MULTI-MISSION EARTH ENTRY VEHICLE SUBSONIC DYNAMIC STABILITY TESTING AND ANALYSES

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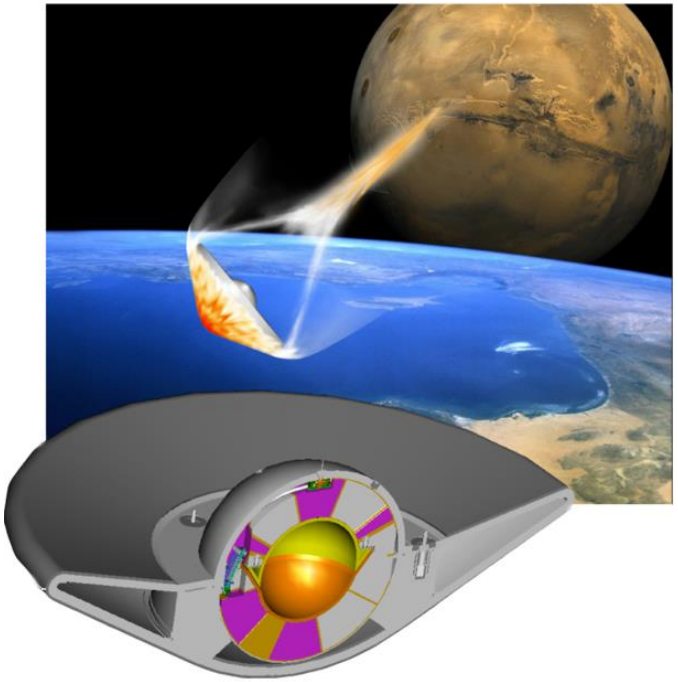
Entry Vehicle Technology Project/In-Space Propulsion Technology Program

Overview and Introduction

- **Multi-Mission Earth Entry Vehicles (MMEEVs)**
  - Considered a family or type of vehicle
  - Can be designed to meet specific mission requirements
  - Achieve high reliability through single-stage EDL concept
  - No reaction control systems, parachutes, etc.
  - Perform “free flight” after release from carrier spacecraft outside of Earth’s atmosphere
  - NASA is developing the trade space and Multi-Disciplinary Design, Analysis and Optimization tools for these vehicles (M-SAPE tool)

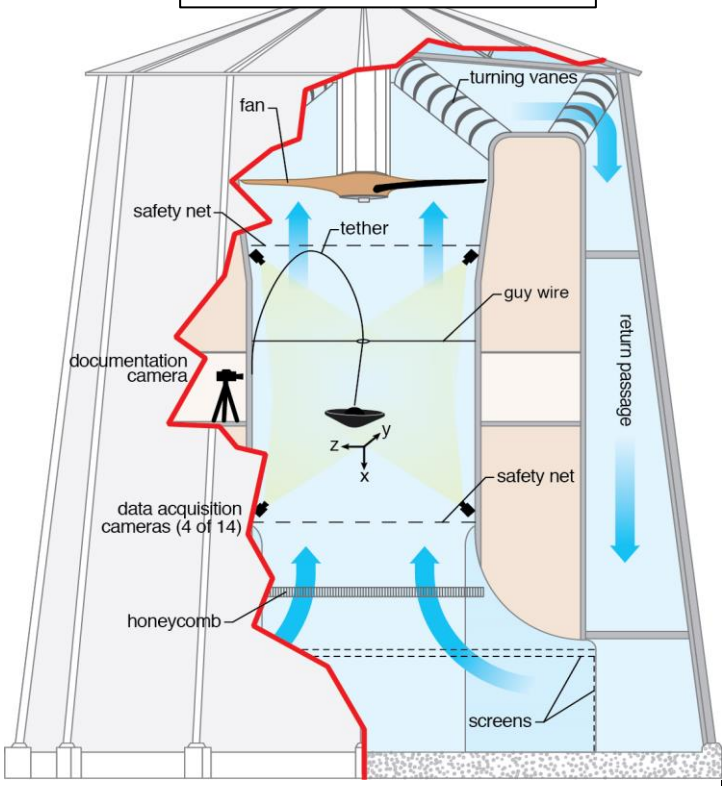


- **MMEEV aero data requirements**
  - Require definition of usable Center of Gravity (CG) limits for 3-DOF trajectory simulations for a range of outer mold lines and mass characteristics
  - Adequate aerodynamic databases for 6-DOF trajectory simulations

Test Objectives, Method, Facility

- **Provide data to support MMEEV parametric subsonic aerodynamic analysis**
  - Range of MMEEVs from 0.9m to 1.8m diameter
  - Range of payloads from 1kg to 25kg
- **Method**
  - Test series of dynamically-scaled MMEEVs in NASA LaRC's 20-FT Vertical Spin Tunnel
  - Range of CGs and inertias
  - Perform SID analysis to define aero models for simulation and stability analyses
- **NASA LaRC 20-FT VST**
  - Max q=431 Pa, Re=1.8X10^6/m
  - For this test series:
    - 77 Pa (1.8m), 118 Pa (1.2m), Re=0.23 to 0.29X10^6
  - Equipped with a Vicon motion tracking system
    - Provided model position, attitudes, and tunnel parameters at 150Hz
    - Attitude accuracy <~0.2 degs
  - Video and photographic documentation provided
- **Combined Test technique:**
  - Provides extended dynamic data compared to flight testing
  - Little to no support interference along with actual model motions

LaRC 20-FT VST



MMEEVs (Full Scale)

1.8m

2010 20-FT VST Entry

1.2m

1.2m+Back Shell Extender

2013 20-FT VST Entry

Full-Scale Vehicle Values (12 km/sec entry speed)

Diameter	1.8m	1.2m	1.2m
Surface Area	2.54m^2	1.13m^2	1.13m^2
Nose Radius	0.173D	0.183D	0.183D
Shoulder Radius	0.029D	0.03D	0.03D
Payload	25 kg	15 kg	15 kg
TPS	PICA	PICA	PICA
Mass	83 kg	44 kg	44 kg

Test Method

- **Unperturbed testing**
  - Required ~45 seconds of data for each run
  - Performed 3 repeats for this test condition
  - Moved CG aft until vehicle became unstable
  - Evaluated CG locations of: 0.214/D, 0.234/D, 0.250/D and 0.257/D
  - Included inertia variation for the 1.8m MMEEV (100 and 150% nominal)
- **Perturbed testing**
  - Required to get 3 usable perturbations
  - A usable perturbation was one that exceeded the nominal oscillations
  - But didn't immediately tumble the vehicle
  - Performed to evaluate stability margin
- **Untethered testing**
  - Performed to evaluate possible tether effects
  - Used most forward (stable) CG locations
- **Initial tunnel entry in 2010, second tunnel entry in 2013**
- **Total number of data runs: 193**

Example Departure Video
Block 18, Run1 (1.2m+BSE CG=0.257)

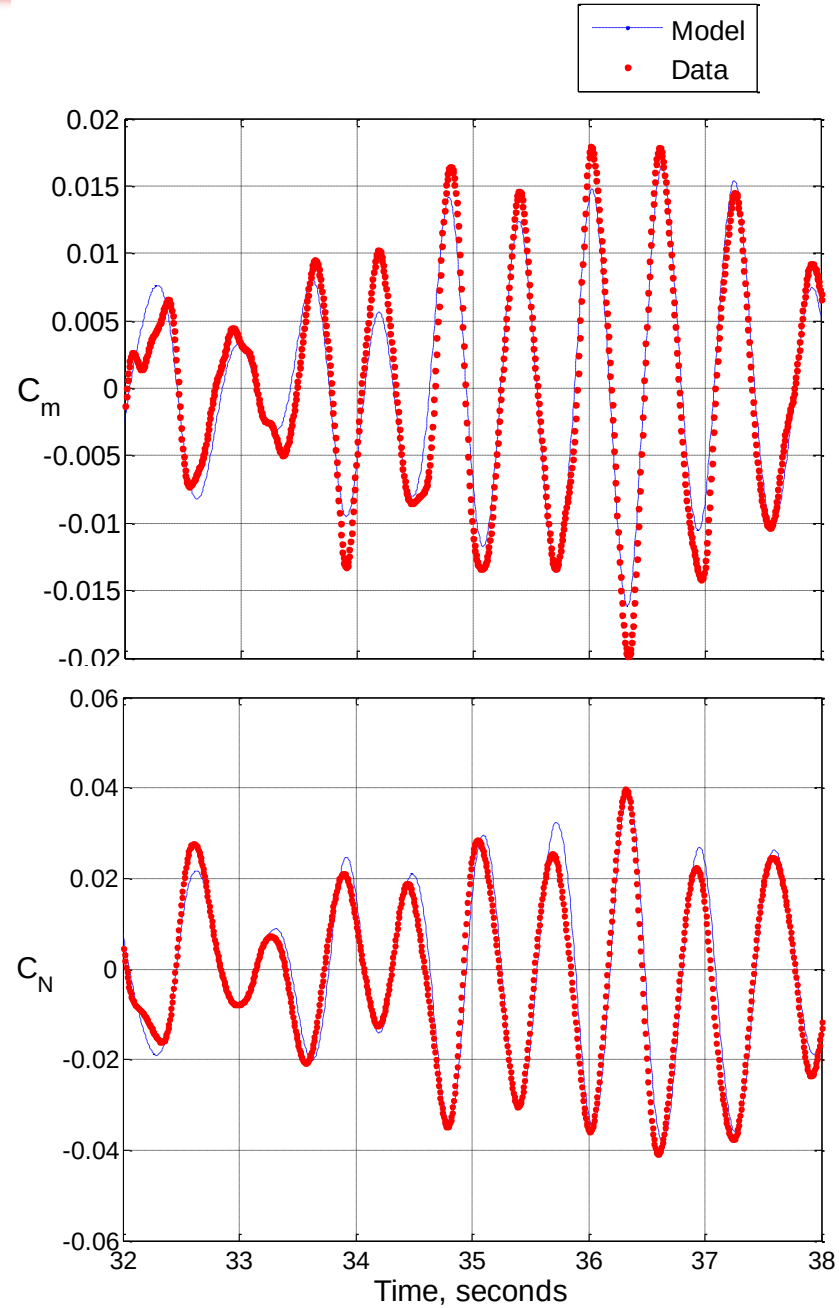
Data Analysis

- **Applied System IDentification Programs for AirCraft (SIDPAC) tools to perform data analysis (V Klein and E Morelli)**
  - Input data included:
    - Model position in the VST (X, Y, Z) and model orientation (Rx, Ry, Rz)
    - Wind-tunnel speed, air density, and model mass characteristics (m, Ixx, Iyy, and Izz)
  - Smoothing of input (SIDPAC SMOO)
    - Used 3 Hz cutoff frequency
    - Provided reasonable smoothing
  - Derived vehicle rates through differentiation (SIDPAC DERIV)
  - Applied Equations of Motion
    - Provided: aerodynamic forces and moments and angles of attack and sideslip as a function of time
  - Derived model parameters (SIDPAC LESQ)
  - Derived standard error (SIDPAC R_COLORES)
- **Corrections to 2010 data**
  - Applied 2.5% Q reduction applied to the 2010 data
  - VST had a major modification between tunnel entries

Results

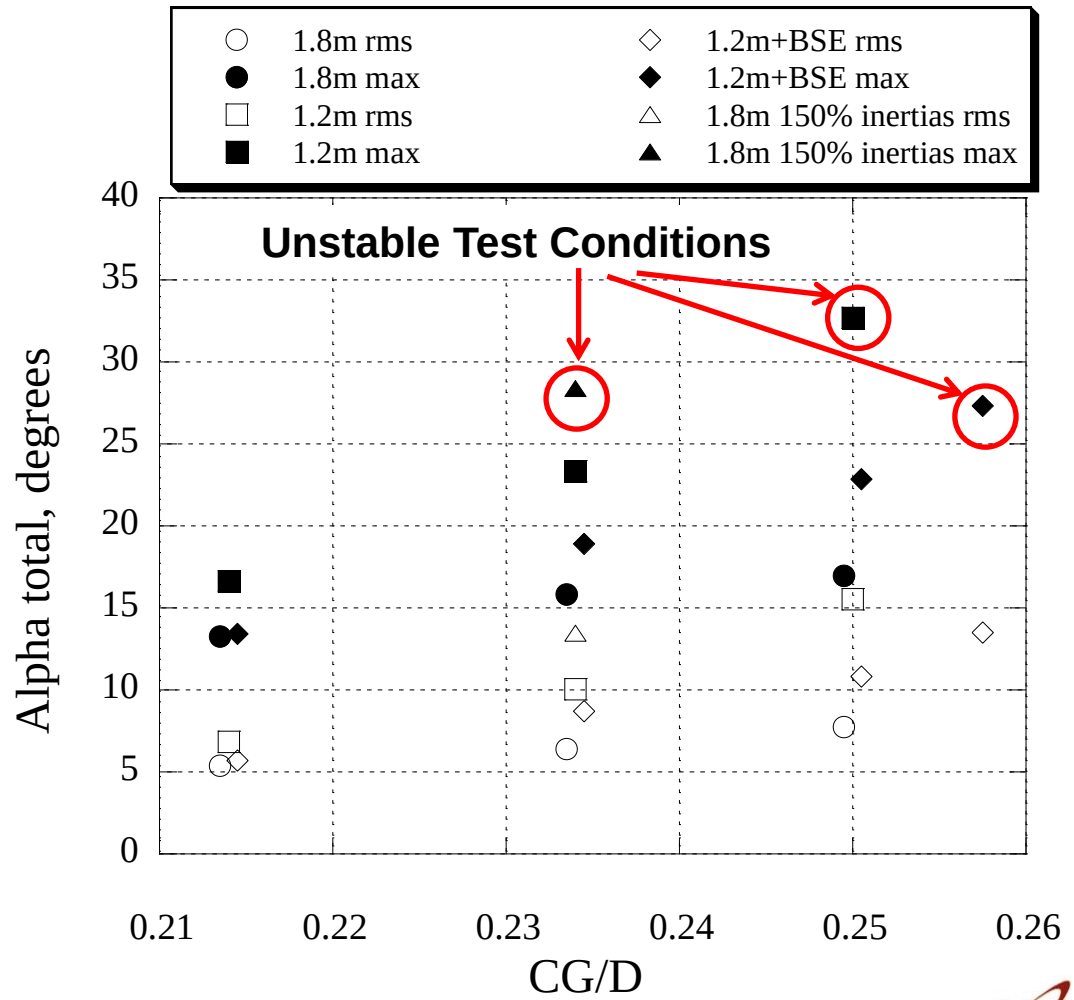
- **Coefficient of Determination and Signal to Noise Ratios**
  - Good results obtained for: C_N, C_Y, C_m, C_n
  - Excessive noise and/or lack of usable motion for: C_A, C_l
  - Used mean C_A, and neglected C_l
- **Equations used:**
  - $C_N = C_{N_0} + C_{N_\alpha}\alpha + C_{N_{\alpha^3}}\alpha^3$
  - $C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\alpha^3}}\alpha^3 + C_{m_q}\hat{q}$
  - $C_Y = C_{Y_0} + C_{Y_\beta}\beta + C_{Y_{\beta^3}}\beta^3$
  - $C_n = C_{n_0} + C_{n_\beta}\beta + C_{n_{\beta^3}}\beta^3 + C_{n_r}\hat{r}$
  - $\hat{q} = \left(\frac{q+\dot{\alpha}}{2}\right) * D/(2 * V_\infty)$
  - $\left(\frac{r+\dot{\beta}}{2}\right) * D/(2 * V_\infty)$

	C_N	C_Y	C_m	C_n
Average R^2	0.85	0.84	0.94	0.94
Average SNR	9.7	9.5	9.2	8.2



Effect of CG on Alpha_Total (α_T)

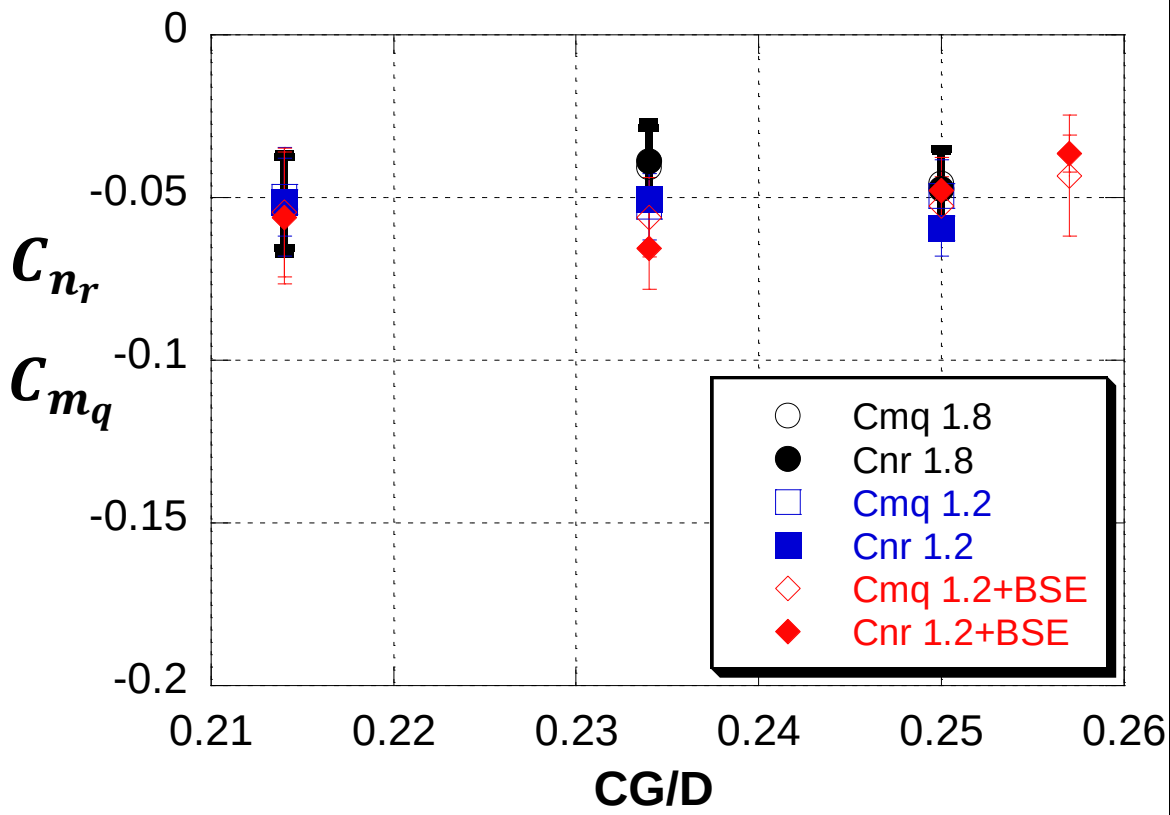
- All configurations indicated increased $\propto_T$ with aft CG position
- 1.8m had the lowest
- 1.2m had the highest
- Increasing model inertia increased $\propto_T$ for the 1.8m
- Test conditions with $\propto_T$ max greater than 25 degs were unstable



CG locations adjusted for clarity

Dynamic stability vs CG (C_{m_q}, C_{n_r})

- **Not effected by CG, and angle of attack range**
- **All configurations indicate similar amount of damping**
- **Symmetry between Normal and Lateral axes shown in the data**
- **Large standard error for damping terms**



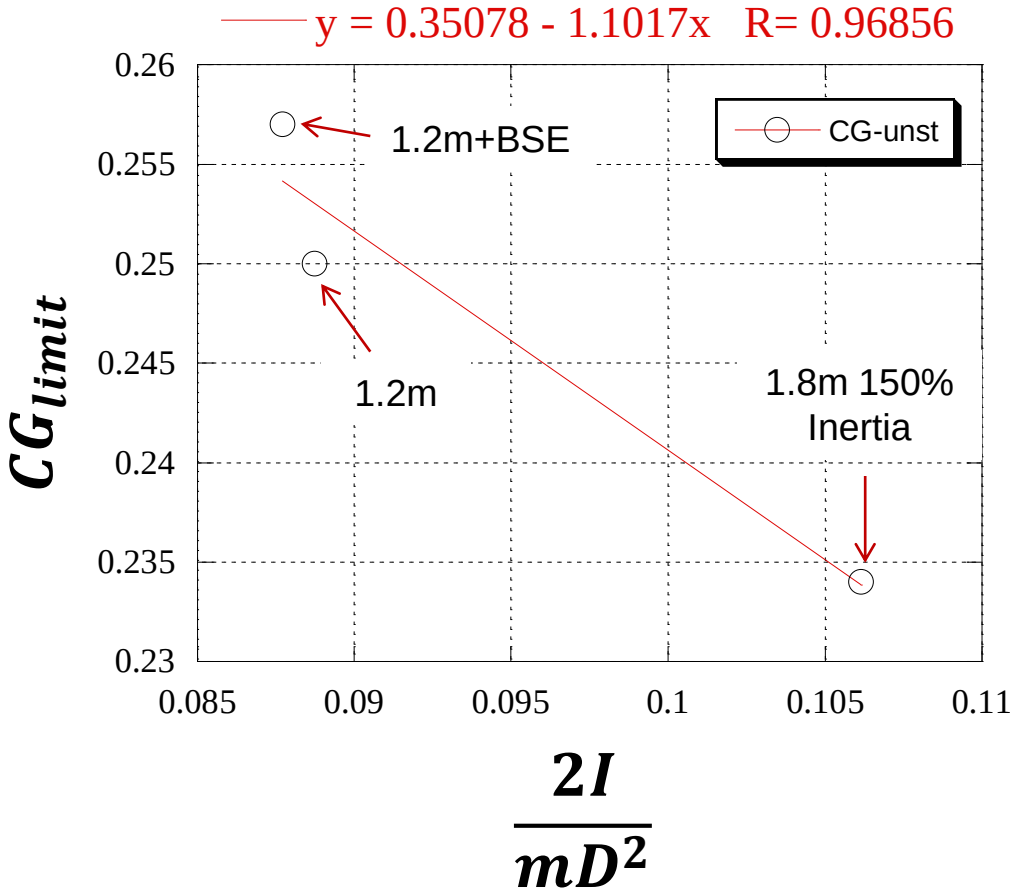
Summary and Conclusions

- **A series of MMEEVs were successfully tested in the 20-FT VST**
  - Multiple tunnel entries (2010 and 2013)
  - 3 MMEEV configurations tested over a range of CGs and Inertias
- **Sufficient data were available for the application of SID techniques**
- **Results from SID analysis indicate:**
  - Axial force and rolling moment data were too noisy for analyses
  - Good results for Normal/Lateral Force/Moment parameters
  - Larger error for dynamic results (~30%)
  - 1.8m MMEEV had lower static stability than the others
  - Dynamic damping results similar for all configurations, CGs, AOA range
- **CG limits for the three MMEEV configurations were established based on mass characteristic term** $\left[\frac{2I}{mD^2}\right]$
- **Future plans**
  - Publish NASA Technical Paper documenting the testing and results
  - Glaab, L; Bean, J.; Morelli, E.; Cruz, J.; Fremaux, M.; Schoenenberger, M.: *Vertical Spin Tunnel Testing and Stability Analysis of Multi-Mission Earth Entry Vehicles*.

BACKUP

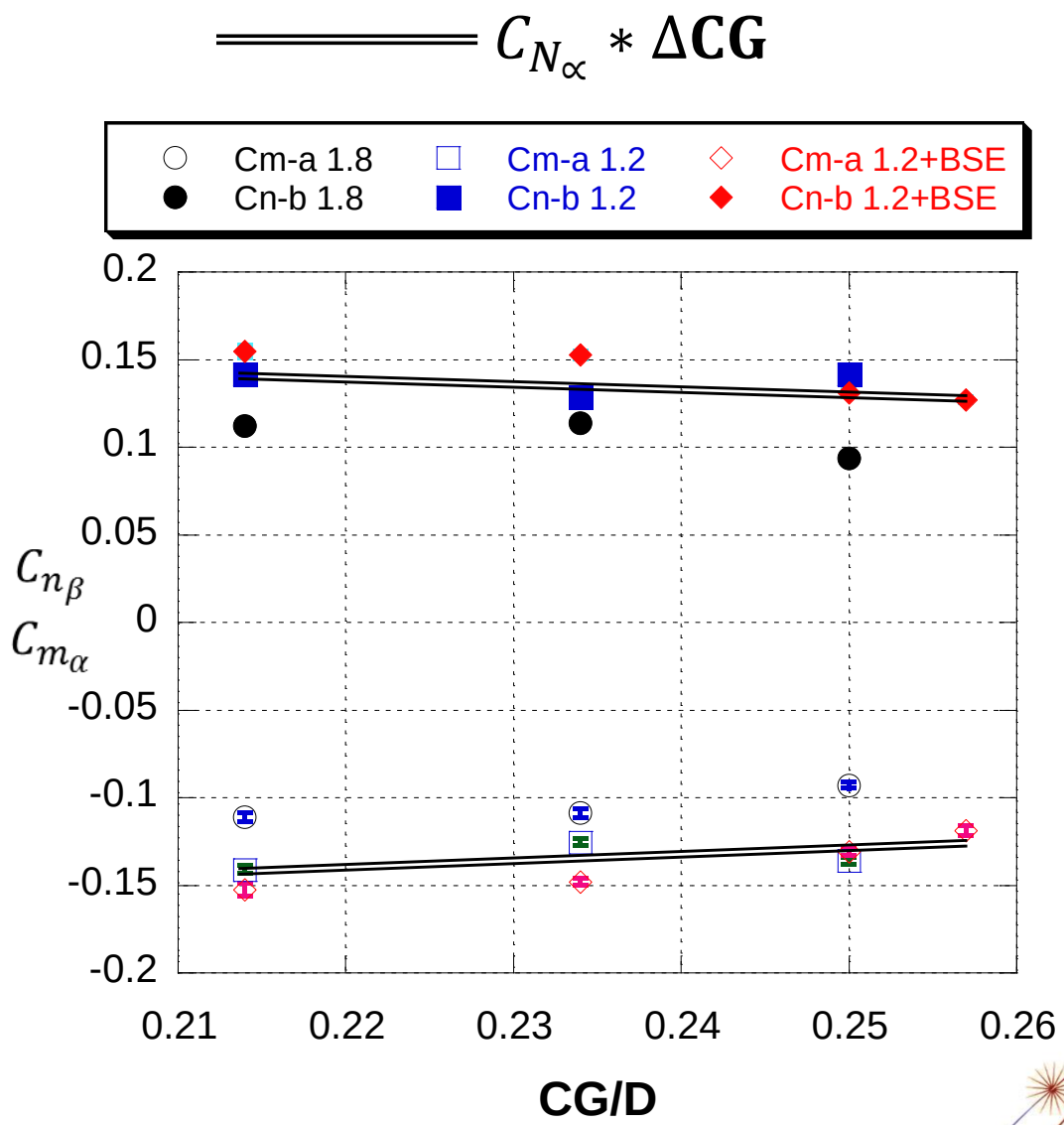
Stability Limit Based on VST Results

- **Two references provide required damping for stable oscillations as a function of mass characteristic and aero terms**
  - Mitchelltree, Fremaux, Yates: AIAA-99-1020
  - Schoenenberger, Queen: NATO Report 2008-10865
  - Req damping $\sim\left(\frac{2I}{mD^2}\right) C_{L_\propto}$
- **Mass characteristic term used to define usable CGs**
- **Results applicable to 60-deg Sphere Cones only**
  - Due to aero term
- **More testing results required to validate**



Static Stability vs CG ($C_{m_\propto}$, C_{n_β})

- **1.8m had lowest static stability**
  - Potentially due to the sharper nose radius
- **Expected decrease in static stability due to aft CG shift is shown in the data**
- **Small standard error**
- **Symmetric results for Normal and Lateral axes**



Standard Error

- **Used r_colores to compute Cramer-Rao accounting for colored residuals (crb)**
- **Standard error = sqrt(diag(crb))**
- **Results presented for all runs >15 seconds (98 runs)**

Force coefficients	$C_{N_\propto}$	$C_{N_{\propto^3}}$	C_{Y_β}	$C_{Y_{\beta^3}}$
Average error	0.0331	0.7667	0.0341	0.7530
Average coeff	0.2626	0.2507	-0.2665	-0.07781
% error	12.6	305	12.8	968

Moment coefficients	$C_{m_\propto}$	$C_{m_{\propto^3}}$	C_{m_q}	C_{n_β}	$C_{n_{\beta^3}}$	C_{n_r}
Average error	0.0034	0.1593	0.0172	0.0035	0.1749	0.0177
Average coeff	-0.1259	0.0894	-0.0529	0.1287	-0.1629	-0.0559
% error	2.7	178	32.5	2.7	107	31.7

Dynamic Scaling Equations

Parameter	Scale Factor (Model/Full-Scale)
Linear Dimension	$N = l_m / l_v$
Relative Density	1
Froude Number	1
Mass	$N^3 \, r_m/r_v$
Moment of Inertia	$N^5 \, r_m/r_v$
Linear Velocity	$N^{1/2}$
Linear Acceleration	1
Angular Velocity	$1/N^{1/2}$
Time	$N^{1/2}$
Reynolds Number	$N^{3/2} \, n_m/n_v$