Static Wind Tunnel Testing of a Legged Venus Lander

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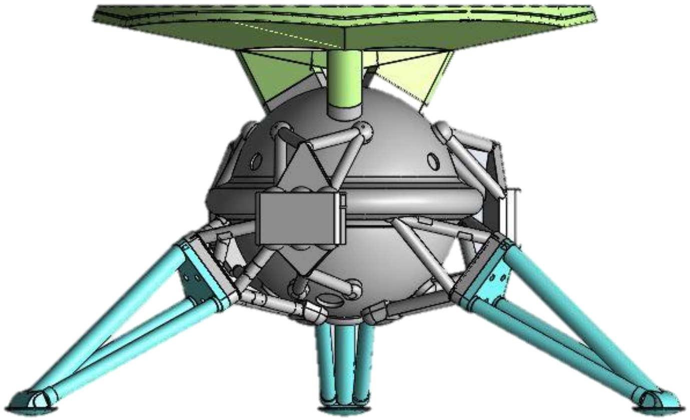
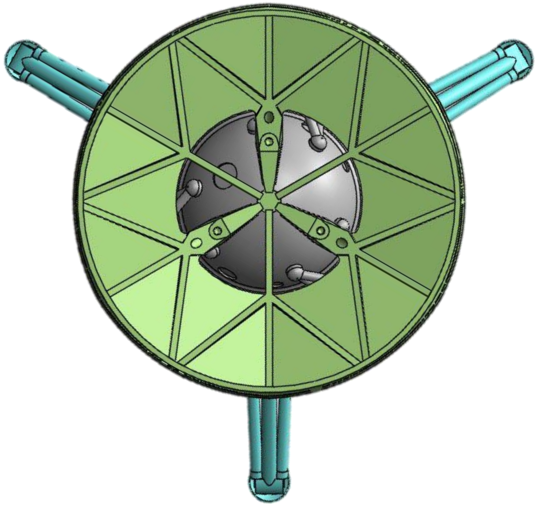


June 7, 2017

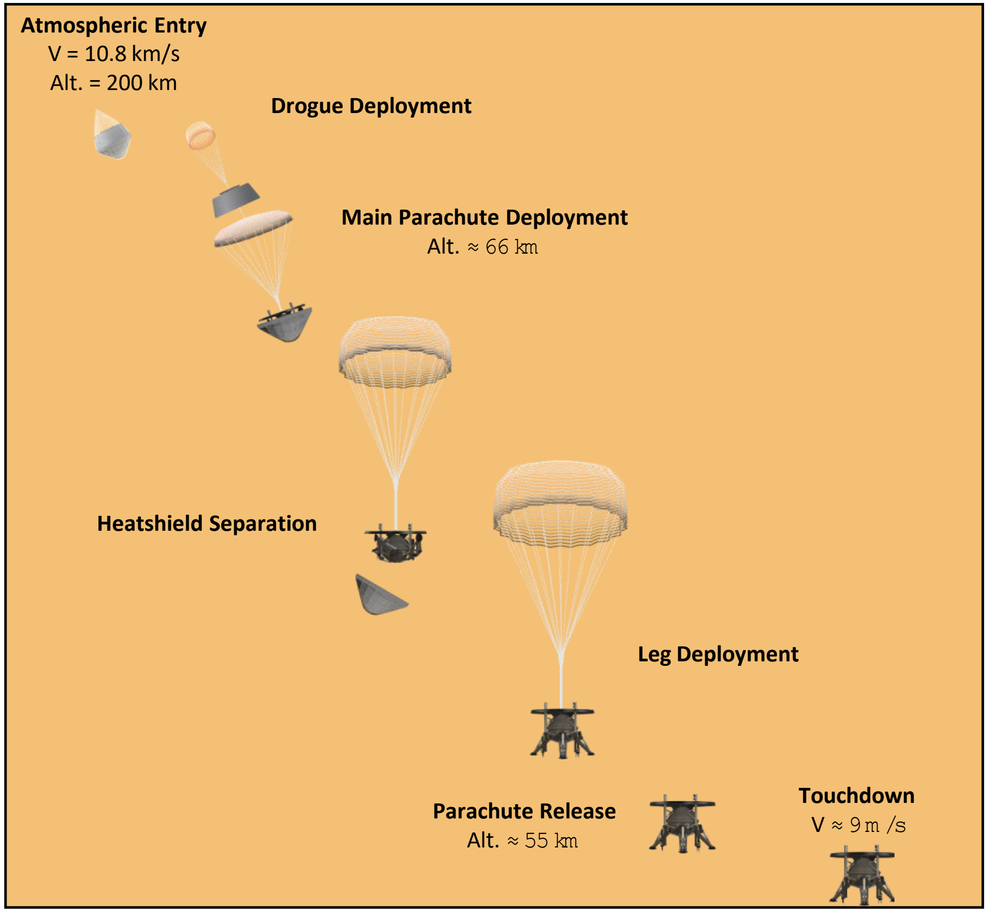


Aerodynamic Decelerator Systems Technology Conference

Introduction

- VISAGE is a Step-1 New Frontiers proposal for a Venus lander mission concept to perform atmospheric and surface science investigations

- Enter Venus atmosphere w/ 45 deg sphere-cone capsule
- Drogue removes backshell
- Backshell deploys main chute
- Heat shield is jettisoned and lander legs are deployed under main chute
- Separate from main chute ~55 km above surface
- Final descent under rigid drag plate, impact surface at ~9 m/s
- Crushable in lander legs for impact attenuation



Test Goals and Objectives

Baseline lander design must include drag plate size & configuration such that it:

- Meets final descent rate requirement (approximately 9 m/s)
- Is statically stable near 0 deg angle of attack, to avoid tumbling

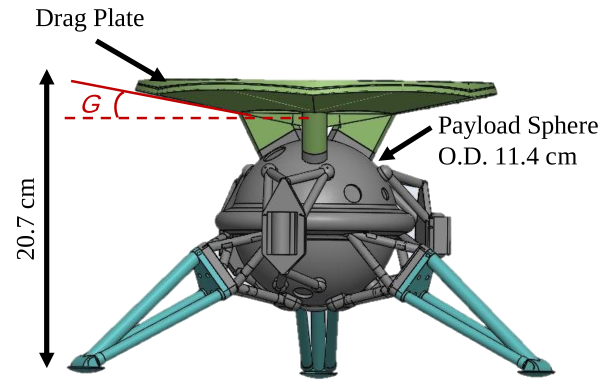
A static test of several preliminary lander designs took place between November 28 & December 5, 2016 at the Caltech Lucas Wind Tunnel (LWT)

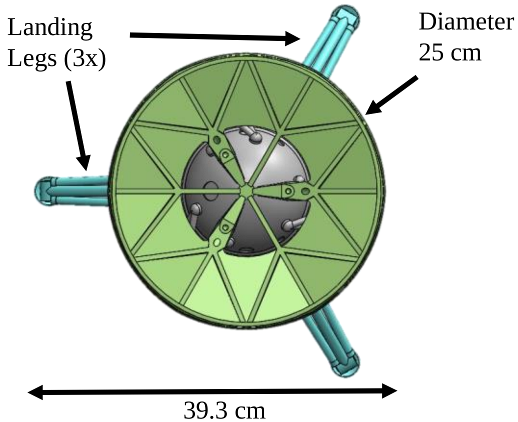
<u>Objectives:</u>

- Determine the drag coefficient of the VISAGE lander, w/a variety of drag plate configurations
- Determine the static force and moment coefficients as a function of angle of attack, for the VISAGE lander w/a variety of drag plate configurations
- Obtained detailed static force and moment coefficients as a function of angle of attack, for the lander w/selected drag plate geometries

Lander Models

- 8.6% scale model of the VISAGE lander 3D-printed out of M39 ABS





- Modular design allowed testing of several model configurations
  - Drag plate dihedral
    - 0 deg
    - 10 deg (baseline)
    - 30 deg
  - Drag plate solidity

    $$\frac{\text{Drag plate solid area}}{\text{Drag plate projected area}}$$

    - 83% (baseline)
    - 87%

0 deg

10 deg

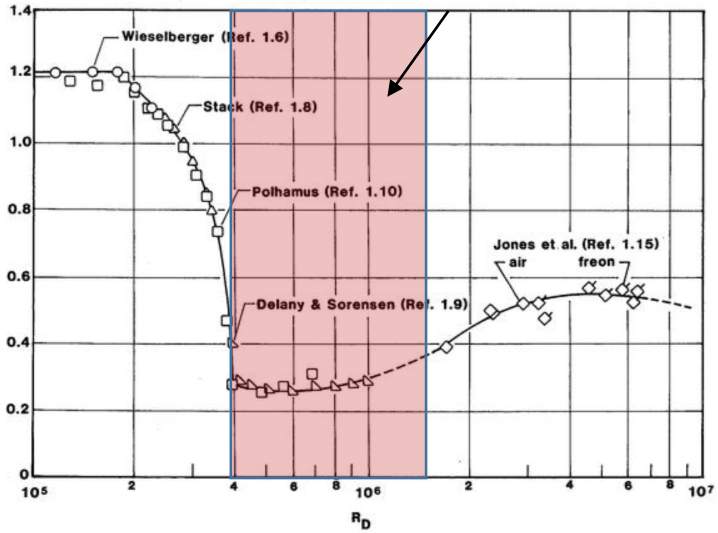
30 deg

Lander Models

- Reynolds number during testing will be 10x-40x *smaller* than at Venus

Expected *Re* of legs below 60 km at Venus

Expected *Re* of legs in tunnel ~ 3×10^4



E. C. Polhamus, NASA CR-3809 (1984)

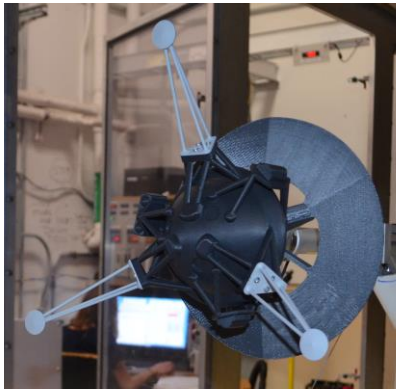
Flow around the leg tubes, was *subcritical* during testing, but *supercritical* at Venus ⟶ C_D of legs will 3x-4x larger in tunnel

Ideally, test models w/leg diameter scaled down to 1/3-1/4. Then: $(C_D)_{Venus} \approx (C_D)_{small}$

- Test models with:
  1. No legs
  2. Geometrically-scaled ("large") legs
  3. Scaled-down ("small") legs

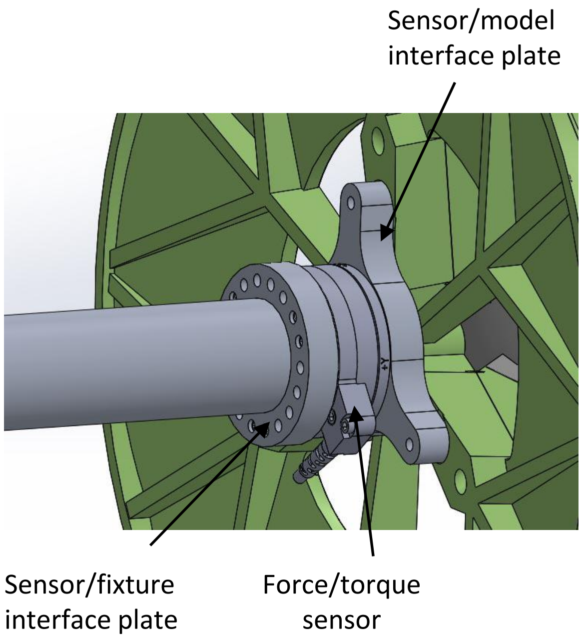
     Diameter of small legs is ~40% large leg diameter, due to manufacturing constraints

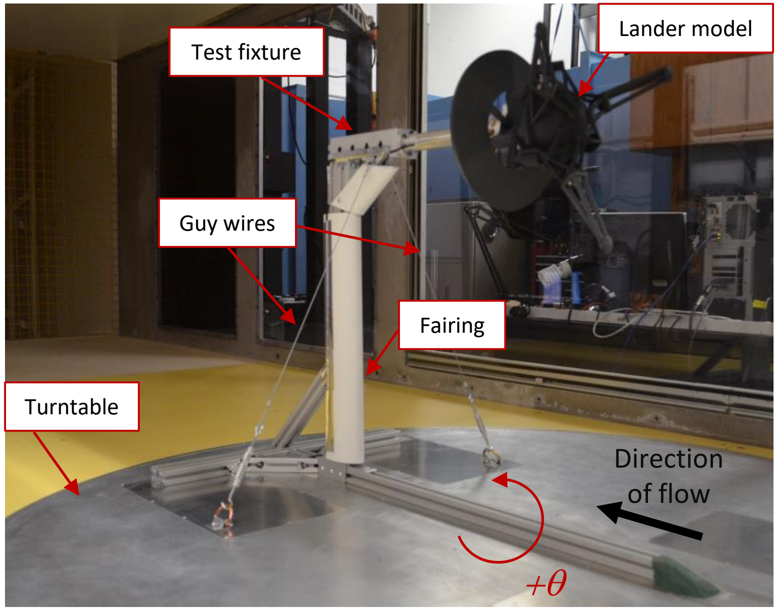
     Will have to scale down small leg results

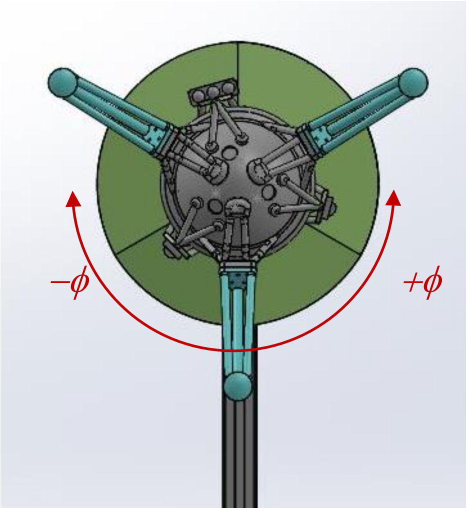


Test Configuration

- Tests conducted at Caltech's Lucas Wind Tunnel (LWT)
  - Test section: 1.3 m x 1.8 x 7.5 m
  - Model mounted on an L-sting. Fairing & guy wires to reduce vibrations
  - Turntable allows testing at different angles (θ)
- Force and moments on model measured using ATI Mini45 6-component sensor
  - Sensor/sting interface plate allows the model + sensor to be rotated in 20 deg increments
  - Allows testing at multiple roll angles (ϕ)







Test Matrix

- The following 12 configurations were tested in two phases:

Configuration ID	Drag Plate Solidity	Drag Plate Γ (deg)	Legs	Available Data
1	83%	10	None	Phase I
2	83%	10	Small	Phase I, Phase II
3	83%	10	Large	Phase I, Phase II
4	87%	10	None	Phase I
5	87%	10	Small	Phase I
6	87%	10	Large	Phase I
7	83%	0	None	Phase I
8	83%	0	Small	Phase I
9	83%	0	Large	Phase I
10	83%	30	None	Phase I
11	83%	30	Small	Phase I
12	83%	30	Large	Phase I

- Phase I: test all configurations at a single roll angle ϕ
- Phase II: selected 2 configurations to test at several roll angles
- During both phases:
  - Turntable angle sweeps of -30 deg to 30 deg
  - Capture force & tunnel data over a 20 sec period for each angle

- Wind Speed: 51 m/s
- Blockage-corrected q: 1610 Pa , Mach: 0.15
- Reynolds number (based on plate diameter): 8.5 x 10^5 (15-60 times lower than at Venus)
- Area blockage: 2%, dynamic pressure blockage: 5%

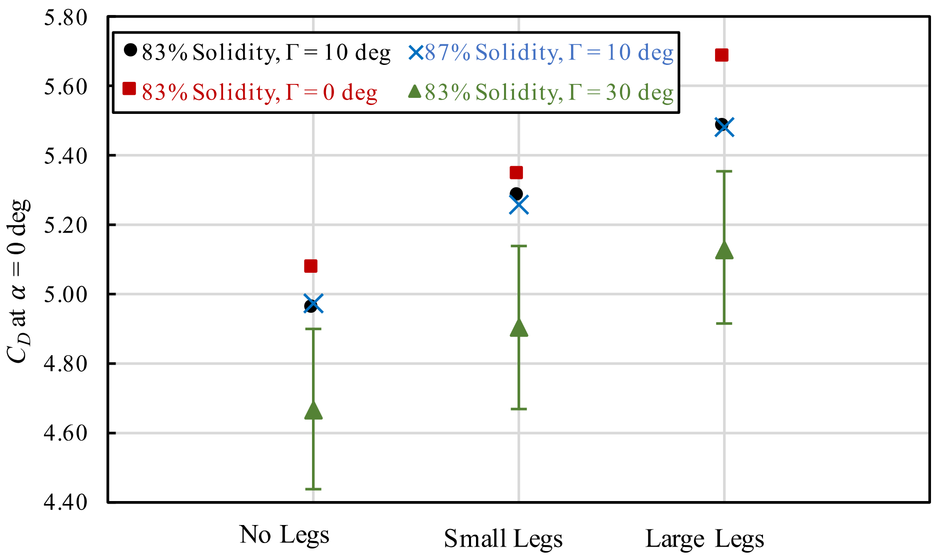
C_D at 0 deg angle of attack

When θ = 0 deg:

$$C_D = \frac{AF}{q_c S_0}$$

q_c is the blockage-corrected q

S_0 is the frontal area of the payload sphere



Error bars: total uncertainty estimates, as a 95% confidence interval (shown on one data set only for clarity)

- C_D increases with increasing leg diameter
  - "at Venus" C_D of full scale lander expected to be slightly smaller than small leg C_D
- C_D decreases with increasing drag plate dihedral
- Negligible difference between the C_D at 0 deg of the models with 83% and 87% solidity
  - No flow through the drag plate opening at 0 deg (verified via smoke visualization)

C_D at 0 deg angle of attack

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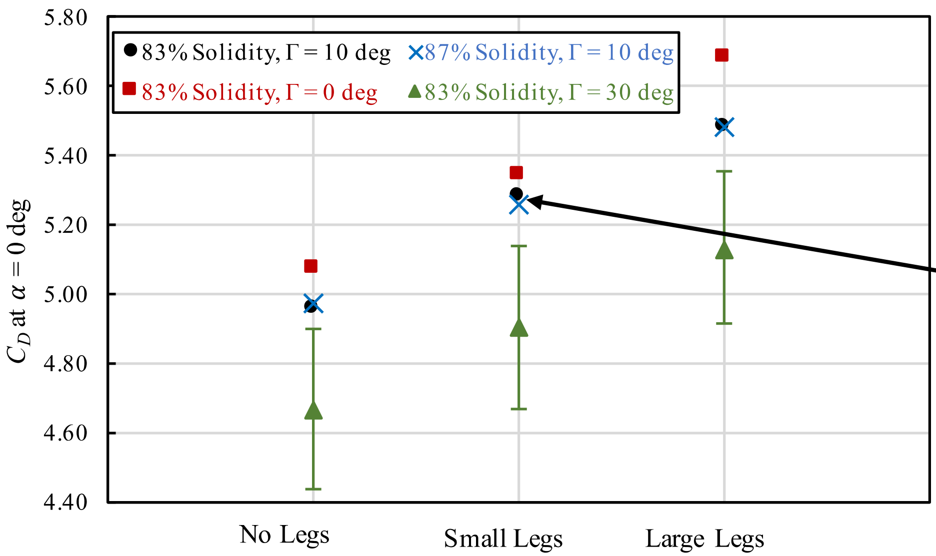
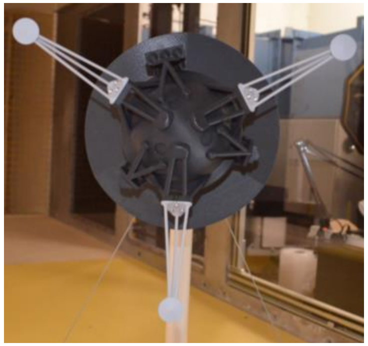


Error bars: total uncertainty estimates, as a 95% confidence interval (shown on one data set only for clarity)

Config. 2:
Γ = 10 deg
83% solidity
Small legs



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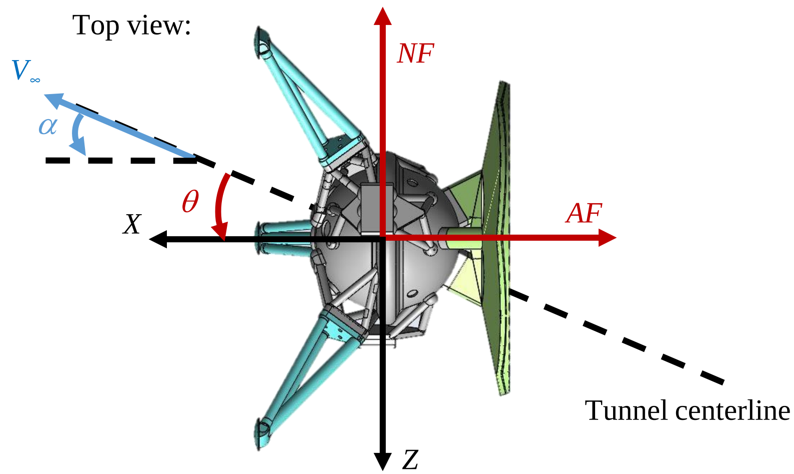
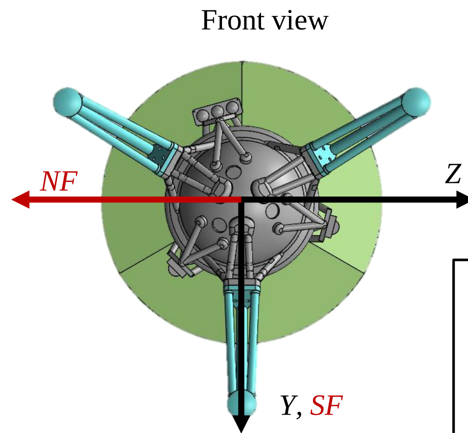
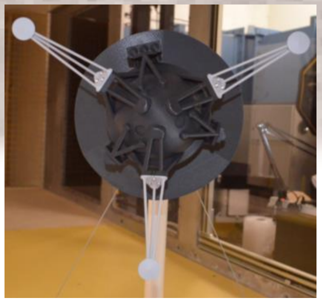
Static Aerodynamics ($\phi \approx 0$)



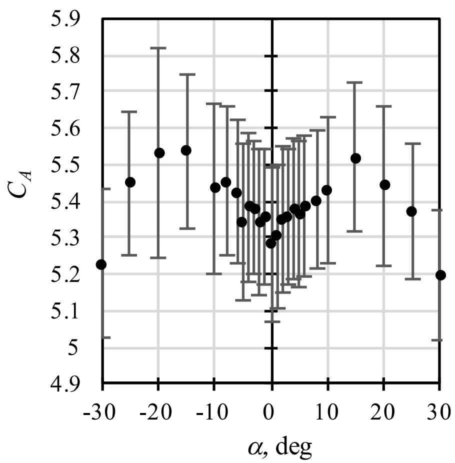




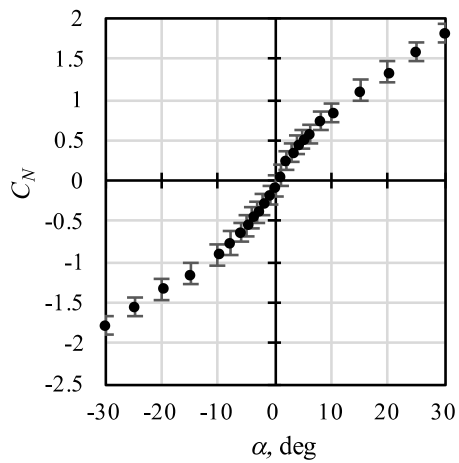
Config. 2

V_∞ is the freestream velocity
q_c is the blockage-corrected q
S_0 is the frontal area of the payload sphere

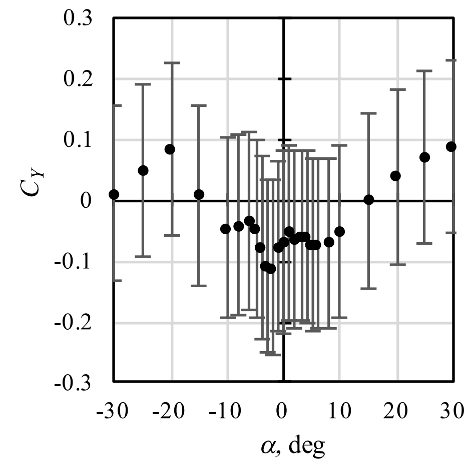
$$C_A = \frac{AF}{q_c S_0}$$



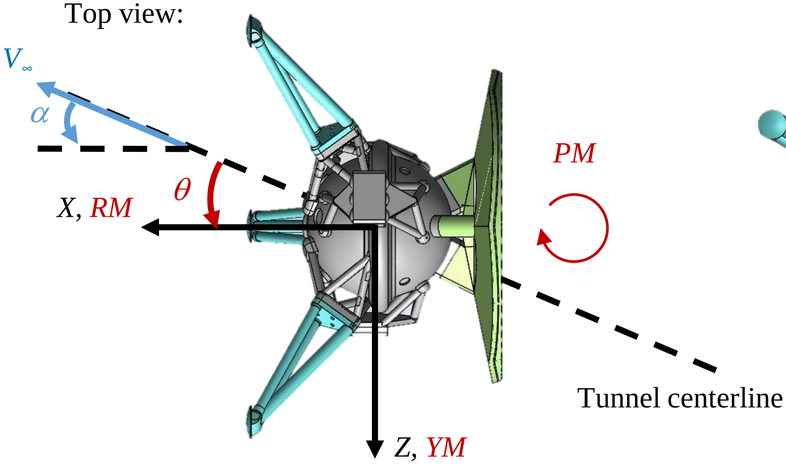
$$C_N = \frac{NF}{q_c S_0}$$

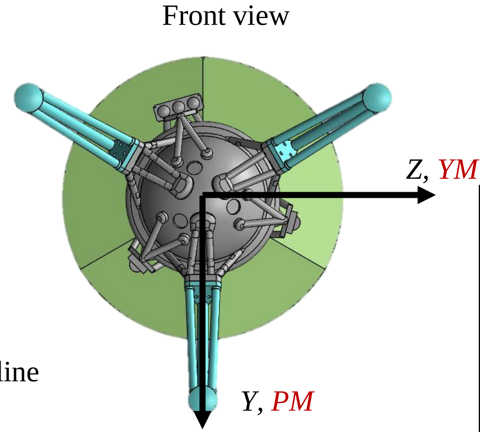


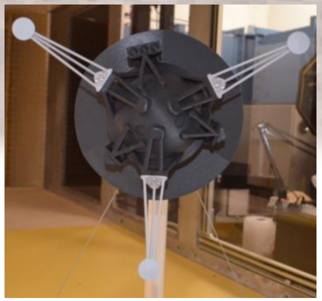
$$C_Y = \frac{SF}{q_c S_0}$$



Static Aerodynamics ($\phi \approx 0$)



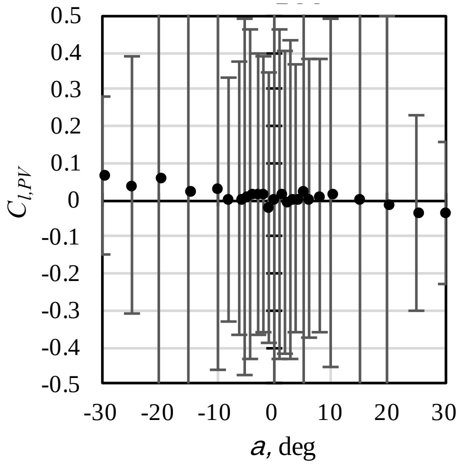




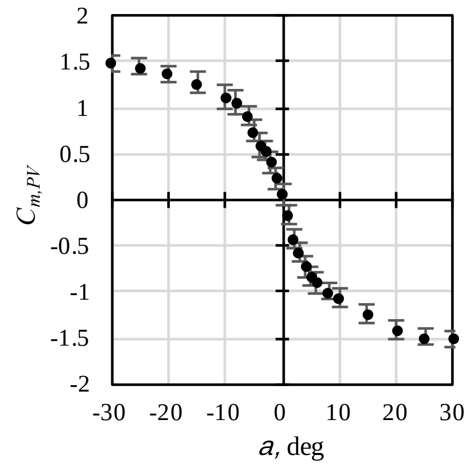
Config. 2

V_∞ is the freestream velocity
q_c is the blockage-corrected q
S_0 is the frontal area of the payload sphere
D_0 is the diameter of the payload sphere

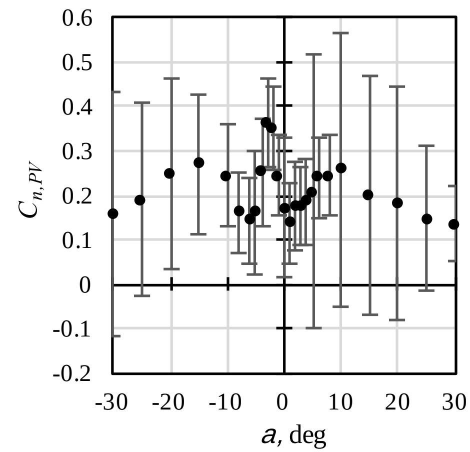
$$C_{l,PV} = \frac{RM}{q_c S_0 D_0}$$



$$C_{m,PV} = \frac{PM}{q_c S_0 D_0}$$

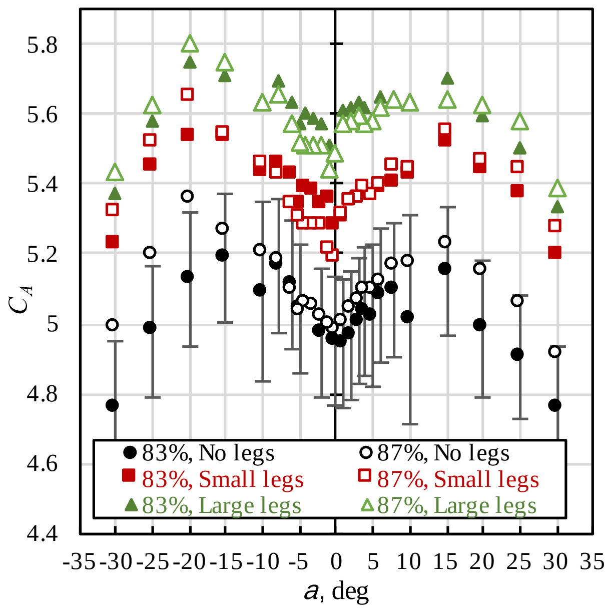


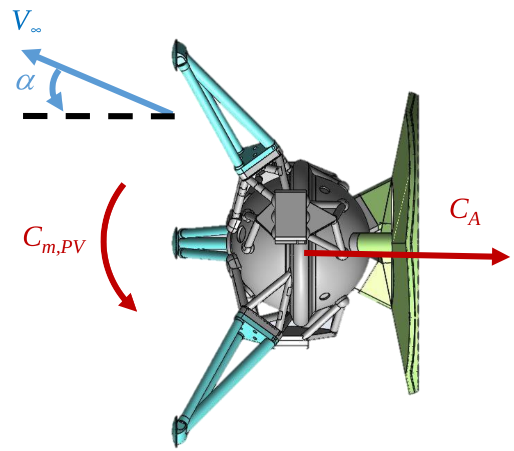
$$C_{n,PV} = \frac{YM}{q_c S_0 D_0}$$

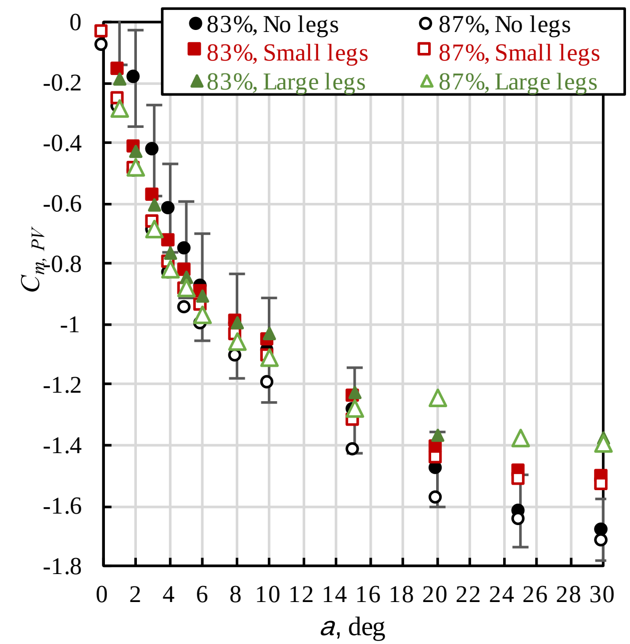


Drag Plate Solidity

Effect of solidity on C_A & $C_{m,PV}$ for configurations with $\Gamma = 10$ deg:



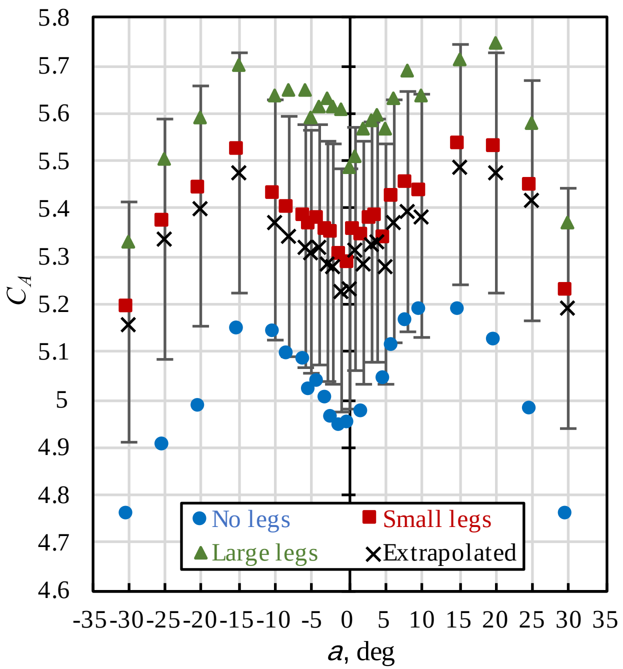


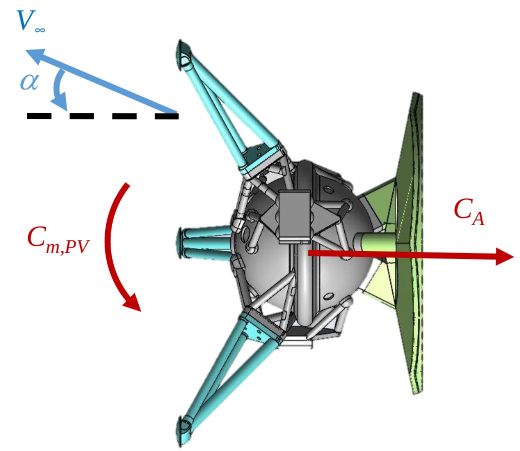


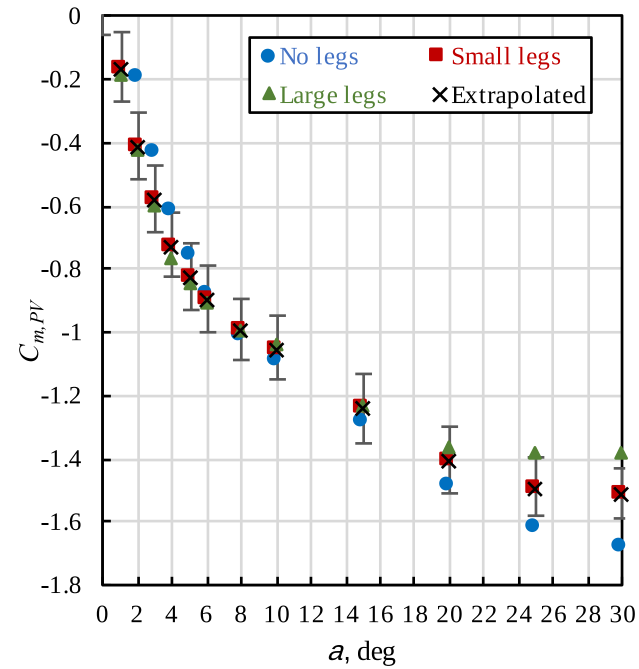
- Solidity has little effect on C_A & $C_{m,PV}$ near α = 0 deg
  - Negligible flow through the drag plate opening at 0 deg
- Solidity has *some* effect at larger α,
  - Increasing flow through opening at larger angles
- Effect of solidity is more noticeable without lander lges

Leg Size/Reynolds Number

C_A & $C_{m,PV}$ for configurations 1, 2 & 3 ($\Gamma = 10$ deg, 83% solidity) :







Extrapolated *"At Venus"* C_A:

$$(C_A)_{\text{Venus}} = (C_A)_{\text{small}} - \frac{(C_A)_{\text{large}} - (C_A)_{\text{small}}}{4}$$

Same procedure used for C_N & C_Y

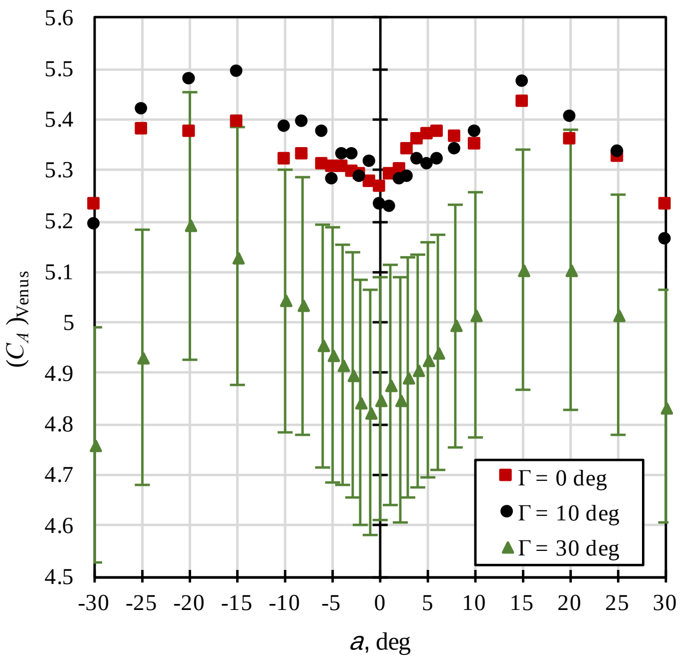
"At Venus" $C_{m,PV}$:

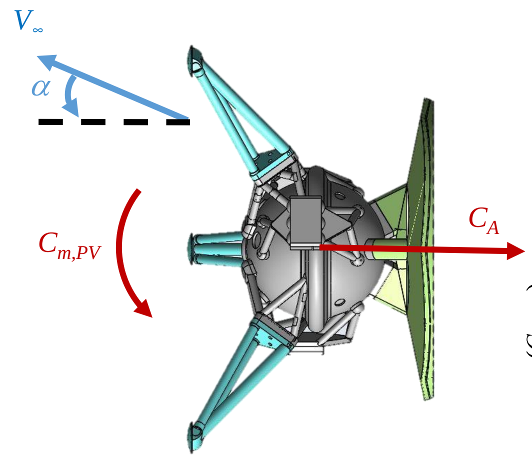
$$(C_{m,PV})_{\text{Venus}} = (C_{m,PV})_{\text{small}}$$

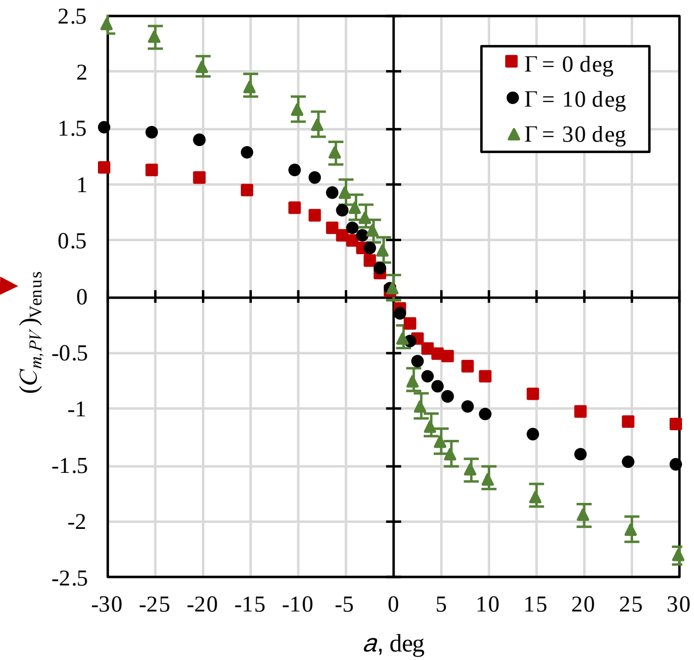
Negligible difference below 10 deg.
$(C_{m,PV})_{small}$ is conservative above 10 deg.
Same procedure for $C_{n,PV}$

Drag Plate Dihedral

"At Venus" C_A & $C_{m,PV}$ for configurations vs Γ (83% solidity drag plates) :



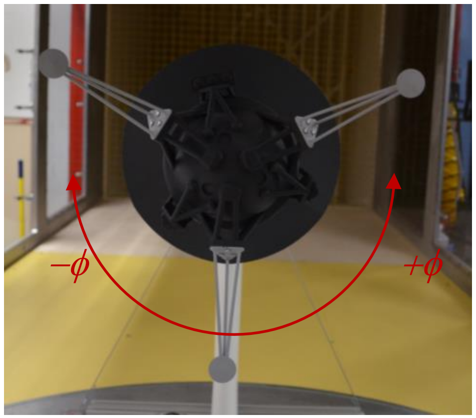


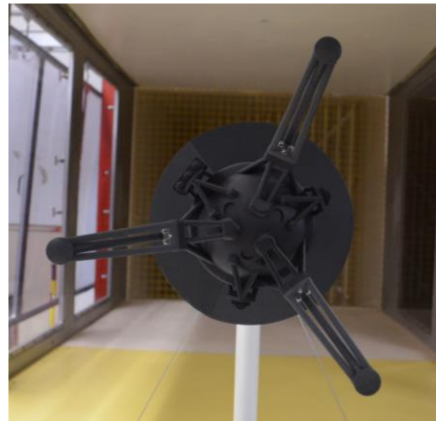


- Lander statically stable near α = 0 deg with all drag plate configurations
- Degree of pitching stability dependent on Γ
- Increasing dihedral improves static pitching stability, but results in lower C_A
- Can decrease Γ to accommodate larger drag plate

Phase II Results

During Phase II, tested configurations 2 & 3 at four different model roll angles:



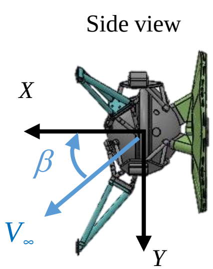


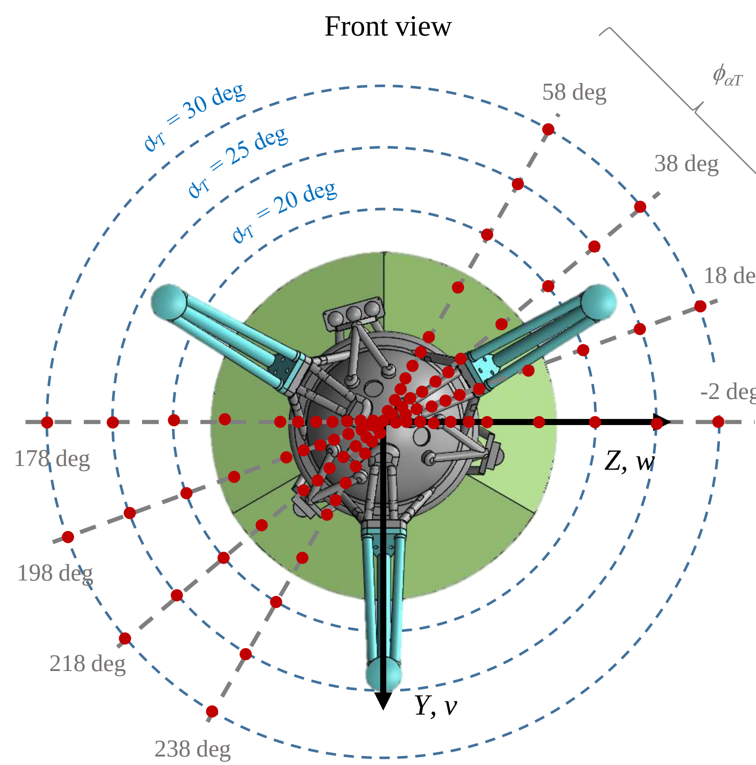
Config. 2: Γ = 10 deg, 83% solidity, small legs

Config. 3: Γ = 10 deg, 83% solidity, large legs

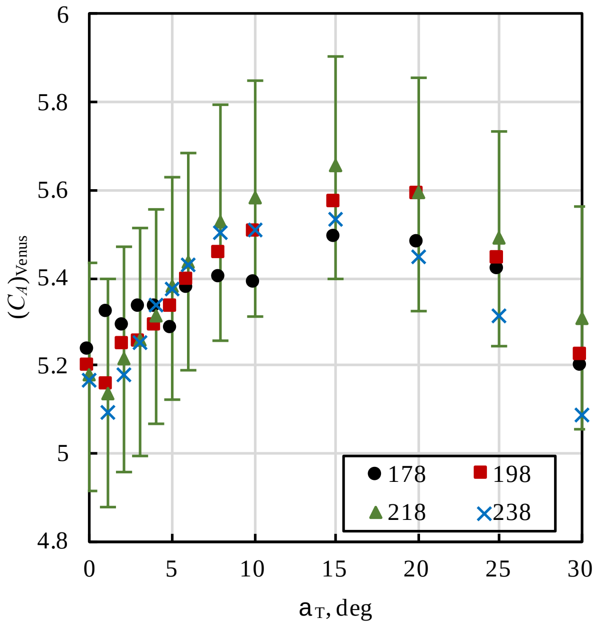
Sufficient to obtain "at Venus" aerodynamics for this drag plate configuration (Γ = 10 deg, 83% solidity)

- Span range of $\alpha_T = \cos^{-1}(\cos\alpha \cos\beta)$ from 0 to 30 deg
- Eight different α_T clock angles
- α ranges from -30 to 30 deg
- β ranges from -25 to 25 deg

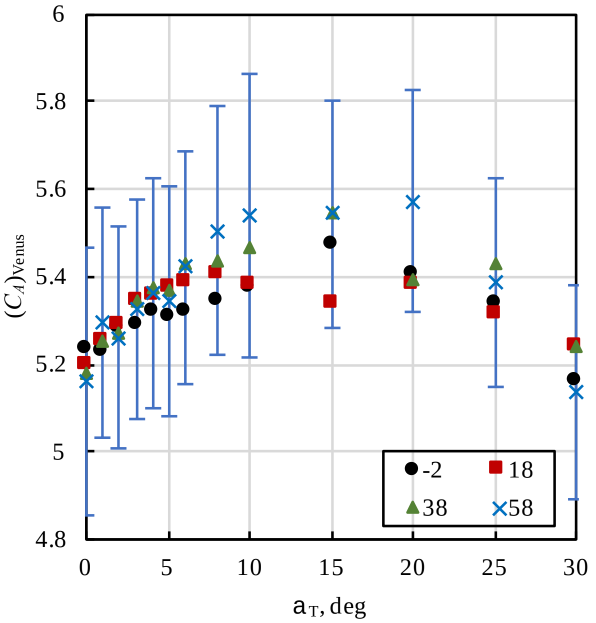




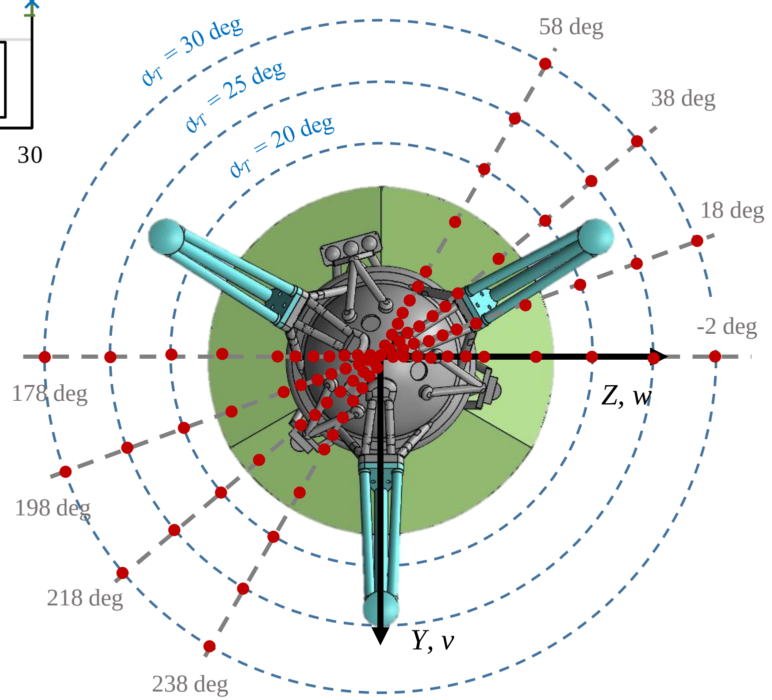
Axial Force v. α_T



"At Venus" axial force coefficient

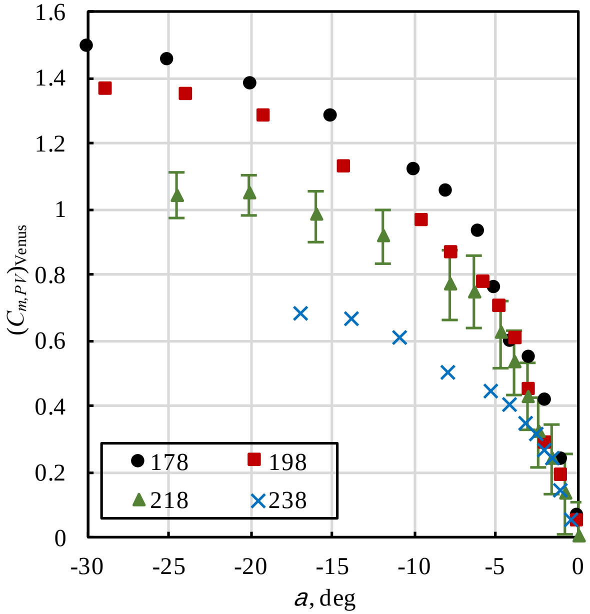


C_A largely symmetric through range of α_T clock angles considered

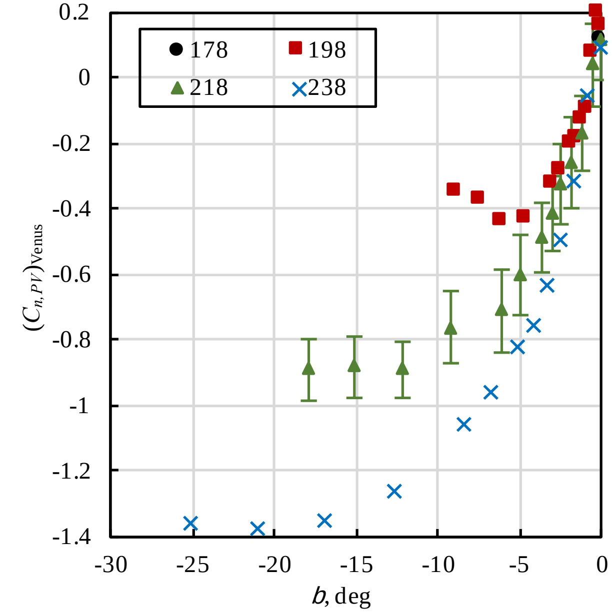


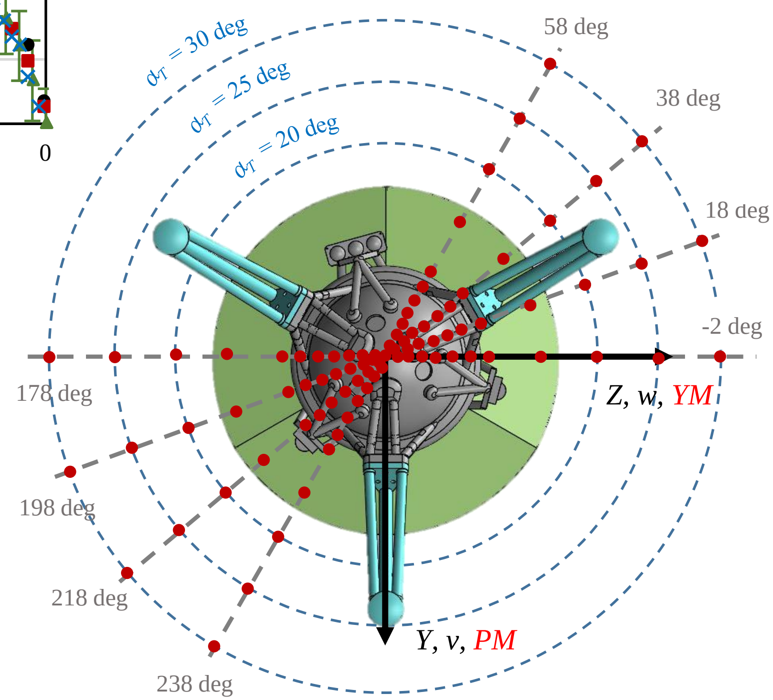
Small asymmetries due to leg geometry & asymmetries in body geometry

Pitching & Yawing Moments



"At Venus" $C_{m,PV}$ and $C_{n,PV}$





Static pitching & yawing behavior shows the appropriate symmetry

Small asymmetries due to leg geometry & asymmetries in body geometry

Summary & Conclusions

- Characterized static aerodynamics of a set of candidate lander configurations for the VISAGE mission concept:
  - C_A, C_N, C_Y, $C_{m,PV}$, $C_{n,PV}$ as a function of α and β
  - Unable to determine static rolling coefficients
- Lander models with different leg diameters allowed scaling of the results to Reynolds numbers relevant to terminal descent at Venus
- Drag plate solidity had a small effect on static aerodynamic coefficients, especially near $\alpha_T = 0$
- Evaluated three drag plate dihedrals: Γ = 0, 10, 30 deg
  - All configurations statically stable about pitching axis at α = 0 deg
  - Improved stability & decreasing C_A with increasing Γ
- For the baseline configuration (Γ = 10 deg) C_A, C_N, C_Y, $C_{m,PV}$, $C_{n,PV}$ are largely symmetric (or anti-symmetric)
  - Deviations from symmetry due to leg geometry & very small deviations due to asymmetries in body
  - Results from α sweep can be used to derive a preliminary aerodynamic database

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