Experimental methods using force application of a single boom for a 500-m²-class solar sail

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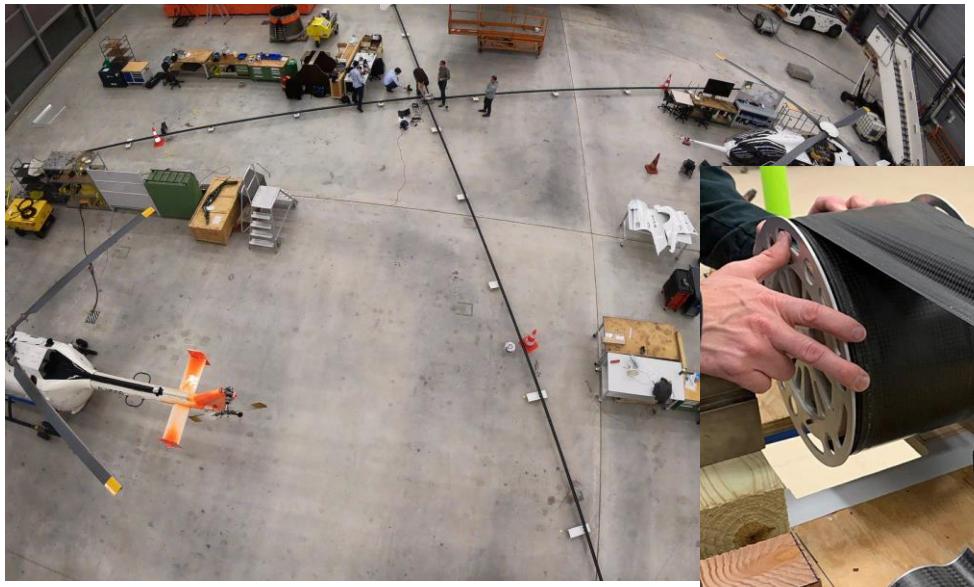
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Outline

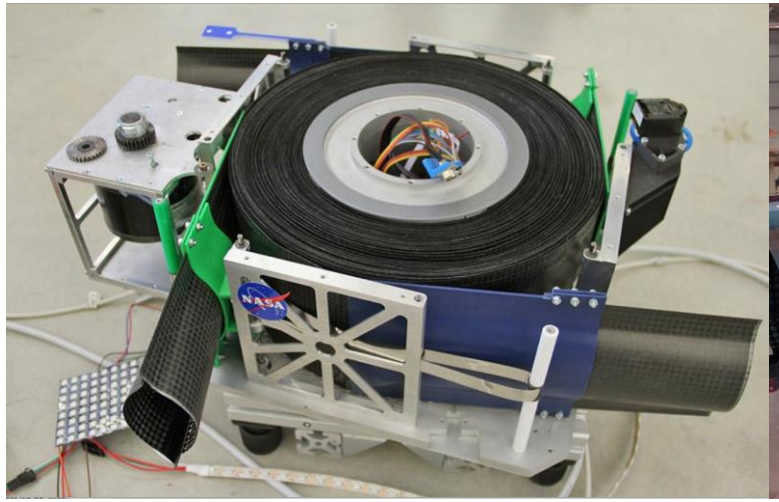
- Background and Experiment Goals
- Ground Experiment (1-g)
- Experiment Setup for Microgravity (0-g)
- Force Application System
- Photogrammetry Camera System
- Experiment Results
- Concluding Remarks and Outlook

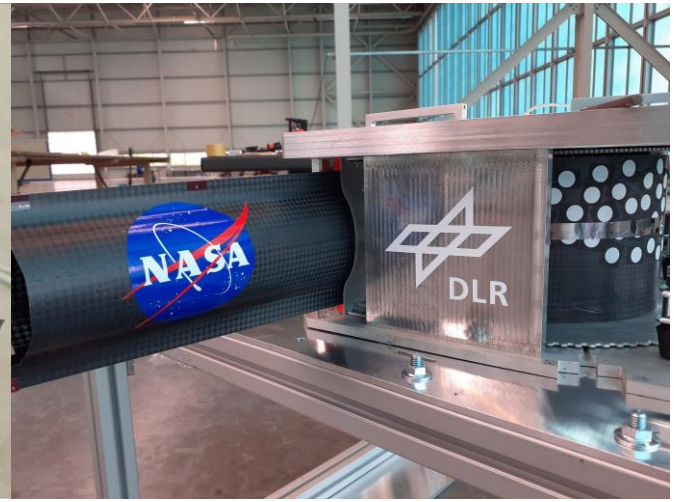
Background and Goals

- Rollable carbon fiber reinforced composite booms and deployment mechanisms
- 5-m to 20-m boom range
- Lenticular closed-section thin-shell boom: Collapsible Tubular Mast (CTM) boom
- Joint DLR/NASA project:
  - NASA: booms, analysis
  - DLR: deployer, testing
- Full-size deployment tests in DLR hangar (four 16.5-m diagonal booms)



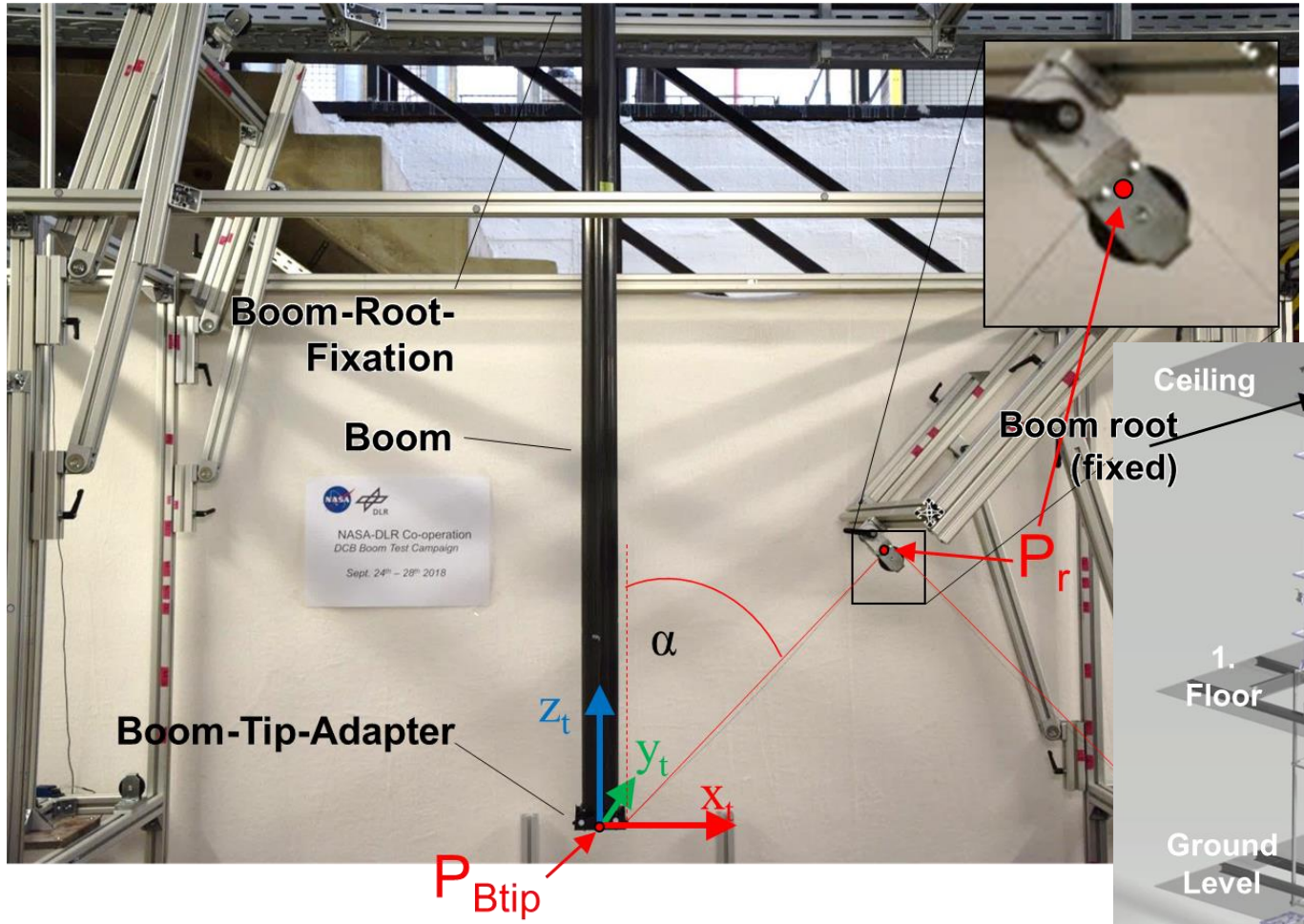


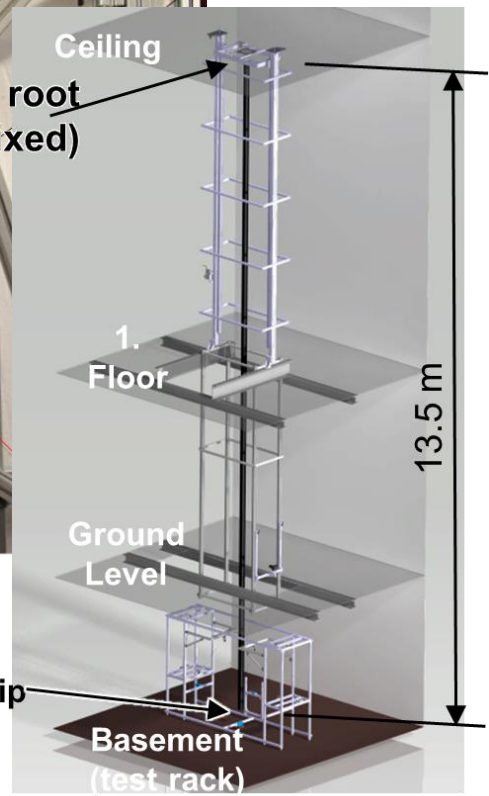




Ground Experiments (1-g)

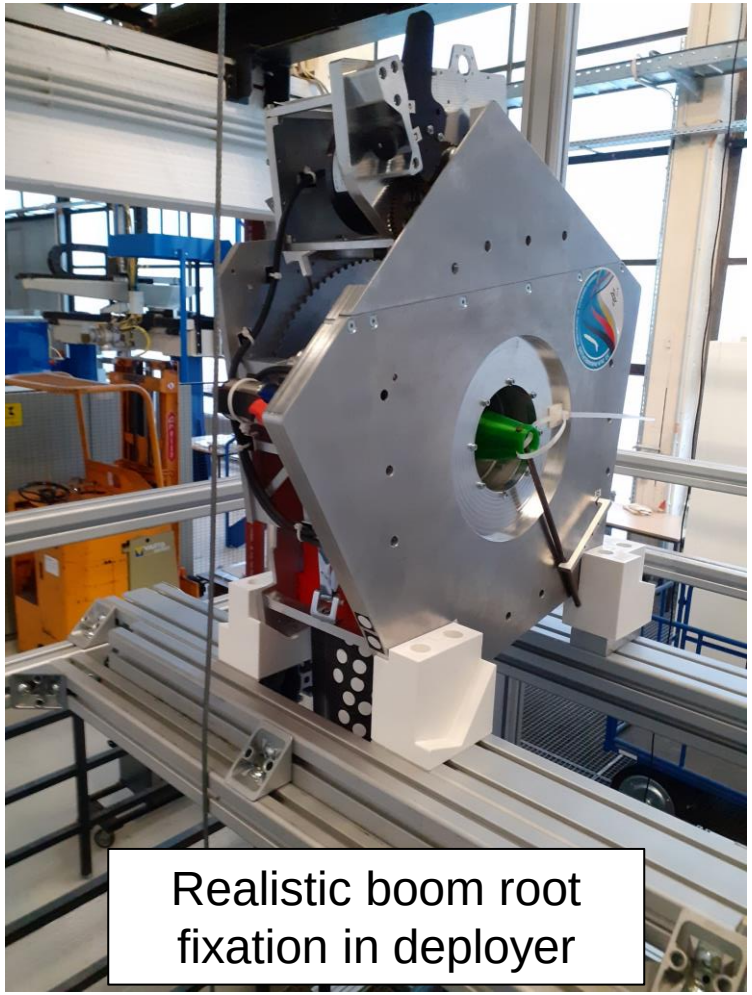
- Mechanical Characterization in vertical ground test stand:
  - Asymmetric lateral bending
  - Symmetric axial compression
- Influence of gravity on test results:
  - Self-weight of boom
  - Mass of tip adapter
  - Leads to “overlapping” load cases
  - Larger effect for longer booms (3.65 m vs 12.76 m)
- Testing in microgravity to eliminate gravity effects



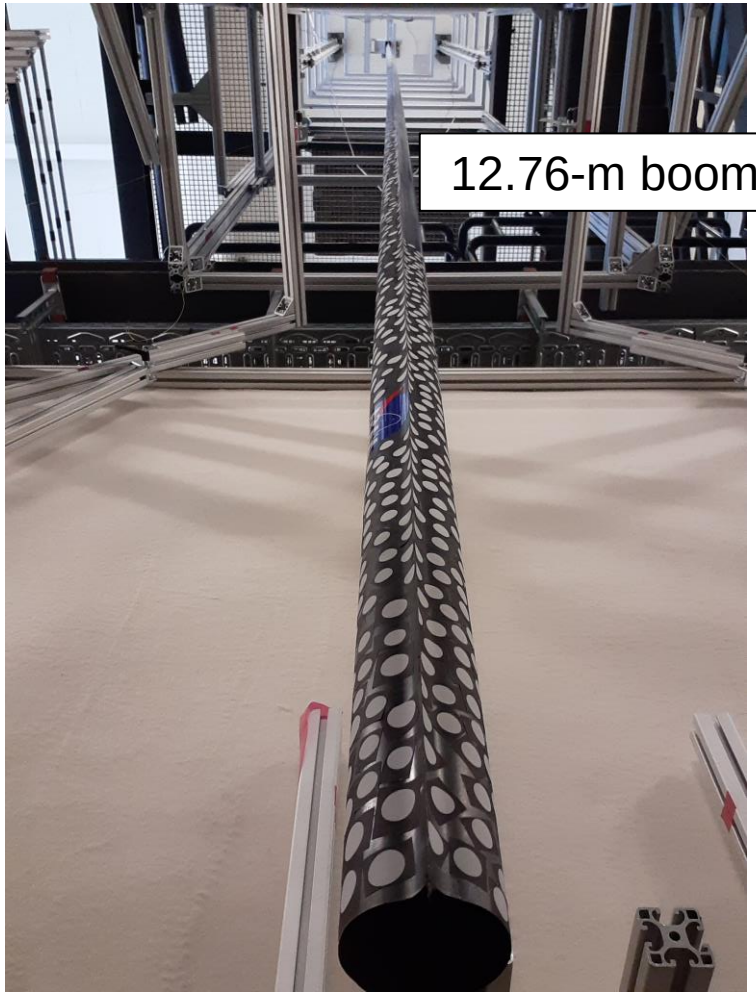


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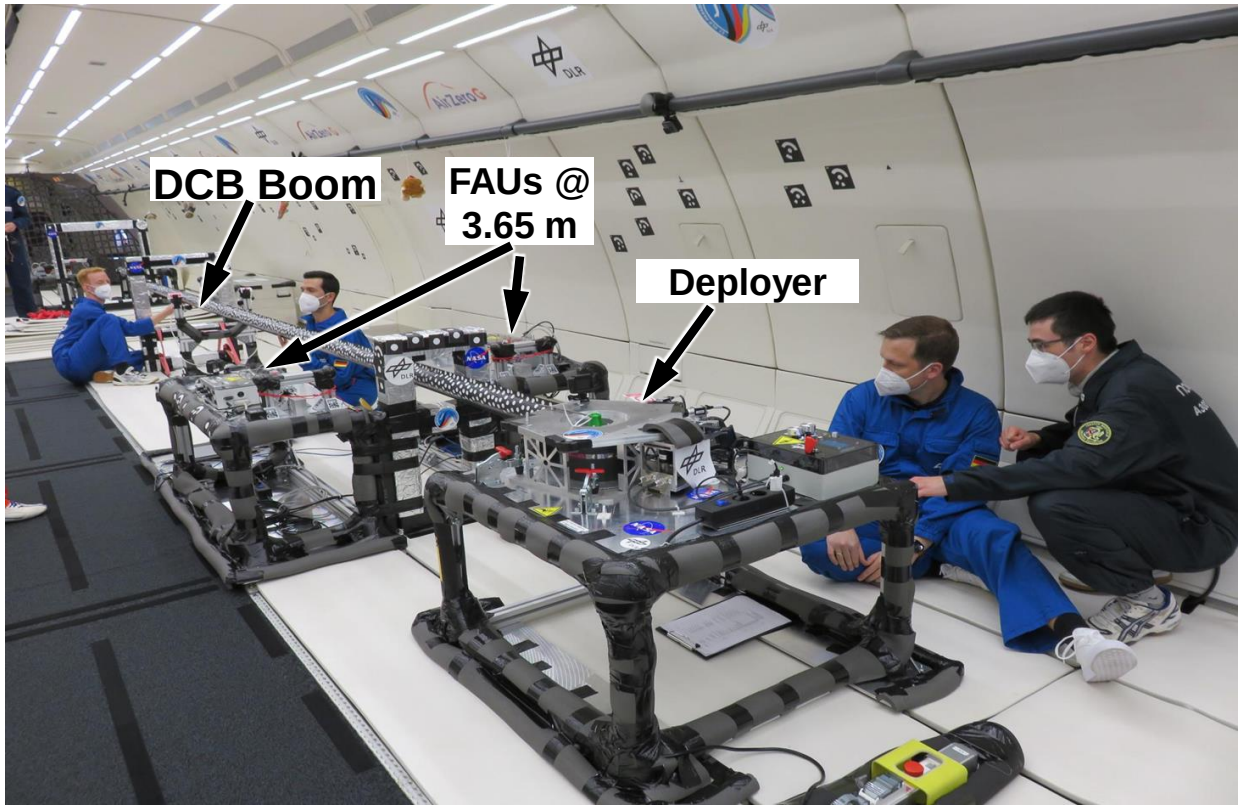
Realistic boom root fixation in deployer



12.76-m boom

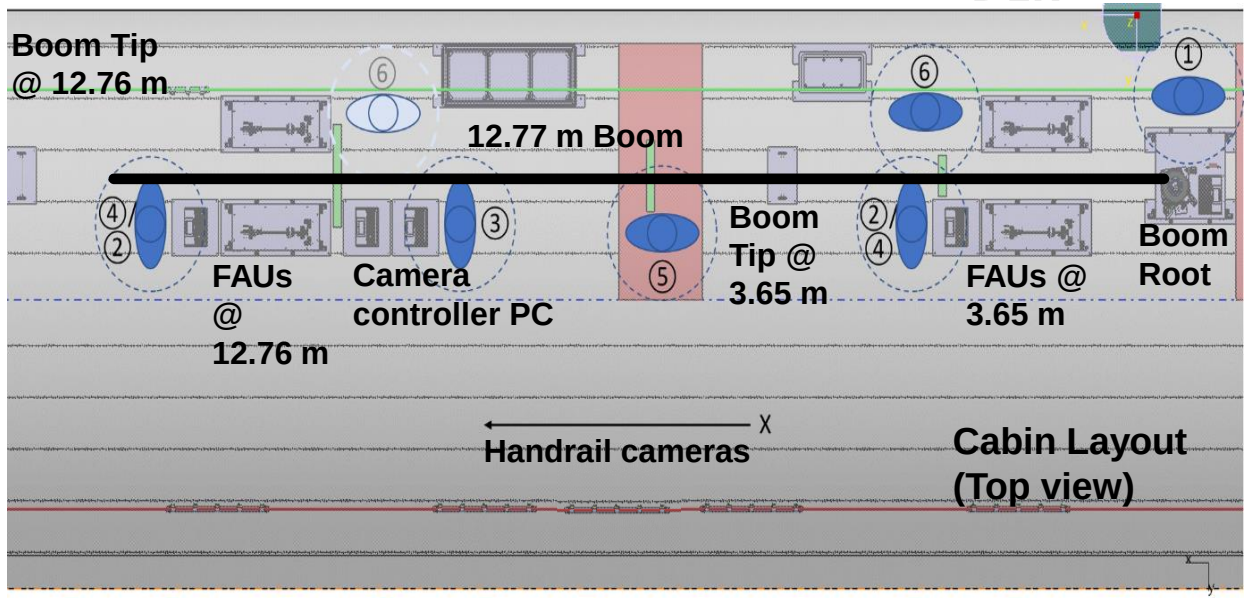
Experiment Setup for Microgravity (0-g)

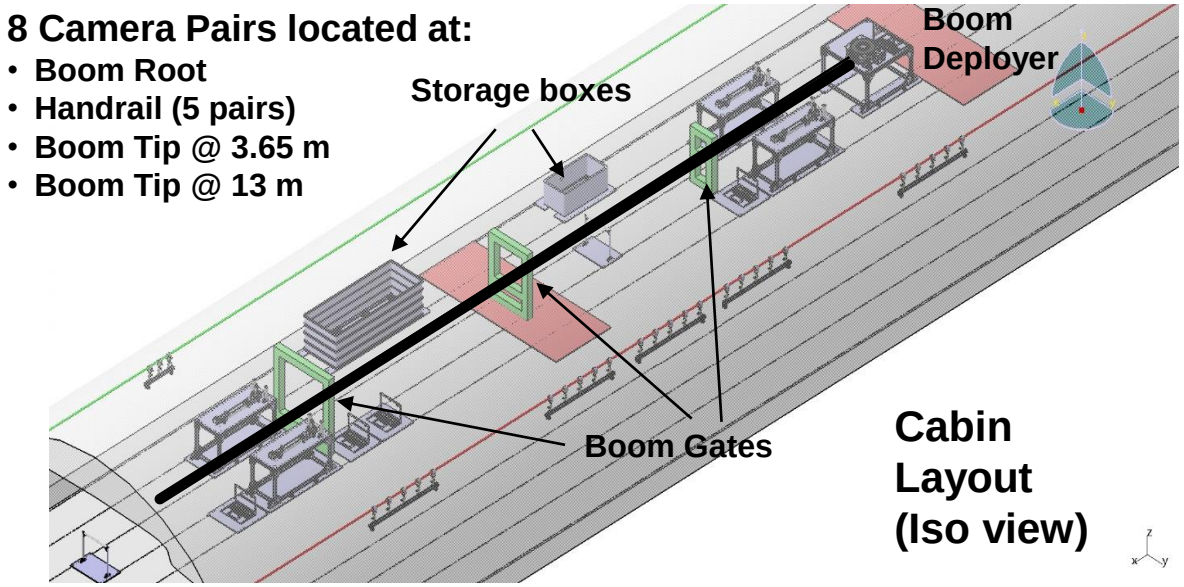
- Deployment and load testing 130 mm-tall, 13-m-long CTM boom in microgravity over 30 test parabolas.
- Test conducted on NoveSpace A-310 ZERO-G in the DLR 37th Parabolic Flight Campaign
- NASA CTM boom deployed using the DLR deployment mechanism
- Boom loading via the DLR force application units (FAUs) – 2 units at each of the 2 test stations
- NASA LaRC developed/provided 16-camera digital image correlation (DIC) photogrammetry system
  - Capture of boom deflections and shape during test sequence
- Static and dynamic load testing performed at 3.65-m and 12.76-m deployed lengths – here only static
- Symmetric and asymmetric loads introduced at the tip of the boom via FAUs with strings and springs



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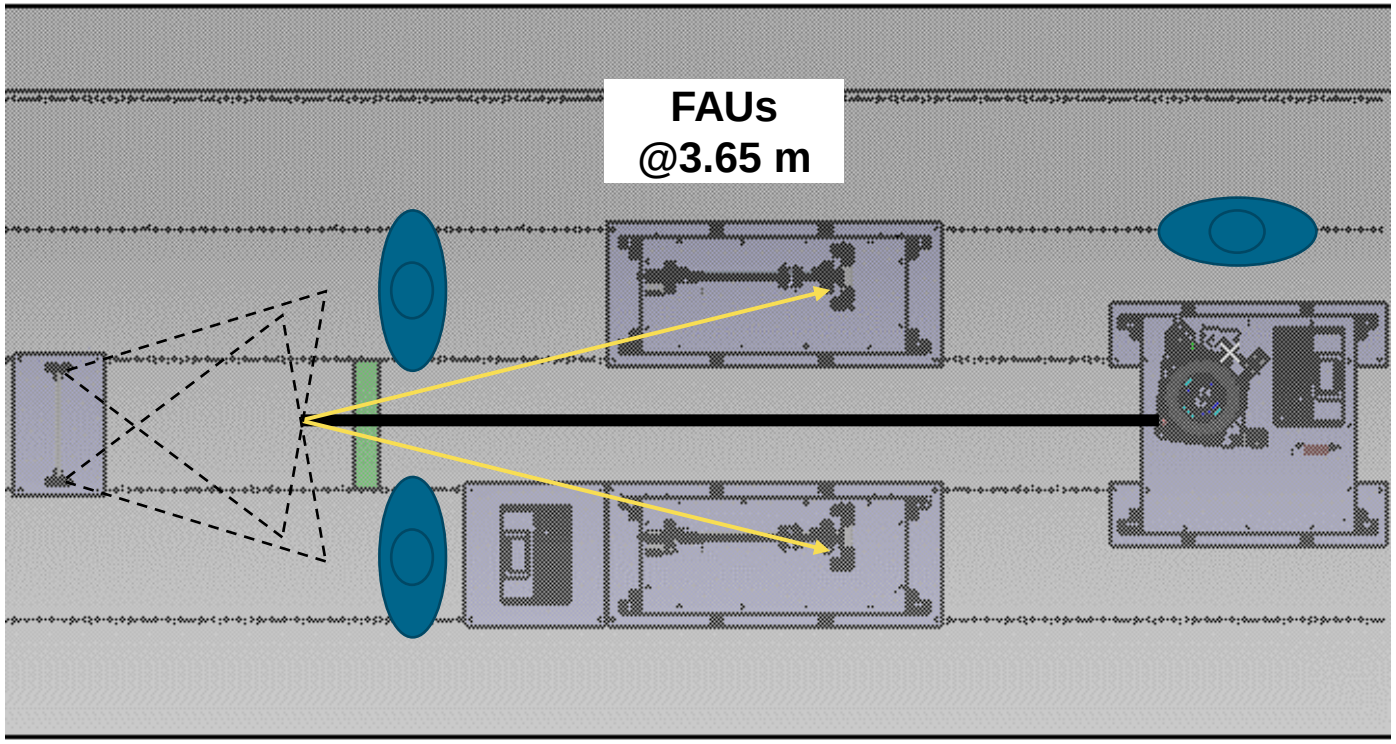


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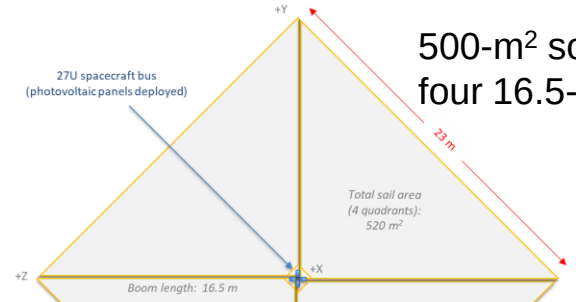
Force Application

- Static and dynamic load testing performed at:
  - 3.65-m deployed length
  - 12.76-m deployed length
- Emulating forces on a boom part of a 500-m^2 square solar sail through deployment and final tensioning to average ~35 kPa (5 psi) sail skin stress
- Symmetric load cases cover nominal conditions
- Asymmetric load cases cover off-nominal scenarios
- Given aircraft volume, sail quadrants are replaced by strings and springs
- Forces applied and measured via FAUs:
  - at 10° angle of attack (worst case)
- Boom displacements measured via photogrammetry cameras

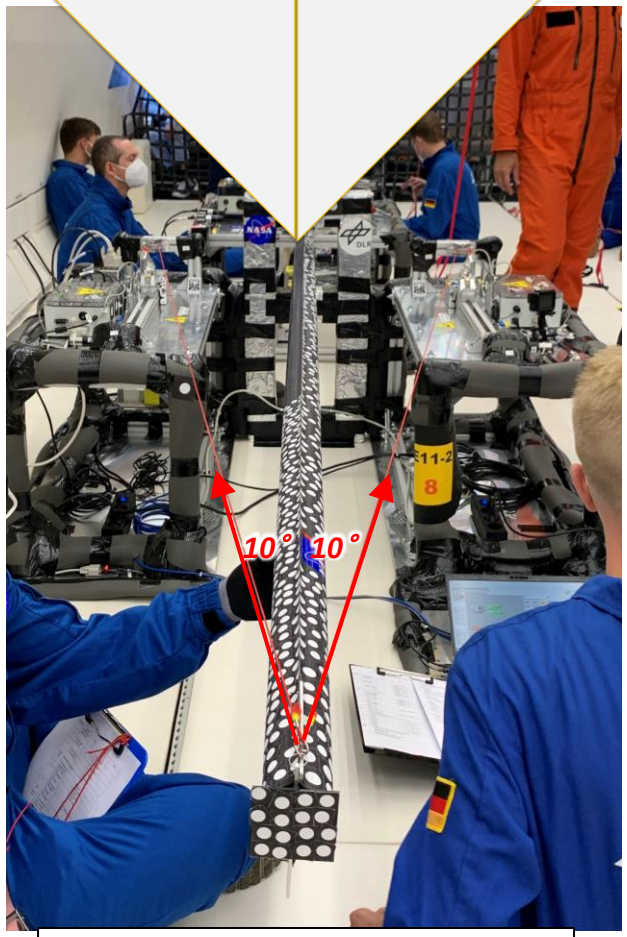


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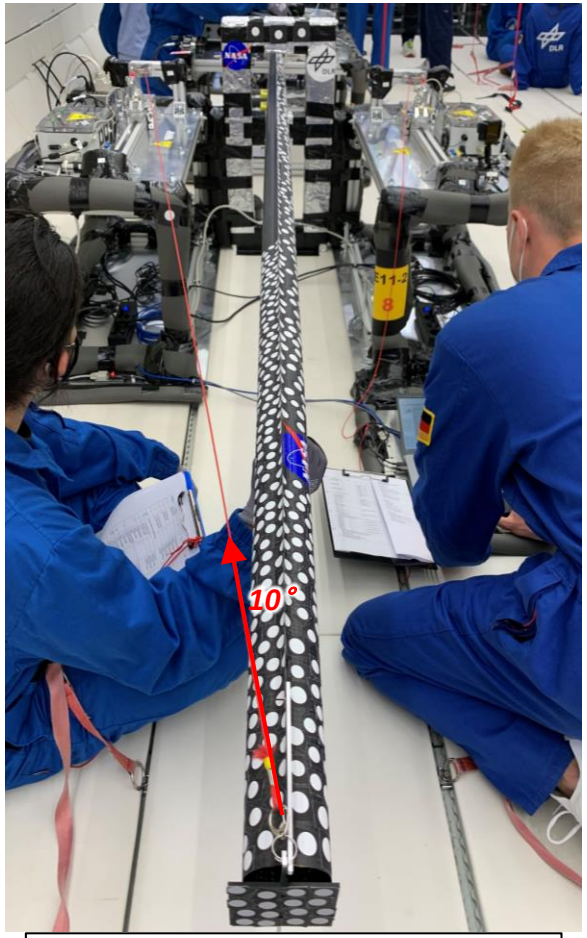
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500-m^2 solar sail with
four 16.5-m diagonal booms



3.65-m Boom
Symmetric Static Test



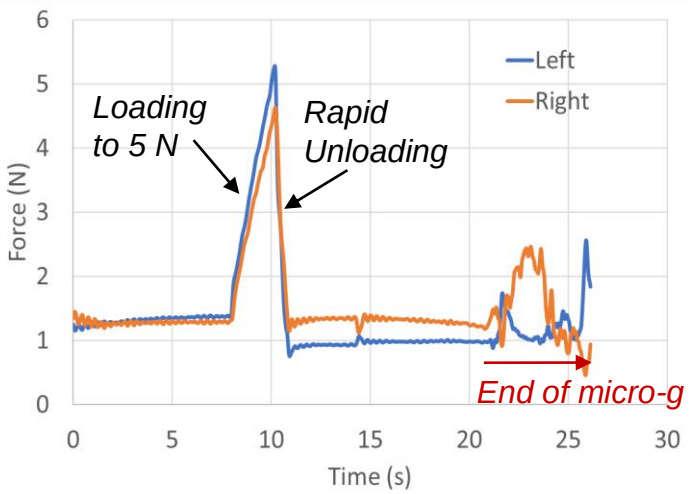
3.65-m Boom
Asymmetric Static Test

Force Application

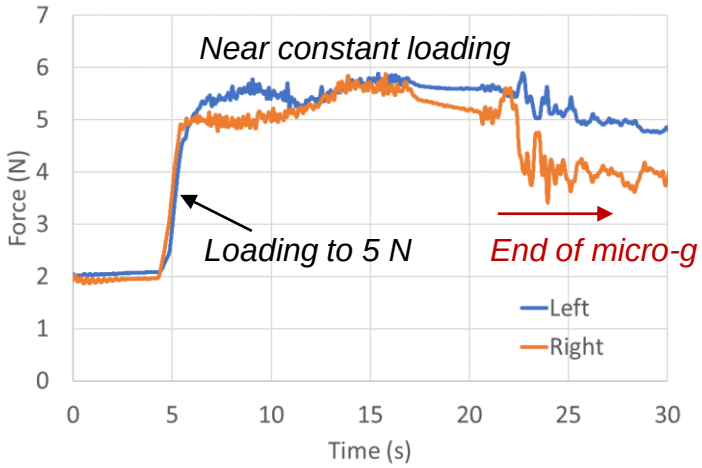
- 30 test parabolas with ~20 s microgravity (< 0.03g) phase between two 25–30 s hyper-g (1.8-g) phases
- Twenty-five parabolas for static and dynamic load tests performed at:
  - 3.65-m deployed boom length
  - 12.76-m deployed boom length
- Five parabolas to partially deploy boom towards the full length
- Symmetric and asymmetric loads testing via FAUs with strings at a 10° angle of attack
- Static tests apply ramp load until 5 N on a fixed boom inducing small boom displacements (< 25 cm) followed by rapid unloading → used to characterize boom stiffness
- Dynamic tests deploy the boom ~10 cm against 5 N constant force springs to emulate sail deployment and final tensioning to 35 kPa

Test sequence

Parabola #	Group of tests
1-5	Static testing at 3.65 m
6-10	Dynamic testing at 3.65 m
11-15	Continuous boom deployment
16-20	Static testing at 12.76 m
21-25	Static testing at 12.76 m
26-30	Dynamic testing at 12.76 m



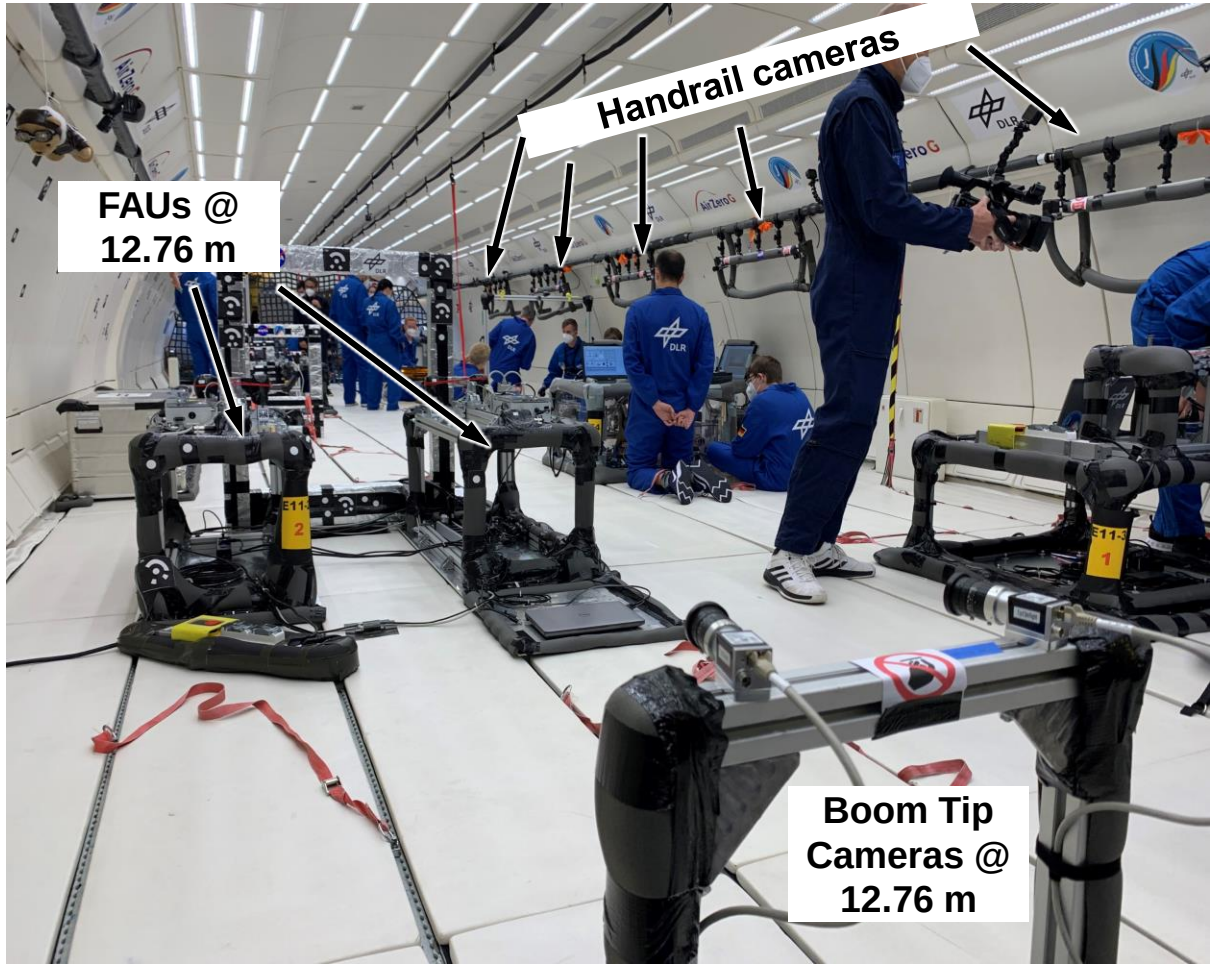
Static Symmetric Test 1 at 3.65 m (Parabola #1)



Dynamic Symmetric Test 2 at 3.65 m (Parabola #10)

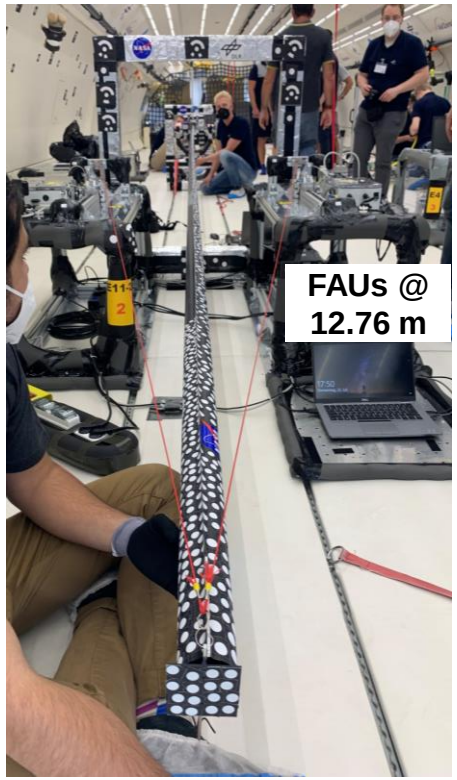
Stereo Photogrammetry Camera System

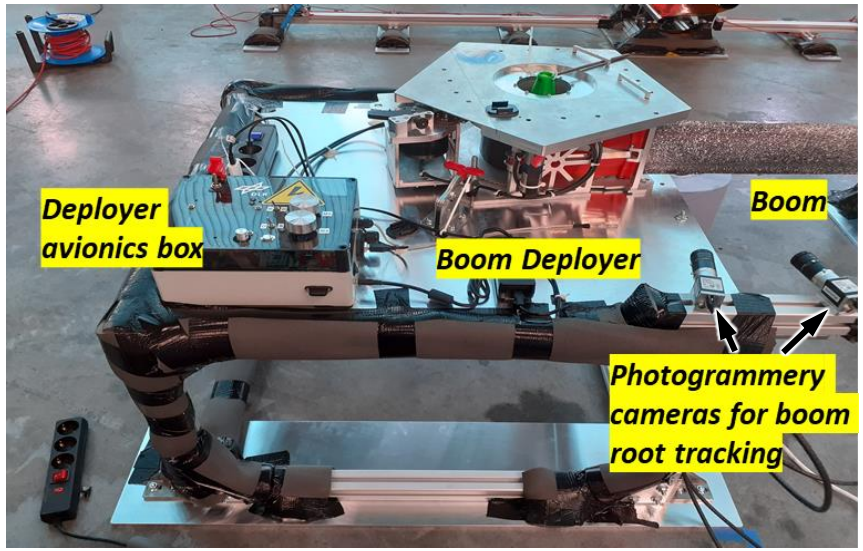
- Eight pairs of photogrammetry cameras at:
  - Boom root – located within the deployer rack.
    - Measure the full field strain of the boom root.
  - Handrail – Five pairs span the entire aircraft wall.
    - Measure boom global shape and displacement.
  - Boom Tip at 3.65 m – Track boom tip displacement.
  - Boom Tip at 12.76 m – Track boom tip displacement.
- 12 mm diameter targets over complete boom surface + tip target plate
- Additional random speckle pattern at boom root
- Goal of measurements:
  - Global displacements of boom
  - Capture of local shell buckling at root (critical area)
- Rate of camera frame acquisition: 4 Hz
- ARAMIS 2020© software developed by GOM Metrology



Stereo Photogrammetry Camera System

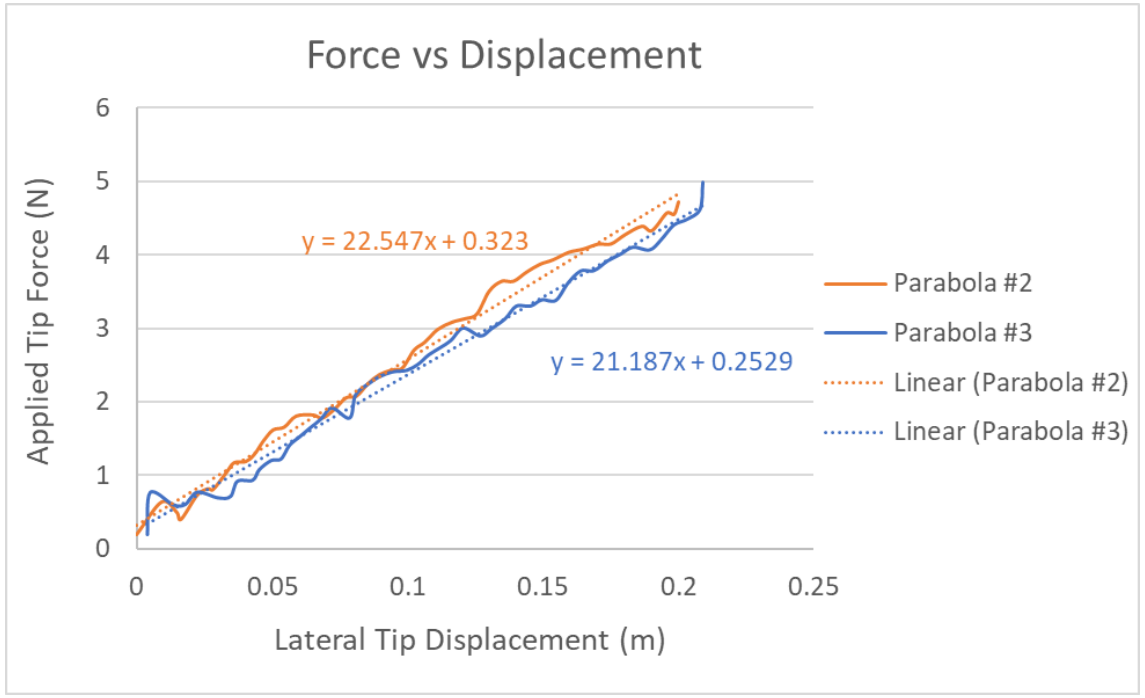
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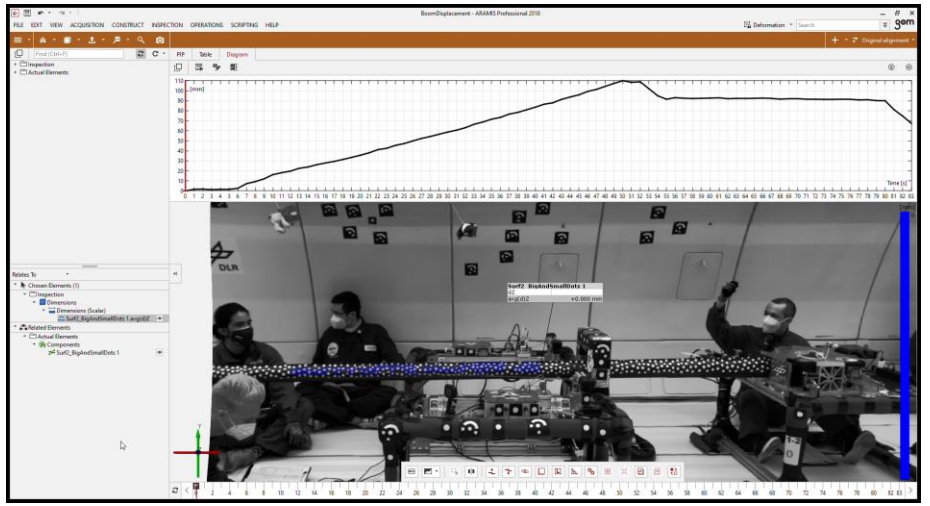


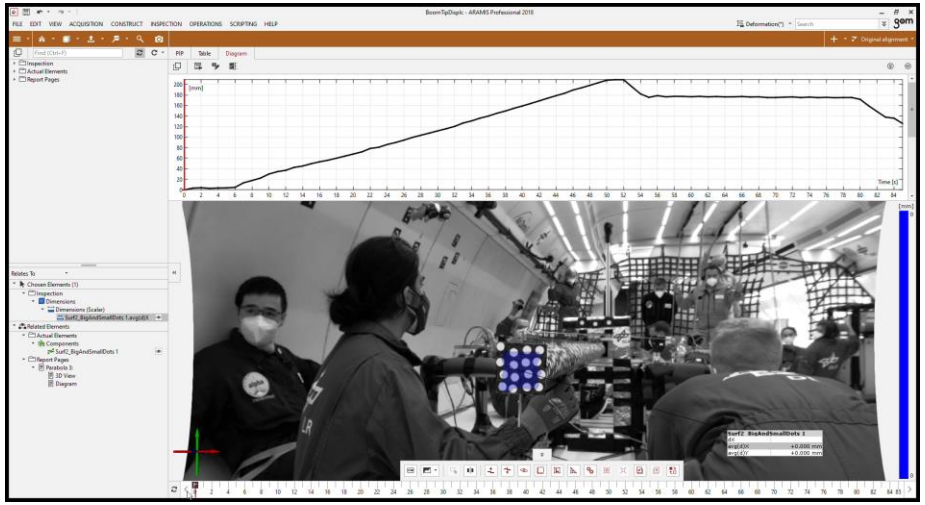
Experimental Results

- Static tests at 3.65-m boom length show repeatable, linear response.
- Parabola #2 and #3: Static Asymmetric Left
  - Linear response: Boom Stiffness ~22 N/m
  - Repeatable data



~1x Speed

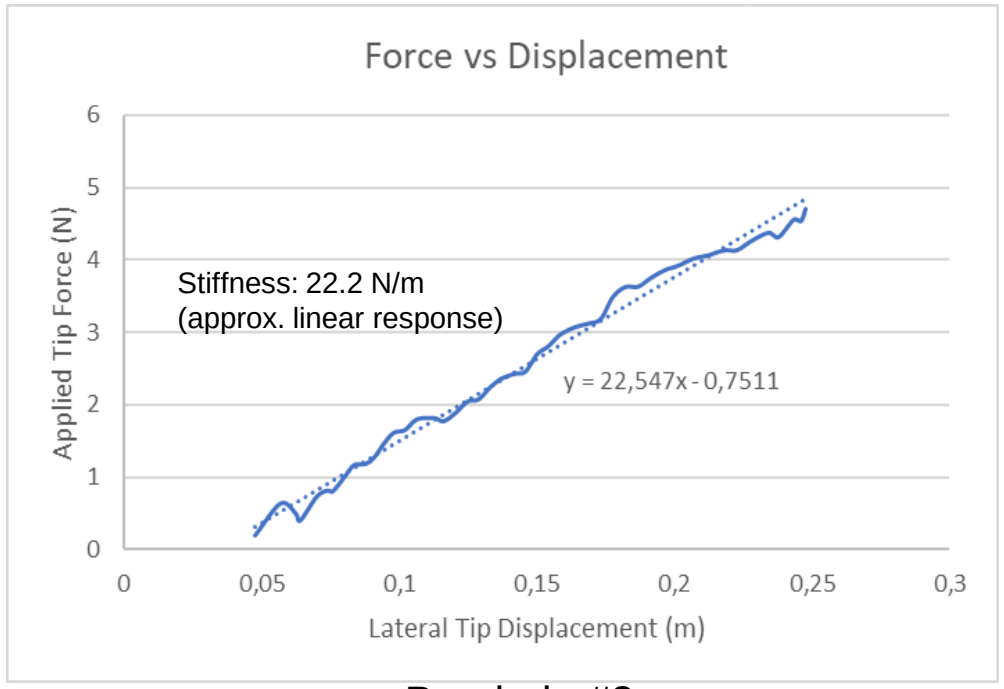




Experimental Results

- Static asymmetric case at 3.65-m deployed boom length:
  - Right side loading ~50% stiffer than left side → asymmetry in boom root guide shell within the deployment mechanism
  - Similar stiffness asymmetry observed in 1-g ground tests

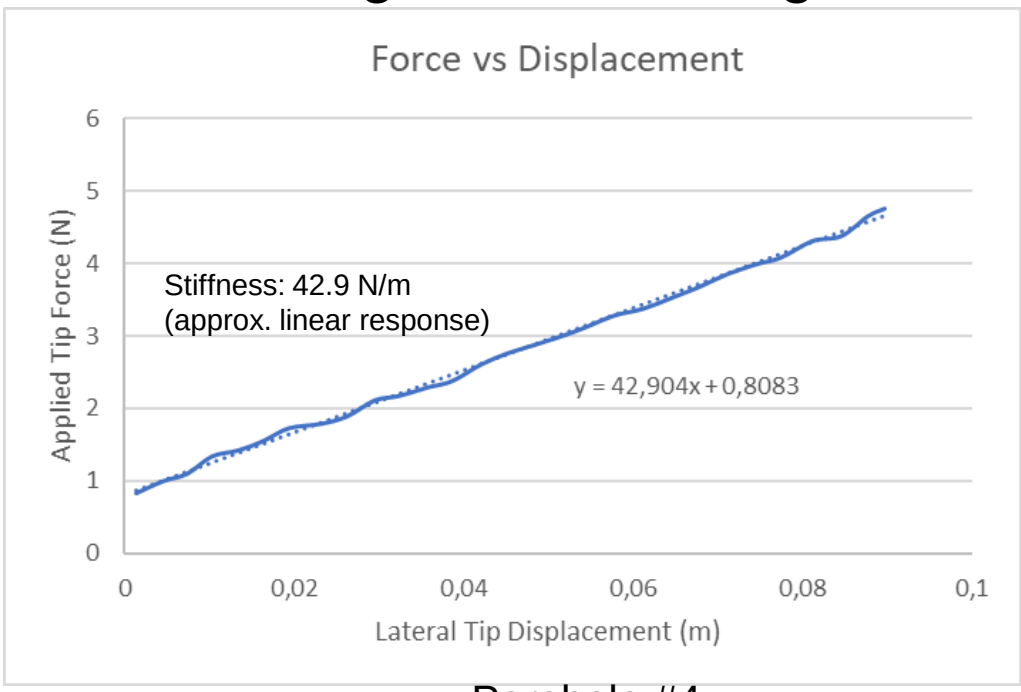
Left-side loading



Parabola #3

vs

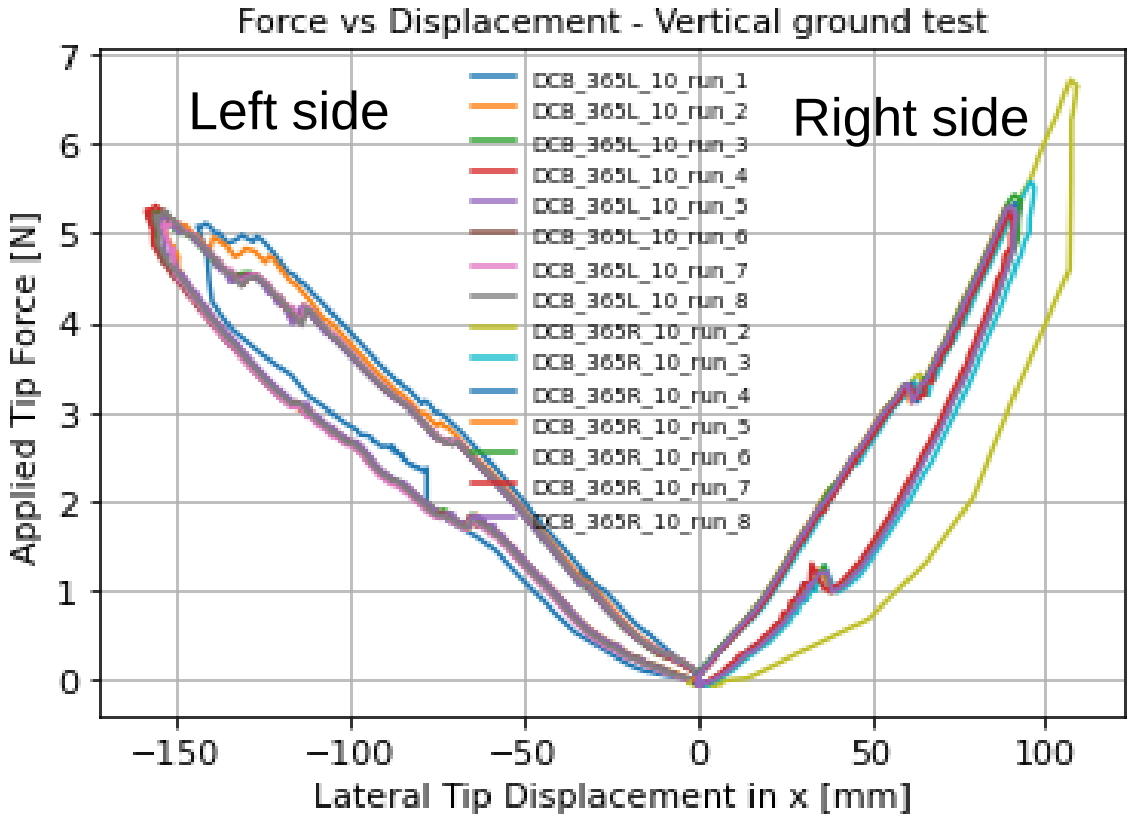
Right-side-loading



Parabola #4

Experimental Results

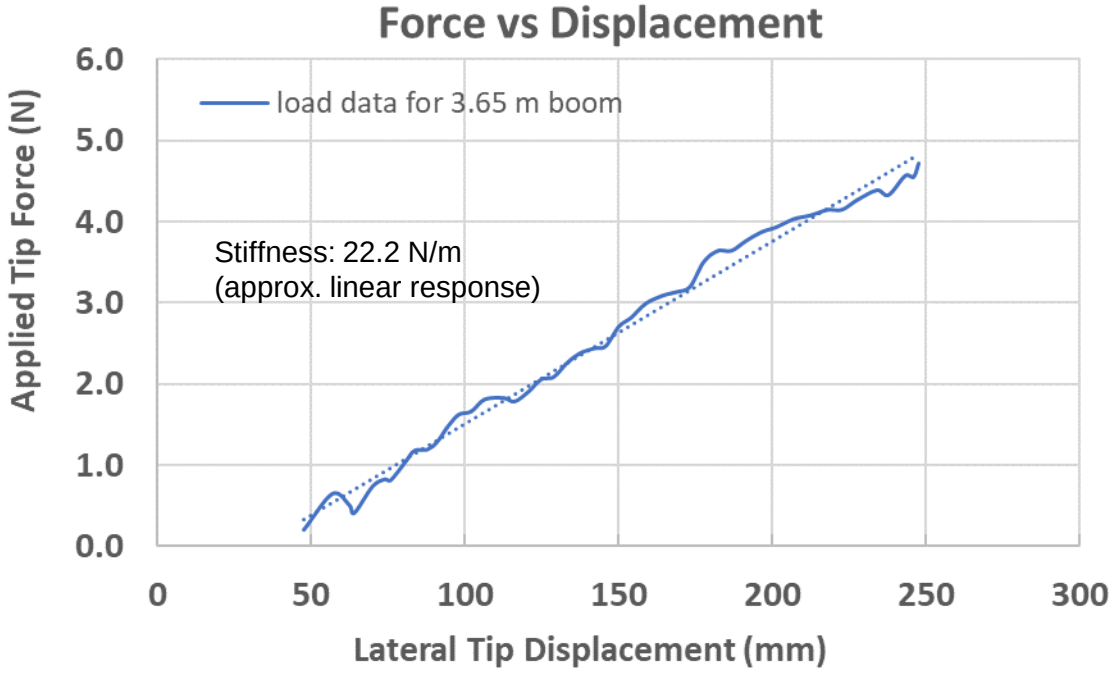
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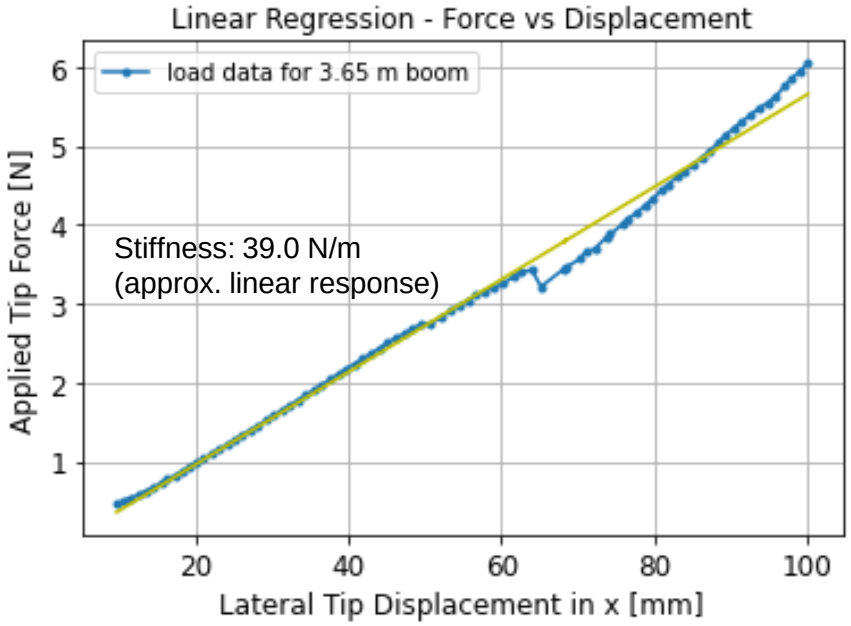
- Static asymmetric case at 3.65-m deployed boom length:
  - Boom stiffness of vertical 1-g ground tests ~30% higher than in microgravity
    - → Self-weight of boom and tip interface mass in 1-g changes bending-compression loading

Left – Microgravity



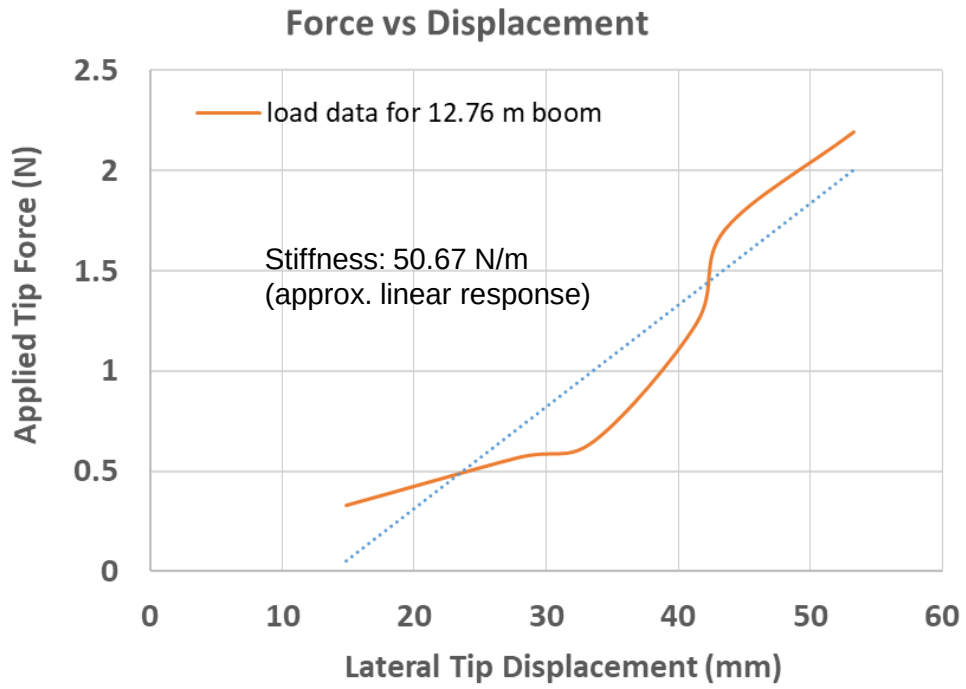
vs

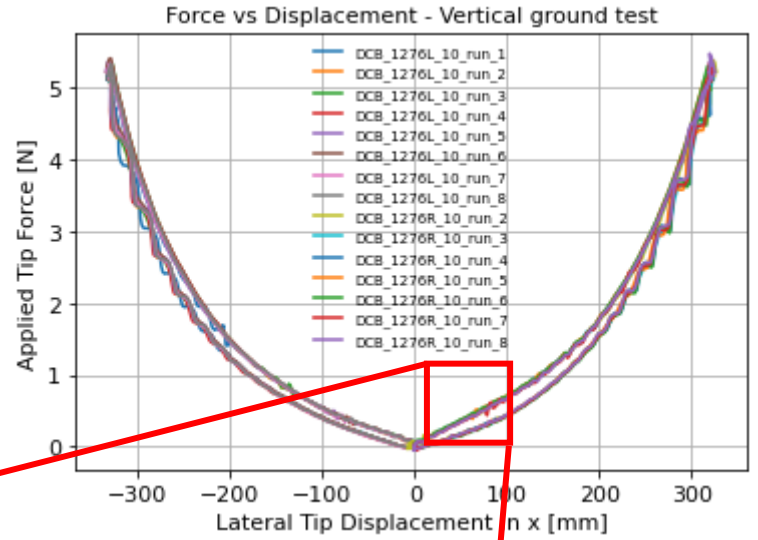
Left – 1-g Vertical

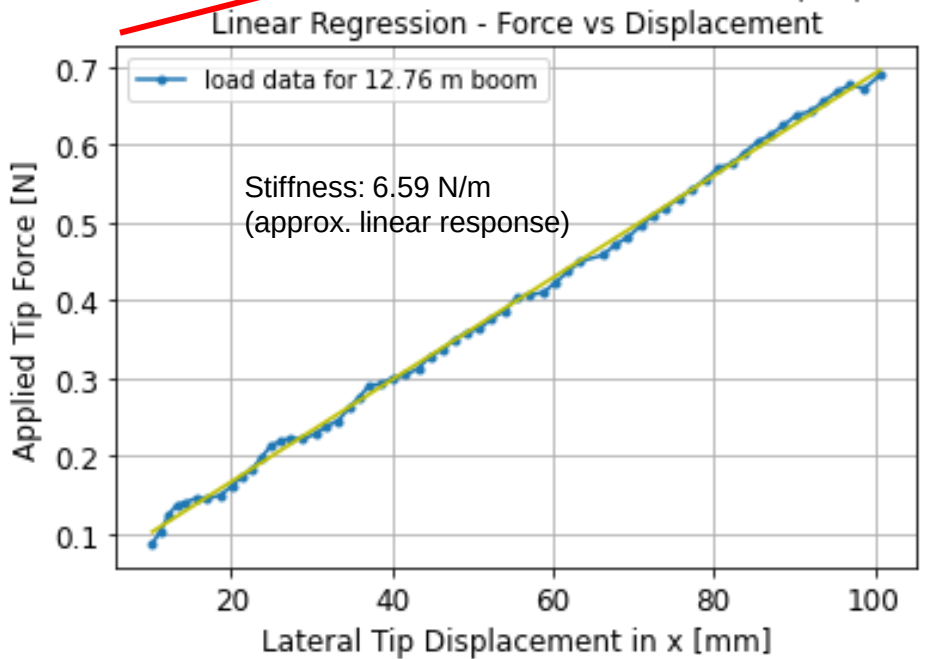


Experimental Results

- Parabola #20: 12.76-m Boom - Static Asymmetric Right
  - Appears to have linear response in microgravity
  - Clear non-linear response in vertical 1-g ground tests
  - In comparable linear range: stiffness in microgravity >> 1-g





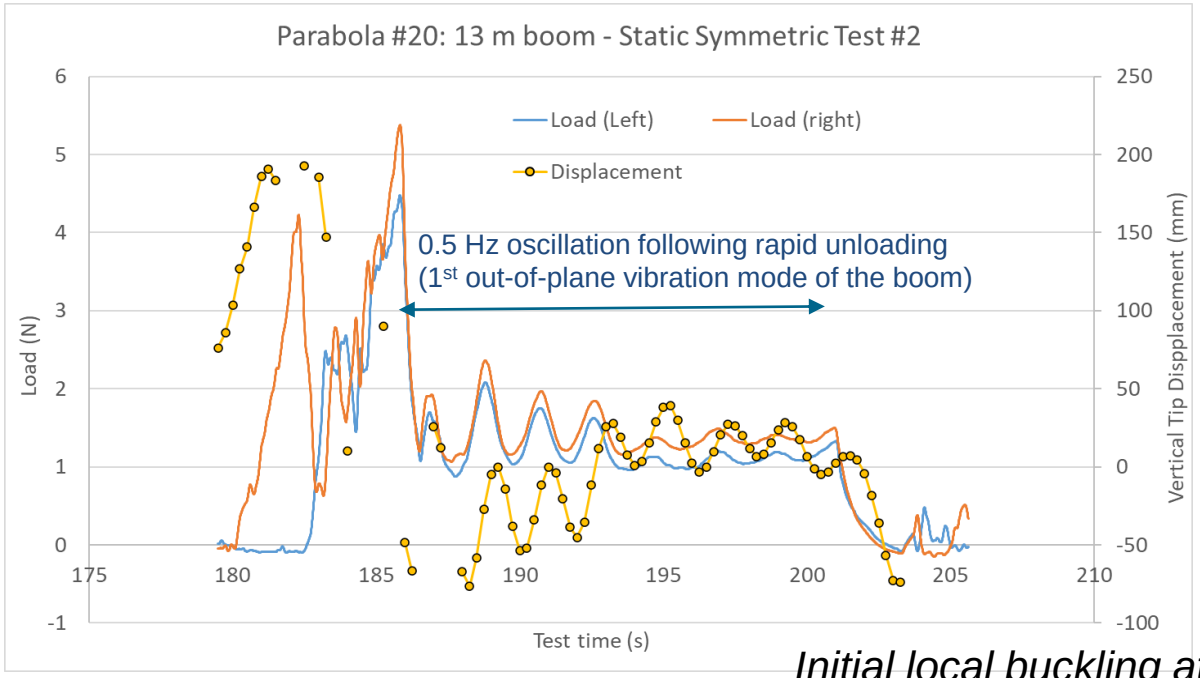


Experimental Results

- Static Asymmetric Cases – Scaling effect
  - In Microgravity, boom stiffness for 3.65-m vs 12.76-m deployed lenghs:
    - Preliminary results show similar stiffness: 43 N/m vs 51 N/m.
    - Measurements appear scalable, though aircraft dynamic environment introduced larger disturbances on the large-scale boom.
    - More flight data analysis at 12.76-m scale necessary to confirm.
  - In vertical 1-g ground tests, boom stiffness 3.65-m vs 12.76-m deployed lenghs:
    - Large discrepancy: 39.0 N/m vs 4.65 N/m.
    - Scalability of measurements only within small boom length range, when the effect of boom self-weight, tip mass, and unknown boundary conditions is smaller.
- Photogrammetry flight data for dynamic test cases still to be analyzed, but boom was effectively loaded to 5 N.

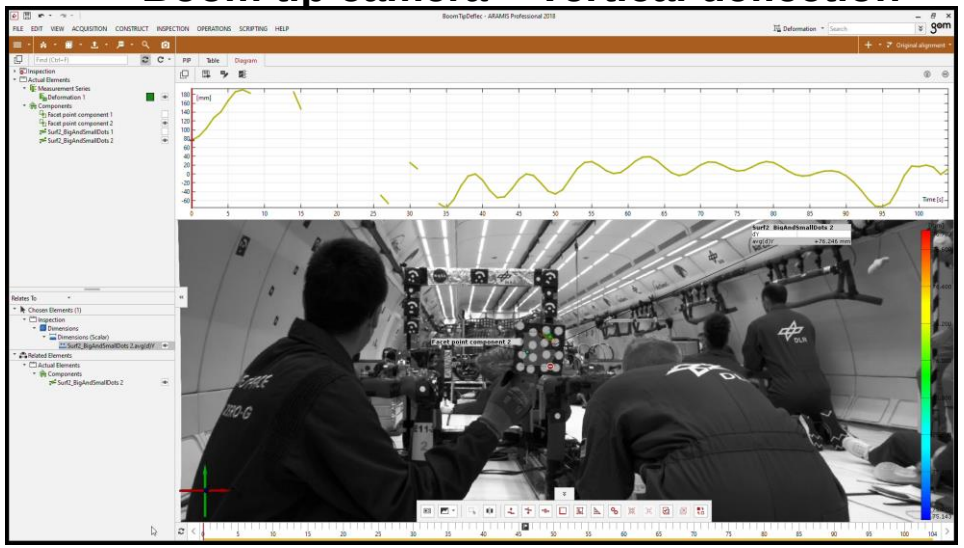
Experimental Results

- Par. #20: 12.76-m Boom – Static Symmetric:
  - 4 Hz frame rate not sufficient to capture rapid loading event to 5 N.
  - Captured an apparent 0.5 Hz out-of-plane vibration mode after string unloading induced by aircraft dynamics.

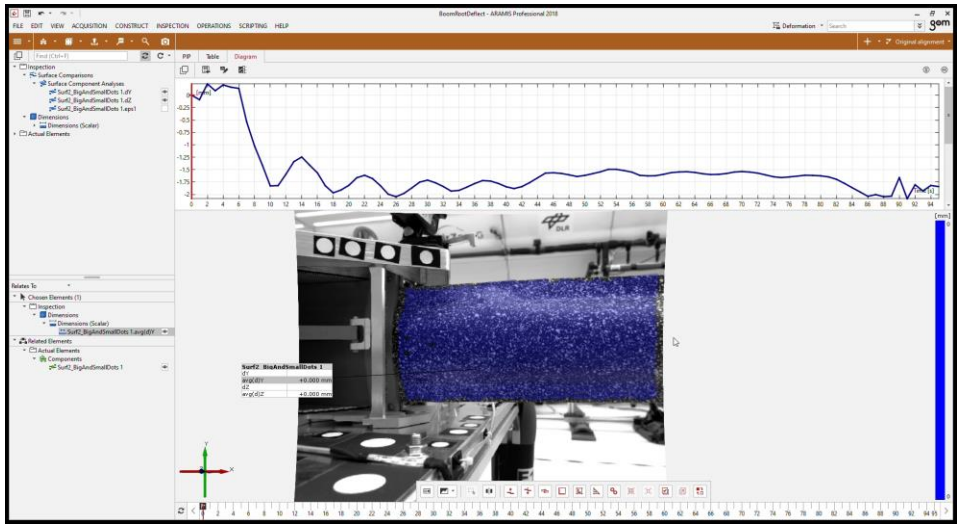


Initial local buckling at boom web due to excessive out-of-plane vertical deformation

Boom tip camera – Vertical deflection



Boom root camera – Vertical deflection



Concluding Remarks and Outlook

- Overall test successful for performing boom static and dynamic load testing at 3.65-m and 12.76-m boom length over 30 test parabolas
- Symmetric and asymmetric loads were effectively introduced/measured via FUAs and boom deflections measured in microgravity
- Testing at large scale (12.76 m) proved difficult due to boom dynamics initially introduced by manual boom release (from hold position during the 1-g and 1.8-g phases) at the entry of the microgravity phase and residual gravity in aircraft (< 0.03 g in all directions)
- Differences in experimental methods and boom response between tests in microgravity and vertical 1-g conditions was presented

Microgravity Tests

- Results provided a seemingly easier scalability analysis of the boom response.
- Proved more challenging to get a more controlled and stable test environment → parabolic aircraft dynamic conditions and manual operator errors were exacerbated at larger scales
- Photogrammetry frame rate of 4 Hz was insufficient to capture rapid boom movements that were induced in large-scale tests during loading event.
- Dynamic tests are still being analyzed.

Concluding Remarks and Outlook

1-g Vertical Ground Tests

- Repeatable and controllable at every test scale
- Provided additional loading factor (gravity) that affect and complicate results → particularly at the larger scale → requires computational correlation for truly characterizing the response of the boom in the intended space environment
- Highly nonlinear tip-load-displacement curves observed in all 12.76-m boom cases tested in 1-g conditions are in disagreement with the linear response measured in microgravity or at the shorter 3.65-m scale

Recommendation for Future

- More gravity off-loaded tests on long specimens; with robotic, synchronized boom release if in parabolic flight
- Ground testing booms by hanging them upwards and downwards to minimize/remove gravity effects

Questions

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