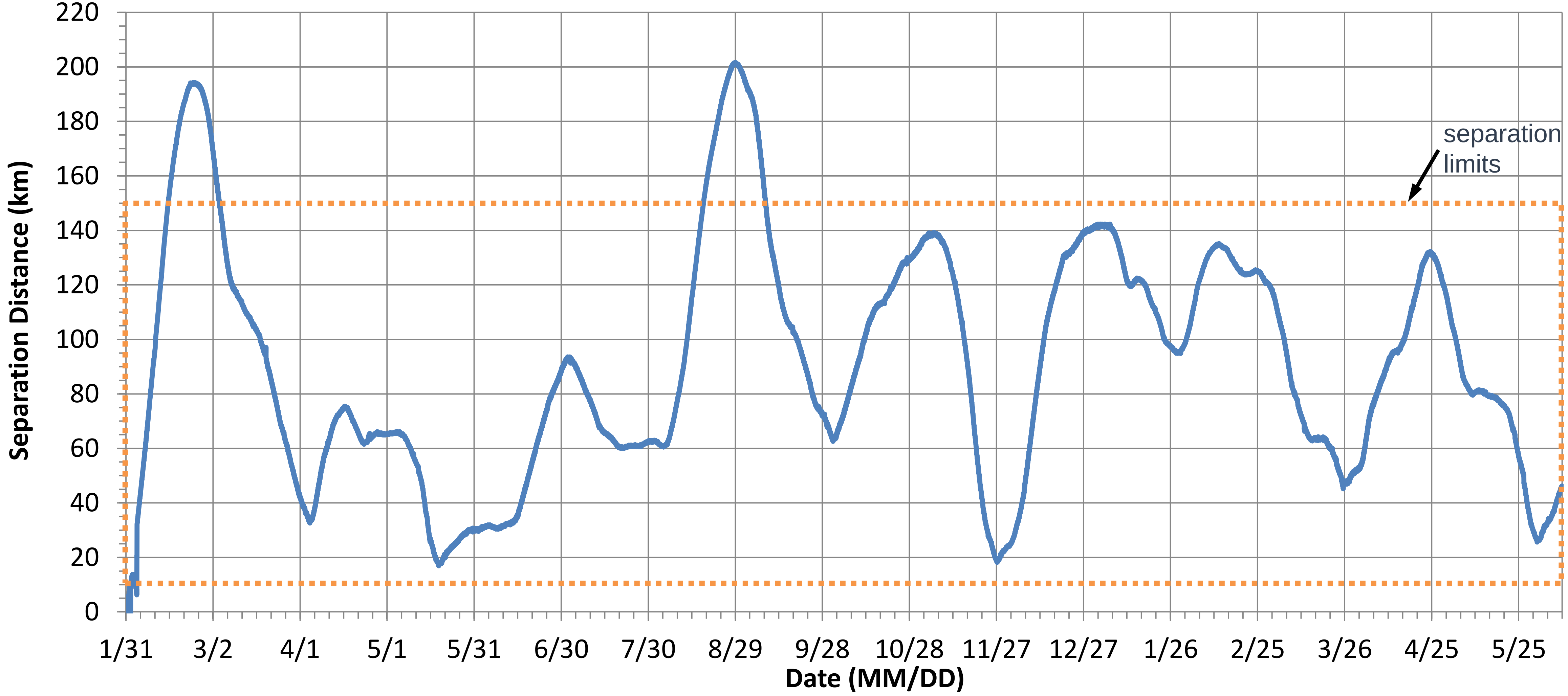


Formation Maintenance

Spacecraft	% of Orbits with Max Drag Maneuvers	% of Time On-Orbit in Safe Mode
CAT-1	15.6	14.1
CAT-2	11.2	14.4

- Weekly updates to drag maneuver plan were not sufficient
  - Drag differential due to safe-mode demotions or command lock-outs could affect spacecraft separation rate too quickly
  - Demotions could cancel scheduled drag maneuvers and exacerbate the issue
- Worked with Mission Ops to create process for adding drag maneuver commands manually to the command loads
  - Manual commands occurred in addition to commands added through CATApp command load generation
  - Initially only used as needed
  - In September 2019, began regularly checking separation trend mid-week based on updated TLEs and used manual commands more aggressively
- Raised the target separation distance from 75 ±25 km to 95 ±25 km in December 2019

Spacecraft Separation Distance Since Launch



Updates to Drag Maneuver Process

- Desire to make the drag maneuver planning more frequent and responsive
- Latest TLE is propagated forward and separation, s, and rate, $\dot{s}$, are calculated
- The desired separation and separation rate are
  - $s_d = 95$ km ± 5 km
  - For $s \leq 90$ km or $s \geq 100$ km, $\dot{s}_d = (s_d - s)/t$, where $t = 21$ days
  - For 90 km < s ≤ 100 km, $\dot{s}_d = 5/t$, where $t = 21$ days
- Bounds on $\dot{s}_d$ become incrementally tighter as the separation approaches 95 km.
- If $\dot{s}$ exceeds the bounds on $\dot{s}_d$
  - Required change in separation rate, $\Delta\dot{s} = \dot{s}_d - \dot{s}$ is calculated
  - Total duration of drag maneuvering is calculated based on previous results and modeling, then divided into number of eclipses
  - Maximum drag maneuvers are added to the appropriate spacecraft's next available command load
- Drag maneuver planning is updated twice a week with at least three days between updates
  - One day for command load creation and upload
  - One day for command execution
  - One day for the TLE to reflect changes in trajectory
- Time required to plan and implement commands decreased from ~ 8 hr./wk. to < 2 hr./wk.
- MD/NAV plans to work with CATApp team to integrate new process directly into the CATApp planning and command generation tool

Conclusion

- CAT mission has been successful in maintaining the desired in-track separation
  - The CAT spacecraft have never been below the 10-km separation range limit and only exceeded the 150-km separation range limit twice
  - First due to initial deployment velocity and delayed initiation of drag maneuvering
  - Second due to a series of untimely safe-mode and command lock-outs
- More frequent maneuver updates in combination with faster maneuver planning methods have been implemented based on lessons learned
- Primary CAT mission was successful and we look forward to a successful extended mission as well

Thank you to our US government sponsor as well as the other members of the CAT MD/NAV and Mission Operations teams!

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY