MARSIS Antenna Deployment Testing and Analysis

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Spacecraft and Launch Vehicle Dynamic Environments Workshop

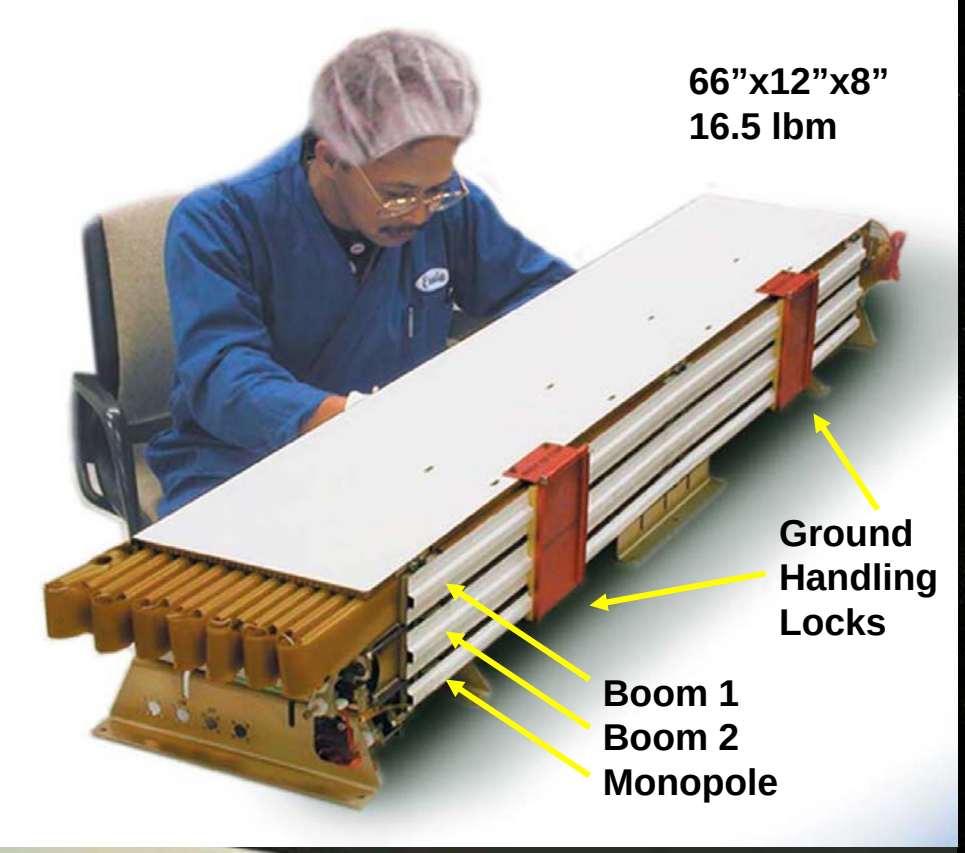
The Aerospace Corporation, El Segundo, CA

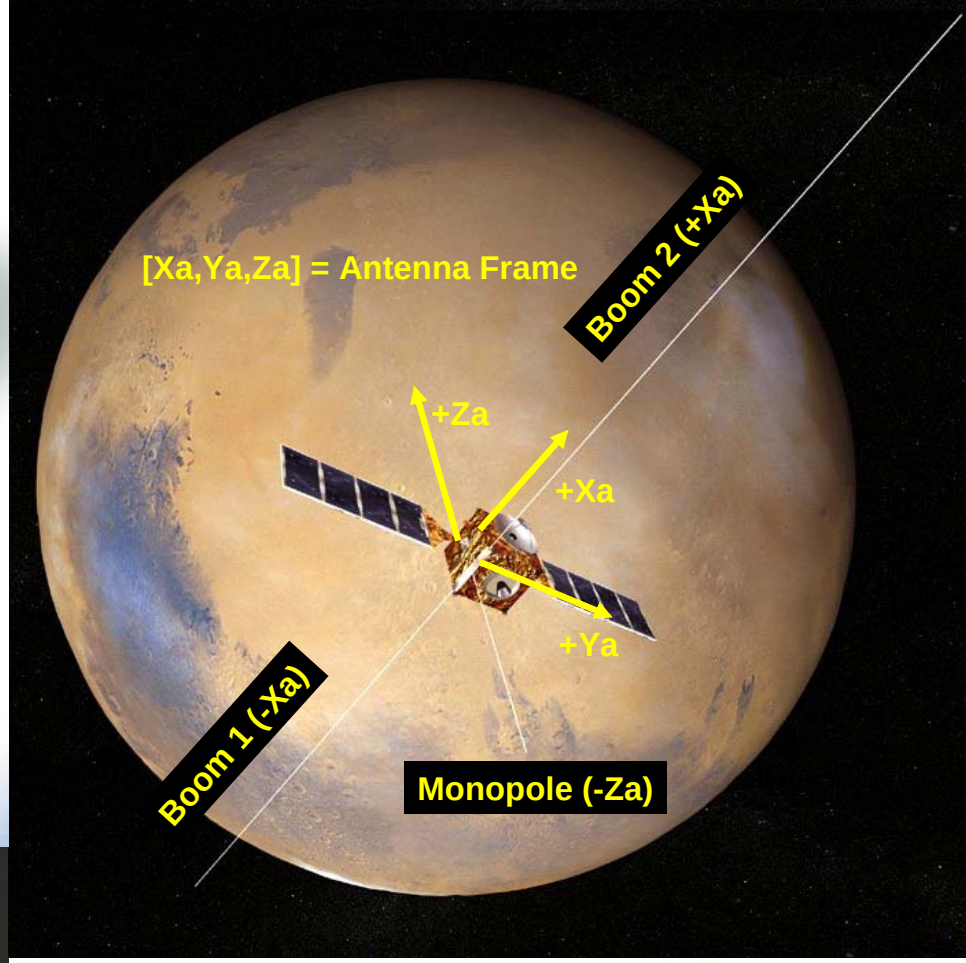
June 21-23, 2005

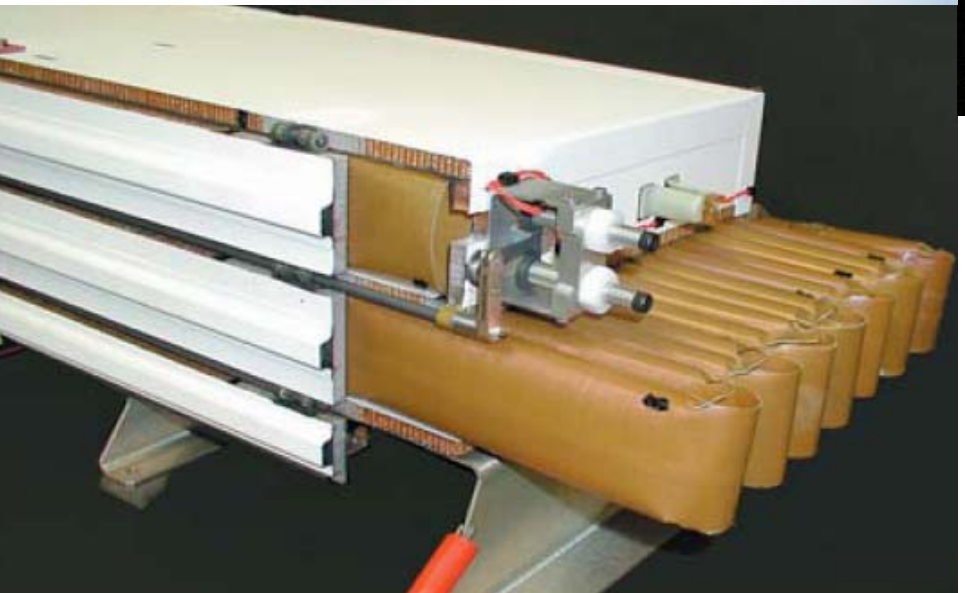
A Brief History of MARSIS

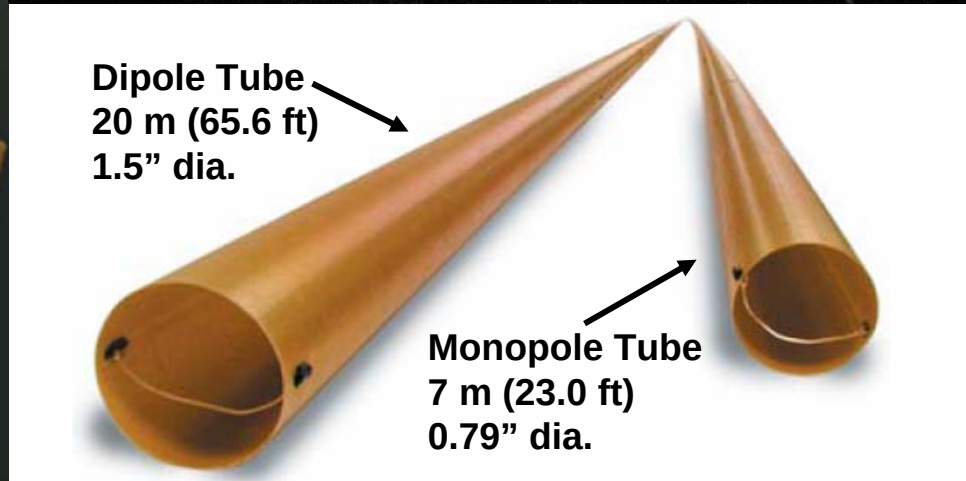
(Mars Advanced Radar for Subsurface and Ionosphere Sounding)

- Original MARSIS deployment analysis performed in 2000
- Subsequent analysis in support of SHARAD in April, 2004 indicated that the MARSIS analysis should be revisited
- Preliminary results from an updated model showed that the hinges experienced more extensive back-buckling than those observed in the original analysis
- The change in expected behavior was reported to JPL and ESA wherein the deployment was delayed pending further review
- An extensive testing and analysis effort was undertaken over the subsequent months in order to better characterize the boom
- These actions culminated in the ultimately successful deployment of MARSIS in May-June, 2005


66”x12”x8”
16.5 lbm
Ground
Handling
Locks
Boom 1
Boom 2
Monopole

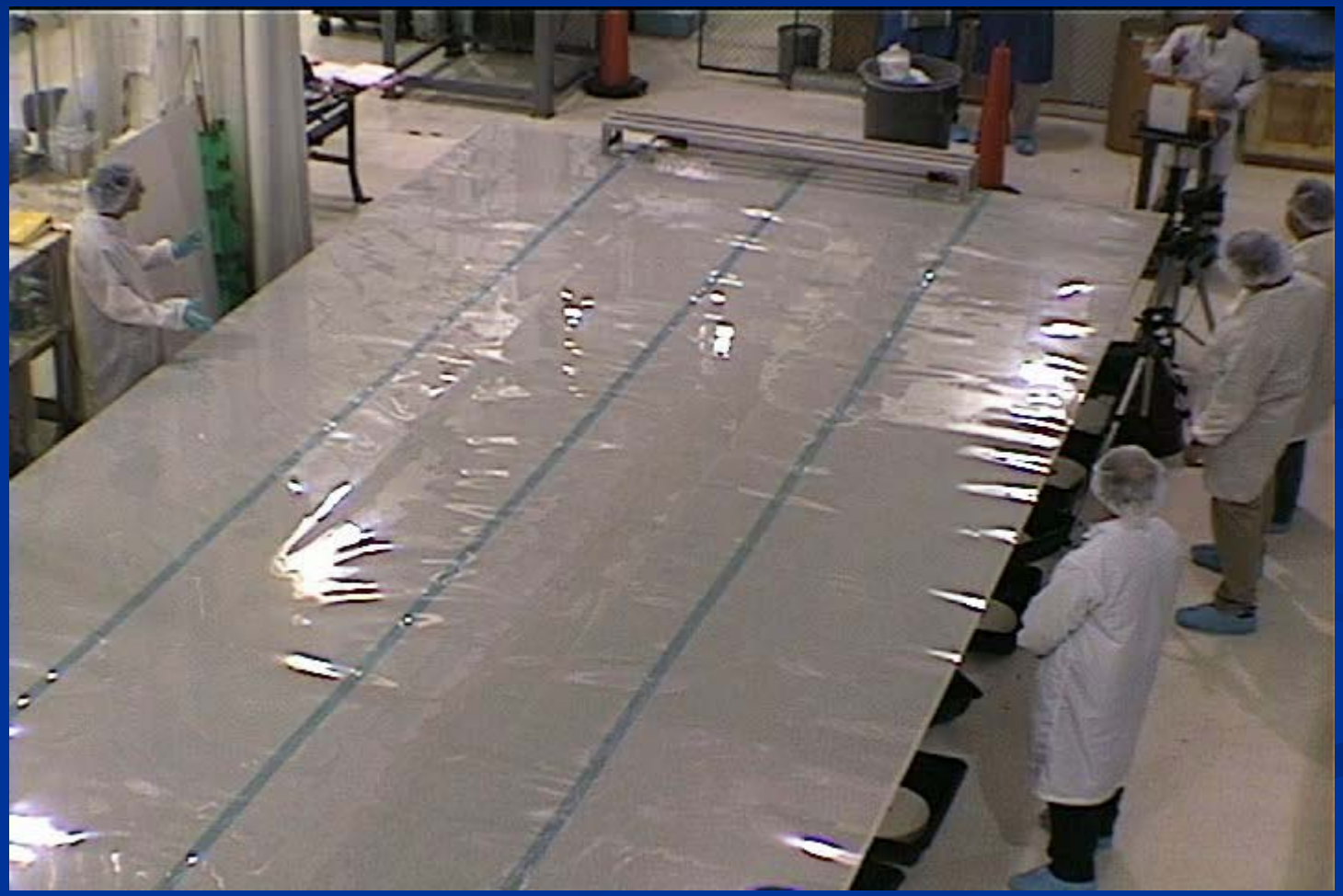

[Xa,Ya,Za] = Antenna Frame
Boom 2 (+Xa)
+Za
+Xa
+Ya
Boom 1 (-Xa)
Monopole (-Za)




Dipole Tube
20 m (65.6 ft)
1.5” dia.
Monopole Tube
7 m (23.0 ft)
0.79” dia.

Difficulties of Ground Testing

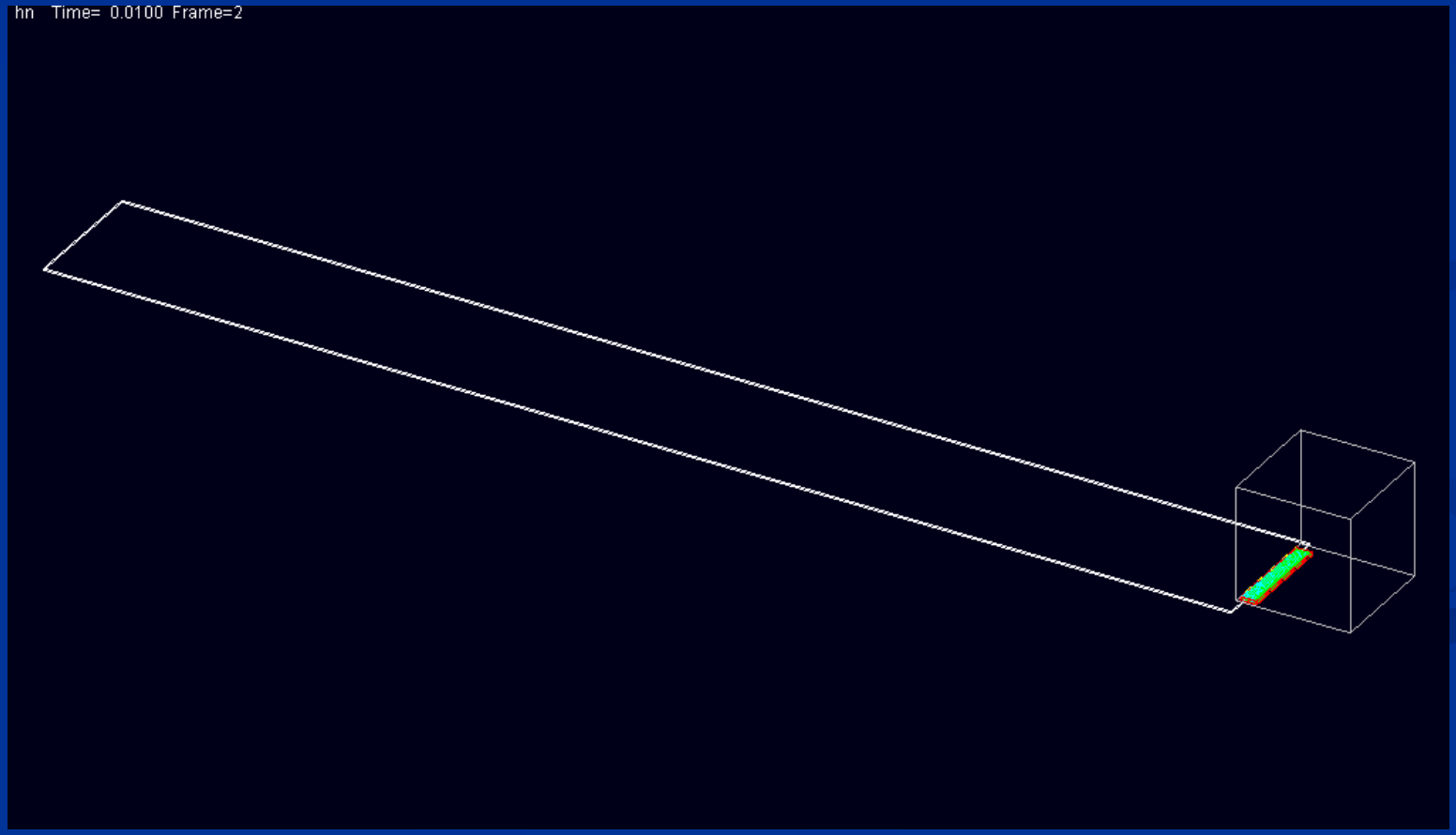
- Friction, gravity, and aerodynamic resistance dominate terrestrial testing
- As a result, it <u>impossible</u> to test the full system behavior prior to flight



Spring 2002 ground test at Astro Aerospace facility in Goleta, CA

Original ADAMS Model

- The original ADAMS model was created using rigid parts representing the boom segments with rotational joints to represent the hinges
- Representative damping for fully deployed antenna results in unrealistically high damping for partially deployed antenna segments



Damping Properties Implementation in ADAMS Software

Equation of motion is given by:

$$M \cdot Y'' + C \cdot Y' + K \cdot Y = F$$

where

M is the mass matrix
C is the damping matrix
K is the stiffness matrix

Equation of motion in normal coord. q is:

$$Y = \phi \cdot q$$

$$q''_i + 2 \cdot \zeta_i \cdot \omega_i \cdot q'_i + \omega_i^2 \cdot q_i = \frac{\phi_i^T}{M_i} \cdot F$$

where

ϕ_i is the ith mode shape

ω_i is the ith natural frequency

M_i is the ith modal mass;

ζ_i is the ith modal damping

$$M_i = \phi_i^T \cdot M \cdot \phi_i$$

$$\omega_i^2 = \frac{K_i}{M_i}$$

$$\frac{C_i}{M_i} = 2 \cdot \zeta_i \cdot \omega_i$$

Rayleigh Damping:

$$C = \alpha \cdot M + \beta \cdot K$$

In ADAMS only β is used:

$$\zeta_i = \frac{\beta \cdot \omega_i}{2} \quad \text{or} \quad \beta = \frac{2 \cdot \zeta_i}{\omega_i}$$

- Acceptable for time-invariant structures, higher damping for higher modes
- Not acceptable for time-variant structures with variable fundamental natural frequencies

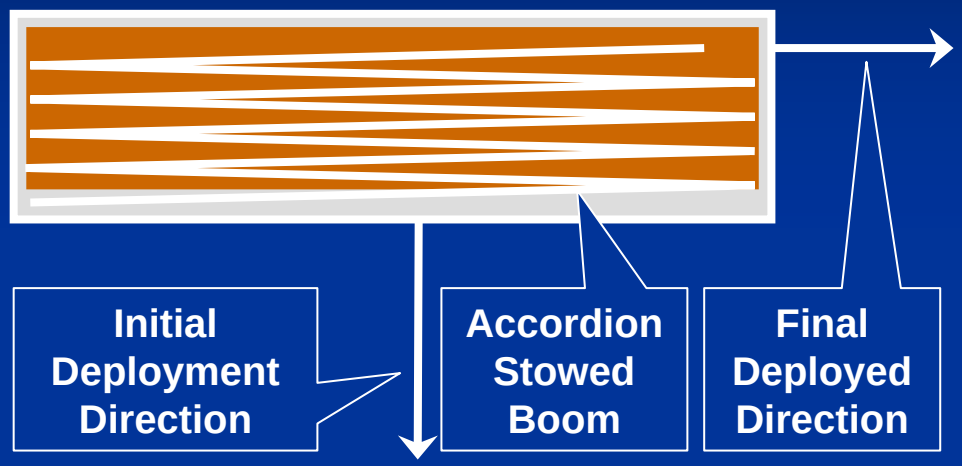
Damping Properties Implementation in ADAMS Software

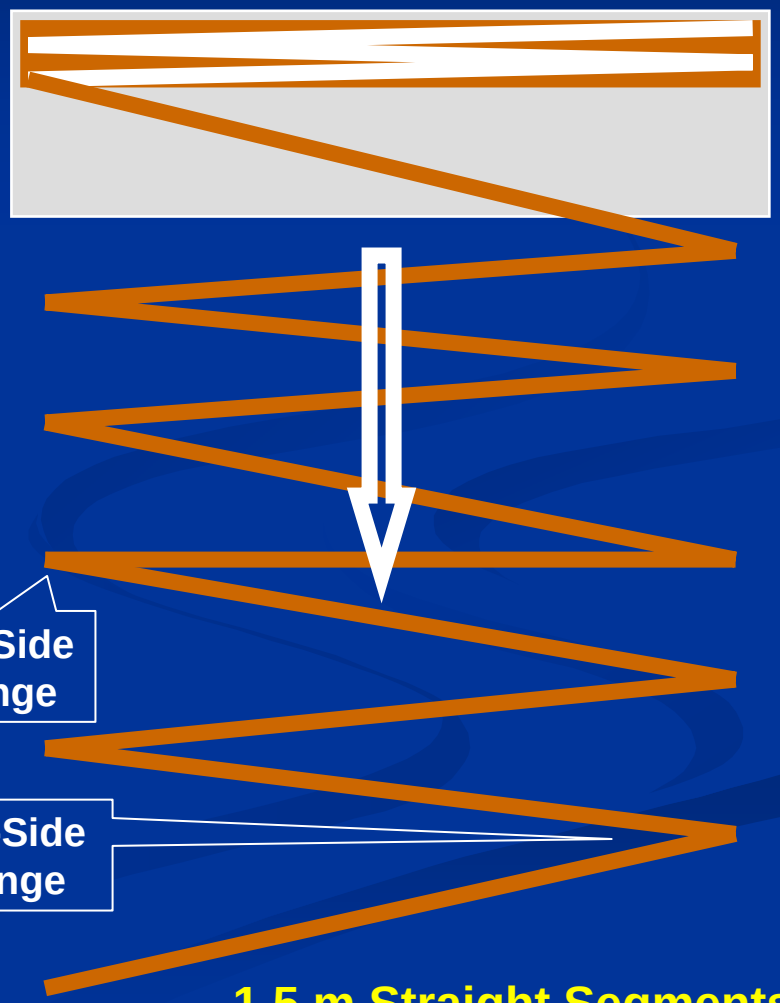
- In the ADAMS documentation the term "structural damping" is used incorrectly to describe the "Rayleigh damping" implementation
- Natural frequency of first two straight segments at the tip is about 15 Hz
  - For modal damping of 1% the damping factor used should be 2e-4
- Natural frequency of the fully deployed antenna is about 0.08 Hz
  - For modal damping of 1% the damping factor should be 0.04
- The same damping factor used for the fully deployed antenna would result in an unrealistic modal damping of 188% if applied for two straight segments
- The damping factor must be updated during the simulation to accurately reflect the instantaneous geometry of the boom
- Don't be fooled! Component modal damping suffers from the same problem!
  - Component damping is only correct in the geometry it is assembled
  - Requires a re-synthesis of the system modal properties each time any hinge locks or buckles
  - This problem was verified at ESOC using a DADS model

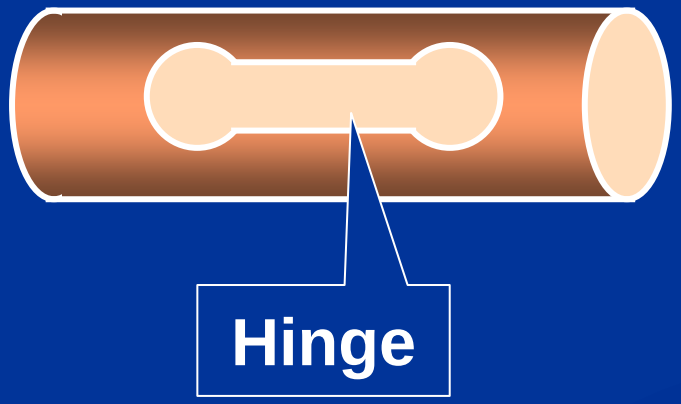
Dipole Boom System Description

Stowed Energy is Achieved by compressing the segments to 50% of their diameter

During deployment hinges unfold and add Hinge Torque Energy



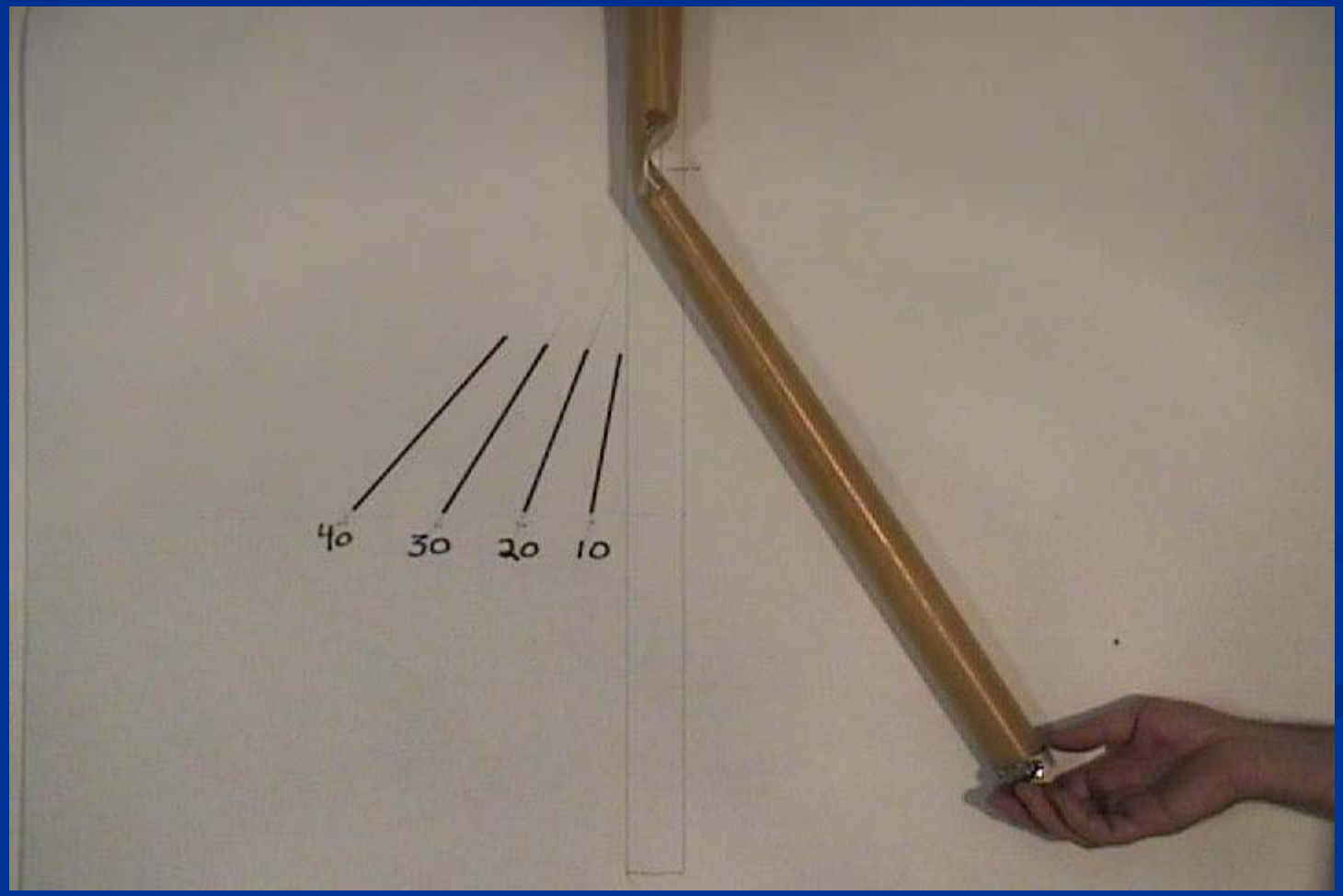




1.5 m Straight Segments

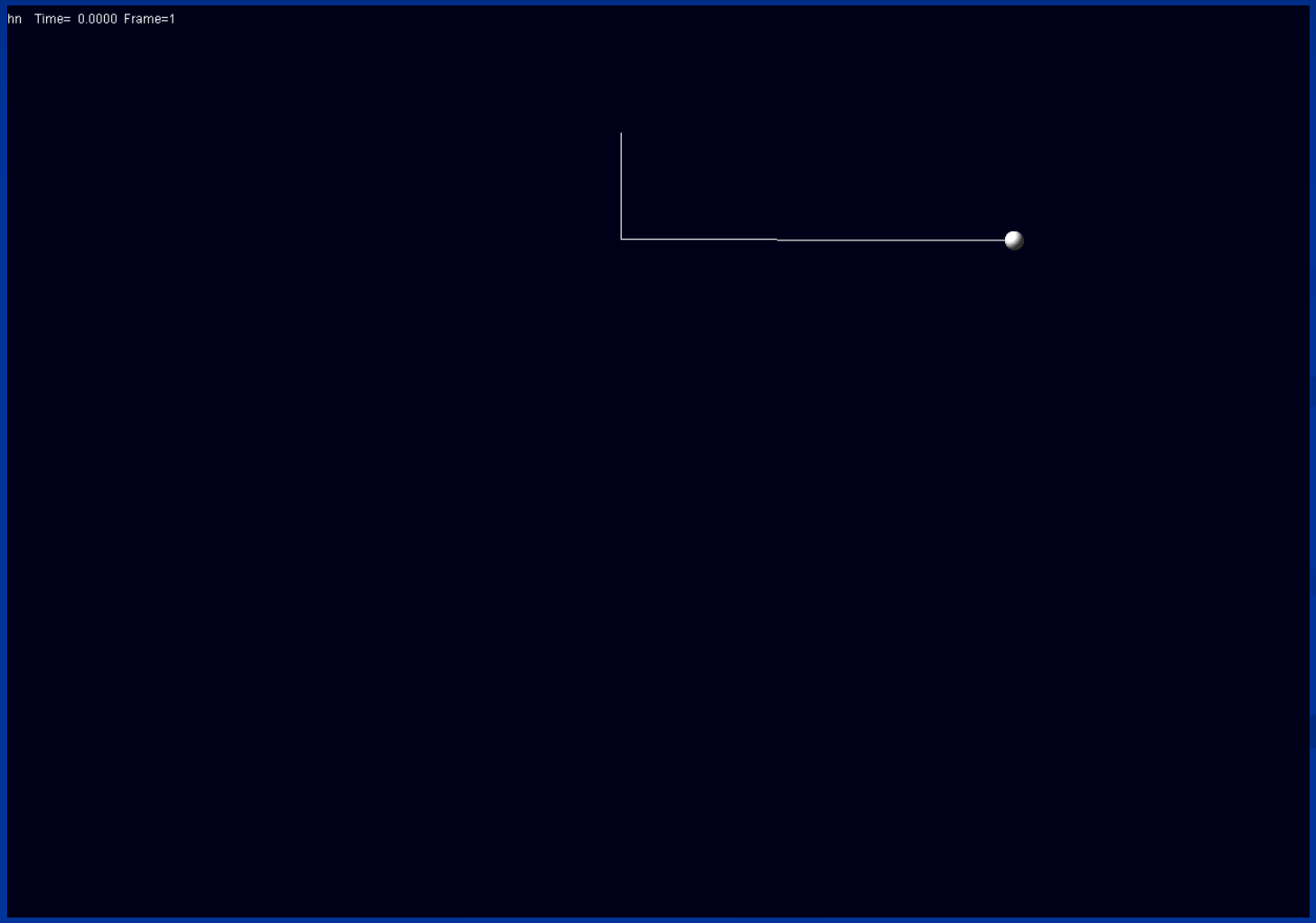
MARSIS Deployment
Vertical Pendulum Test

- Used to help validate the ADAMS hinge model implementation
  - A tip mass was added to amplify the loads at the hinge



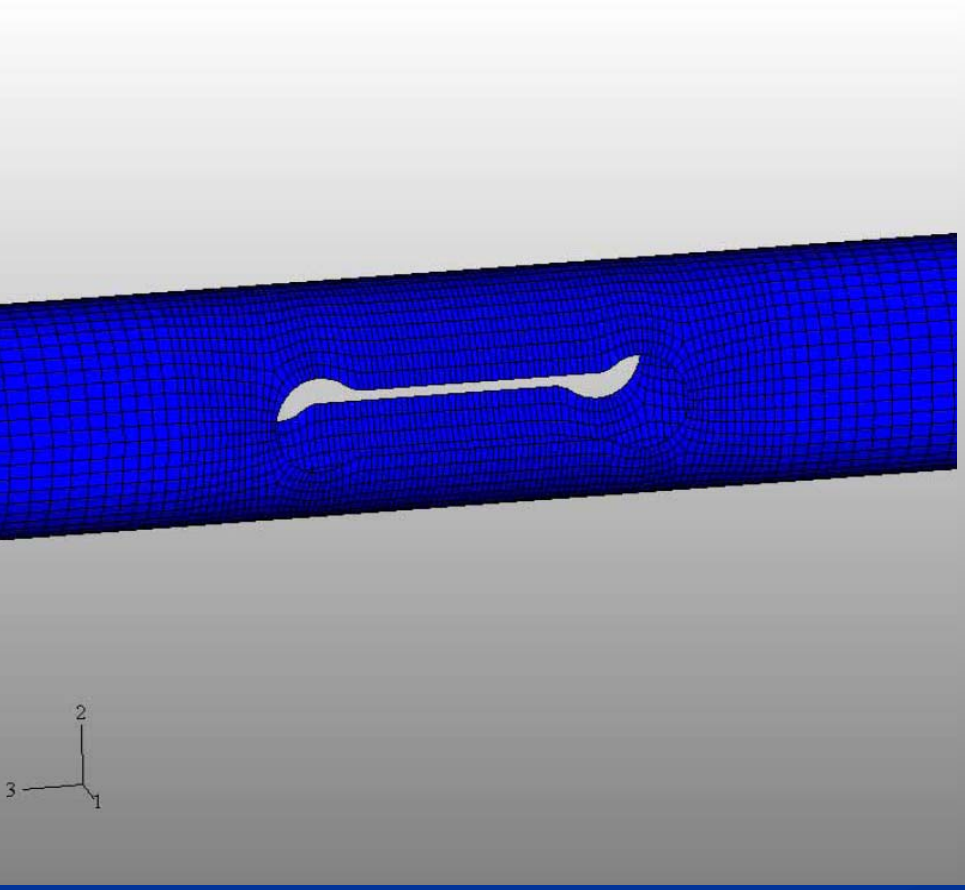
Initial MARSIS Hinge Model Validation

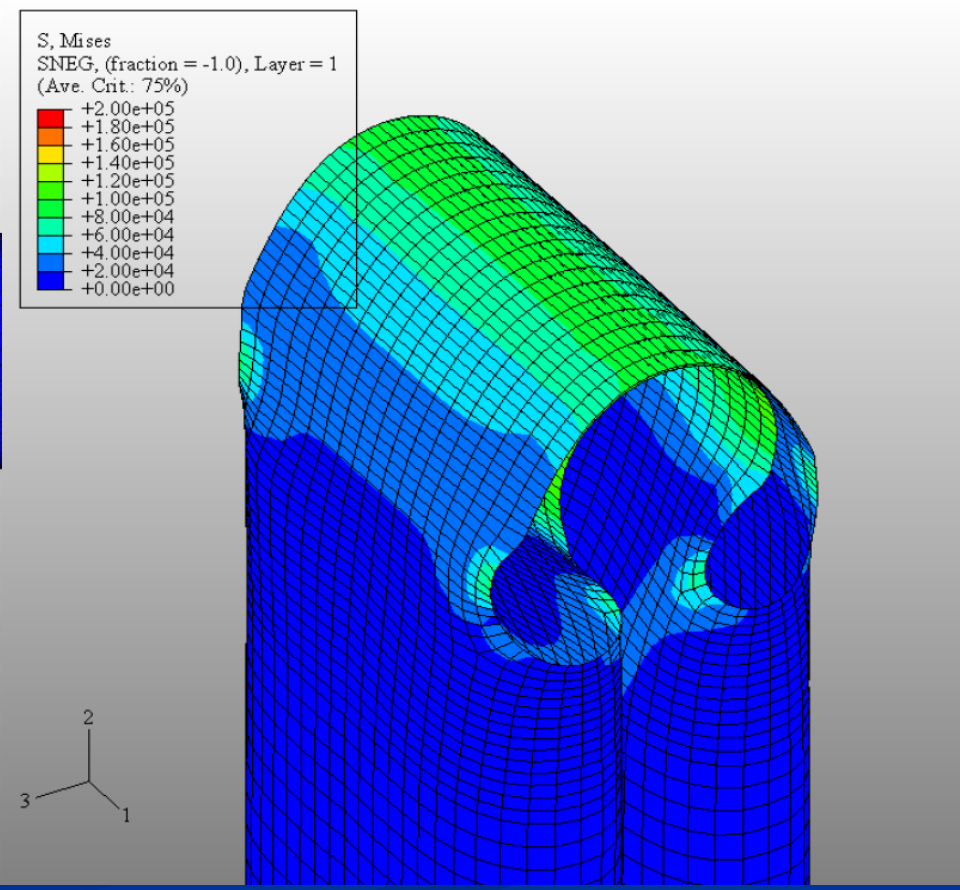
- ADAMS simulation of the vertical pendulum compared favorably with the test results



ABAQUS Hinge Model

- An ABAQUS shell model of the hinge and tube were used to investigate the local hinge behavior

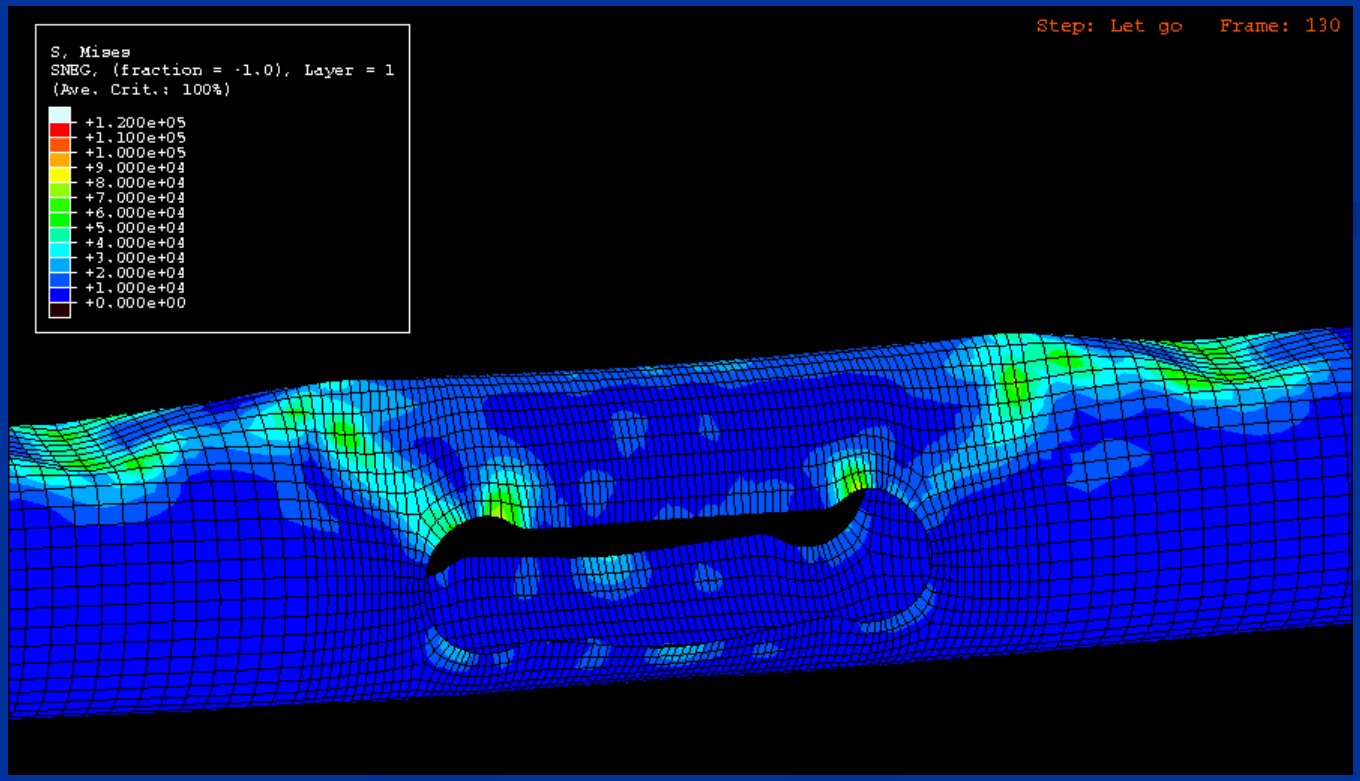




Undeformed Geometry **Stowed Geometry**

Shell Model Dynamic Results

- Buckling was observed at locations outside of the hinge columns in laboratory testing
- The dynamic ABAQUS shell model confirmed the mechanism and location for this phenomena



Key Model Verification Parameters

Critical Parameter List:	Pre-Launch	April and May, '04	Current
Test-1: Structural Damping (%)	~188 *	3.5	3.5
Test-2: Stowed Energy (in-lb)	350	280	215
Test-3: Hinge Deploy Energy (in-lb)	~3.0	~3.0	1.5
Test-4: Hinge Buckling Torque (in-lb)	160	120	104 & 93
Test-4: Hinge Post Buckling Hys. (in-lb)	~2.0	~2.0	7.5 & 5.7

* The original damping parameters were caused by incorrect ADAMS S/W modeling documentation.

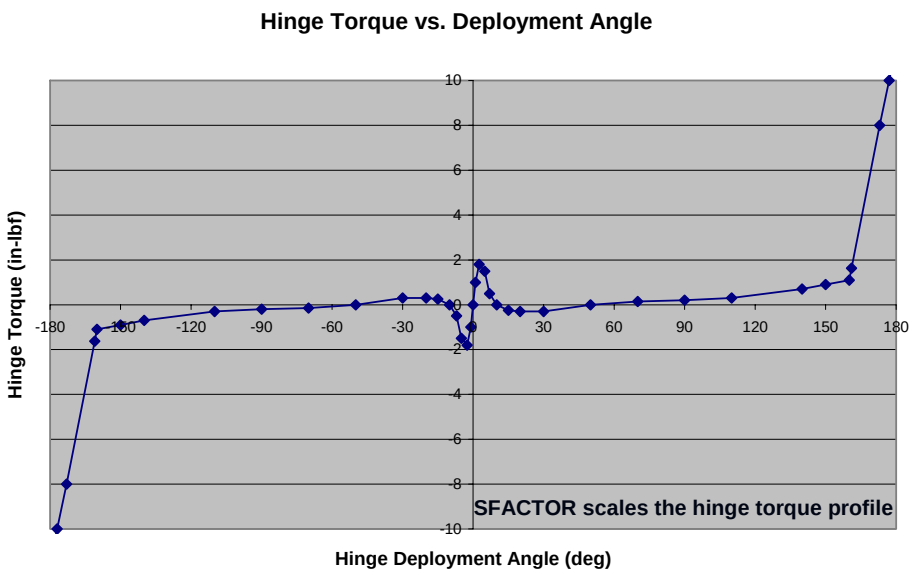
Critical Parameter Sensitivities Evaluated:

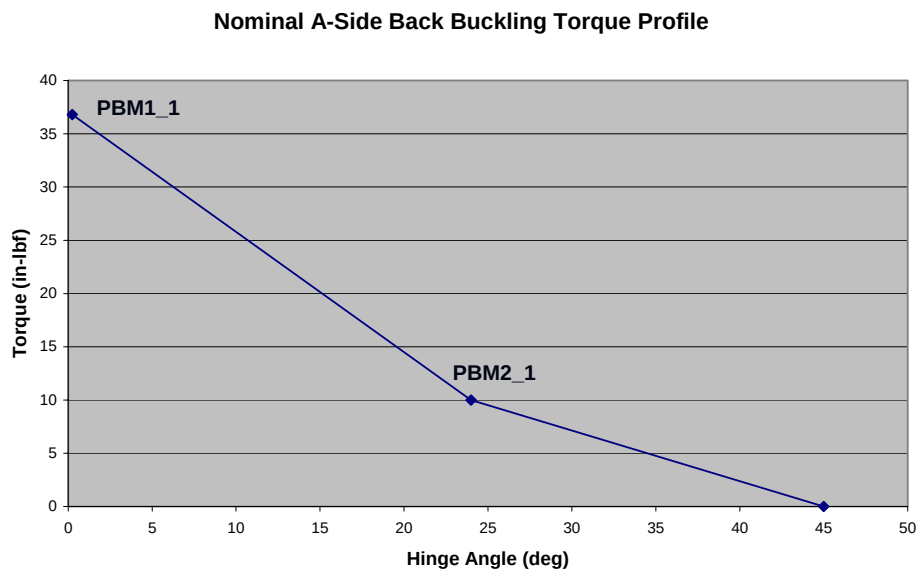
- Cold temperature
- Load onset rates
- Process control
- Vacuum/moisture out-gassing
- Long term storage under load
- Thermal cycling and Loads

Deployment Monte Carlo Simulations

- A Monte Carlo approach was employed to help better understand the behavior of the booms due to the highly unstable nature of the deployment
- Total of 1000 cases run for a 10 second critical period

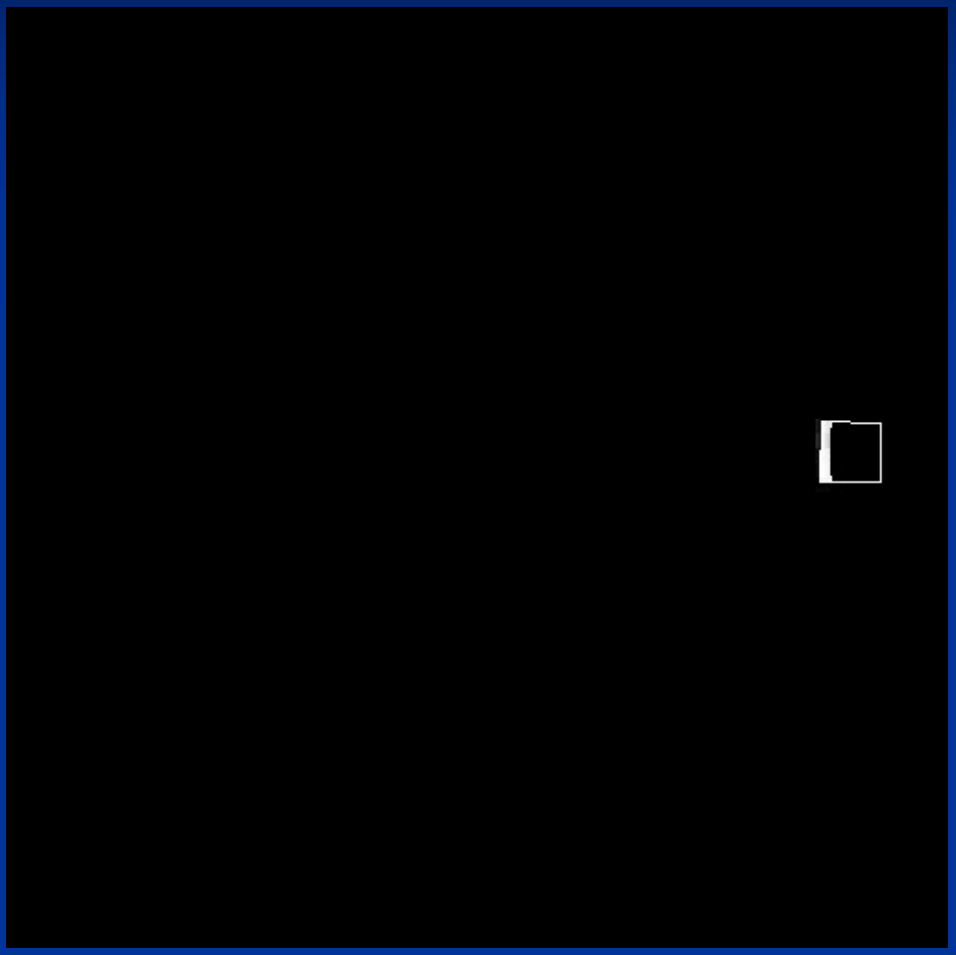
Variable	Nominal	Range	Distribution	Description
ZETA	3.5%	2% - 5%	Gaussian	Beam proportional damping ratio
SFACTOR	0.6	0.4 - 0.8	Uniform	Hinge spline scaling factor (used to vary the hinge torque profile & energy)
ENERGY	215	205 - 225	Uniform	Stored compressive energy (in-lbf)
ABUCKLE	104	78 - 130	Uniform	A-side or back buckling direction hinge strength (in-lbf)
BBUCKLE	0.9	0.8 - 1.0	Uniform	B-side or hinge direction strength as a fraction of the A-side strength
PBM1_1	36.8	18.4 - 55.2	Uniform	Post buckling moment 1 (in-lbf)
PBM2_1	10	5 - 15	Uniform	Post buckling moment 2 scaled using the same fraction of nominal as 1 (in-lbf)



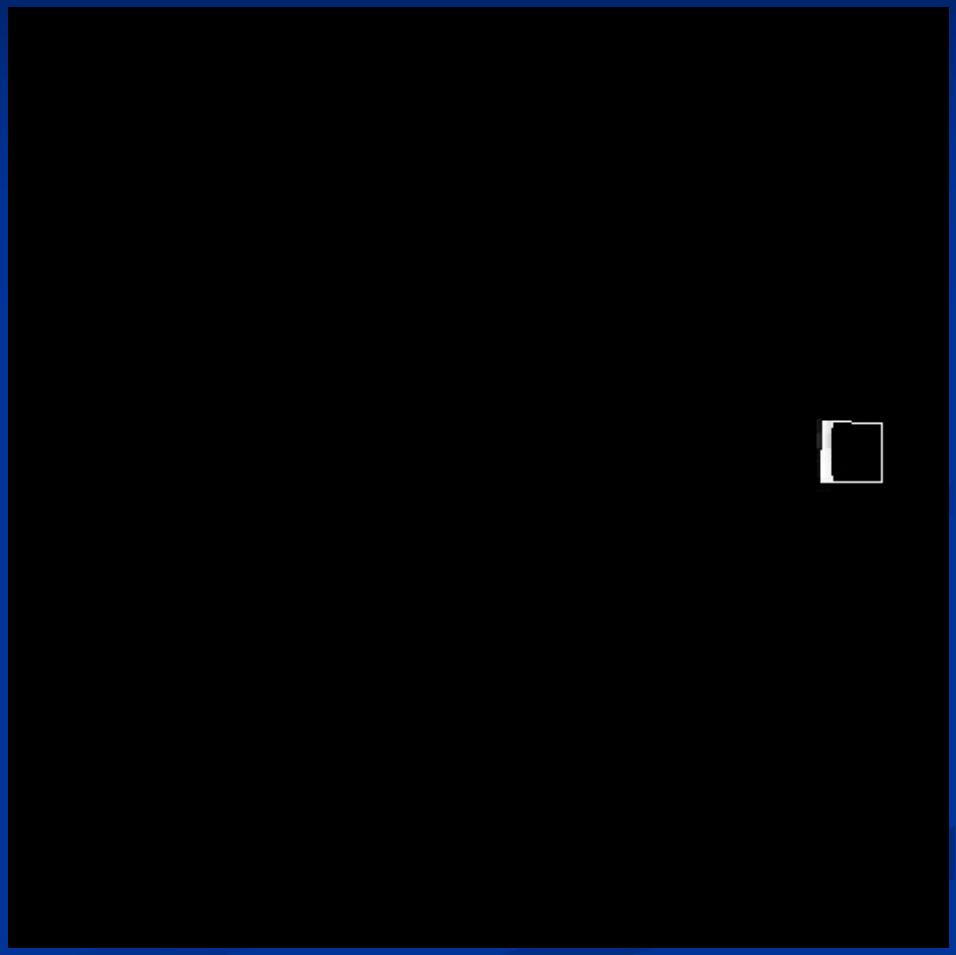


Sample Monte Carlo Results

"Slap" Case (Run 3)



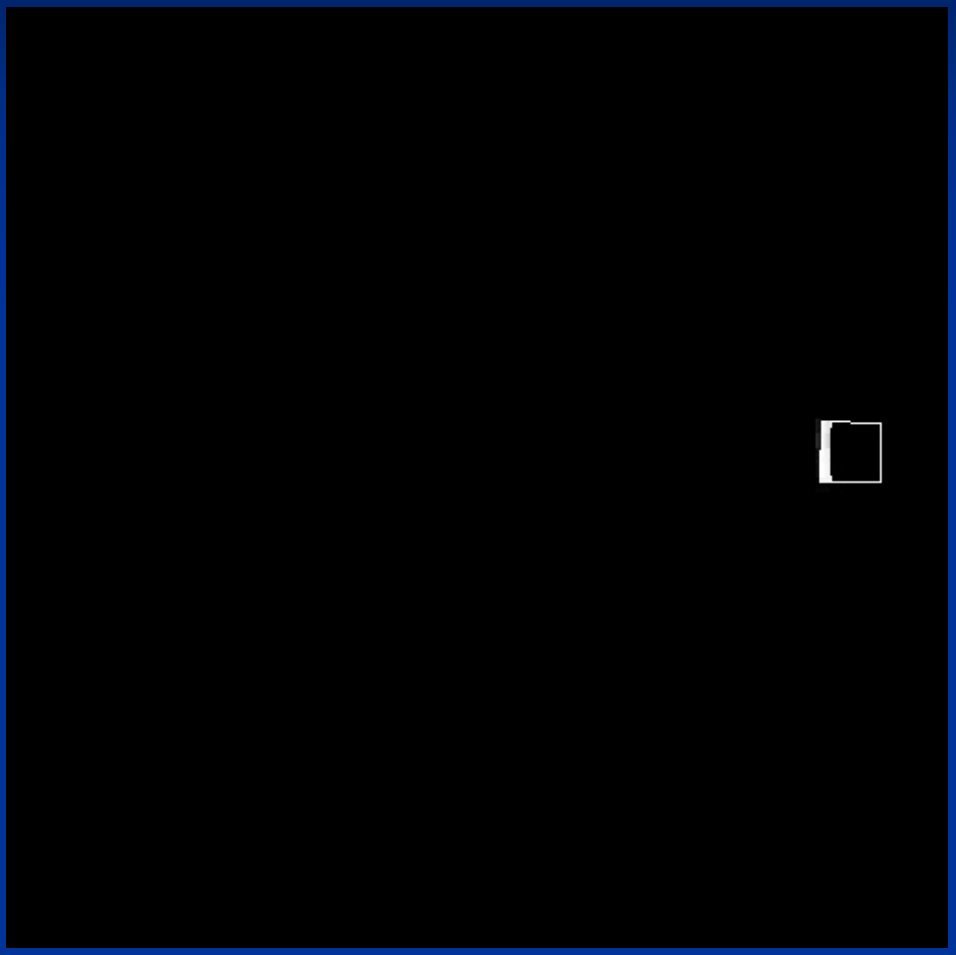
"Poke" Case (Run 139)



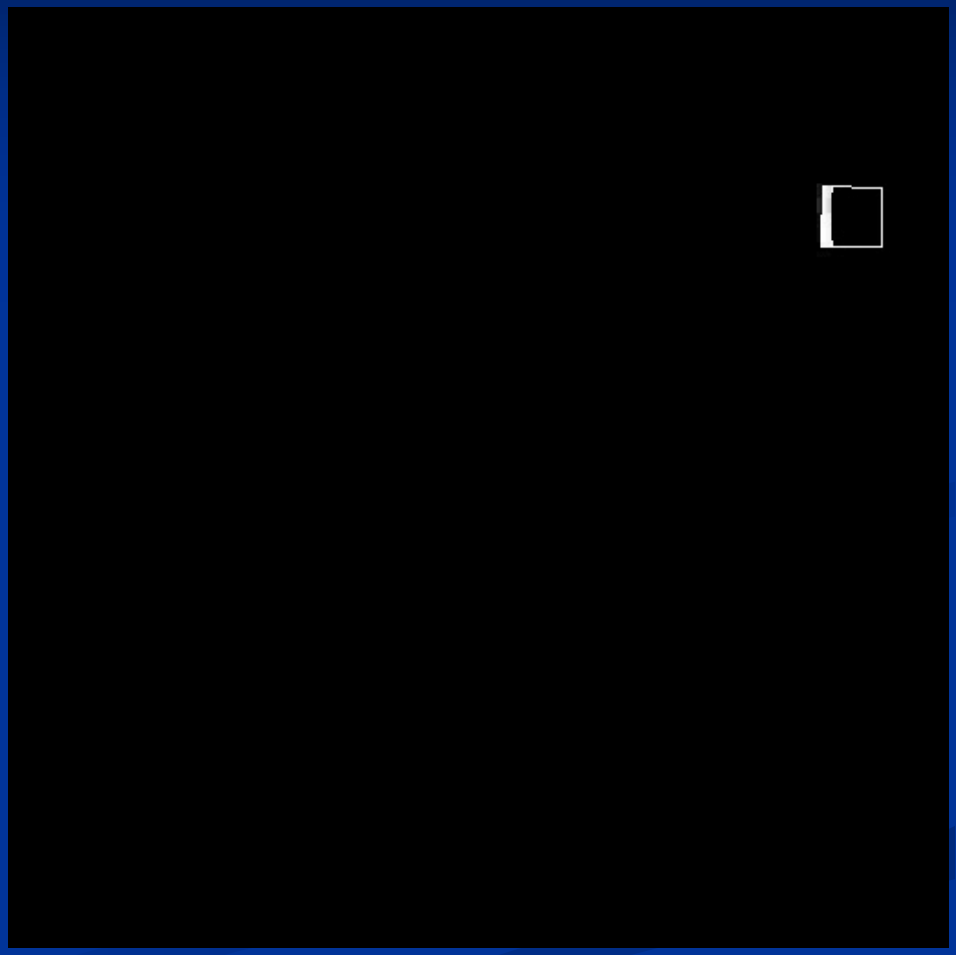
1 Buckle 2 Buckles 3 Buckles 4+ Buckles

Sample Monte Carlo Results

"Hole-in-One" Case (Run 933)

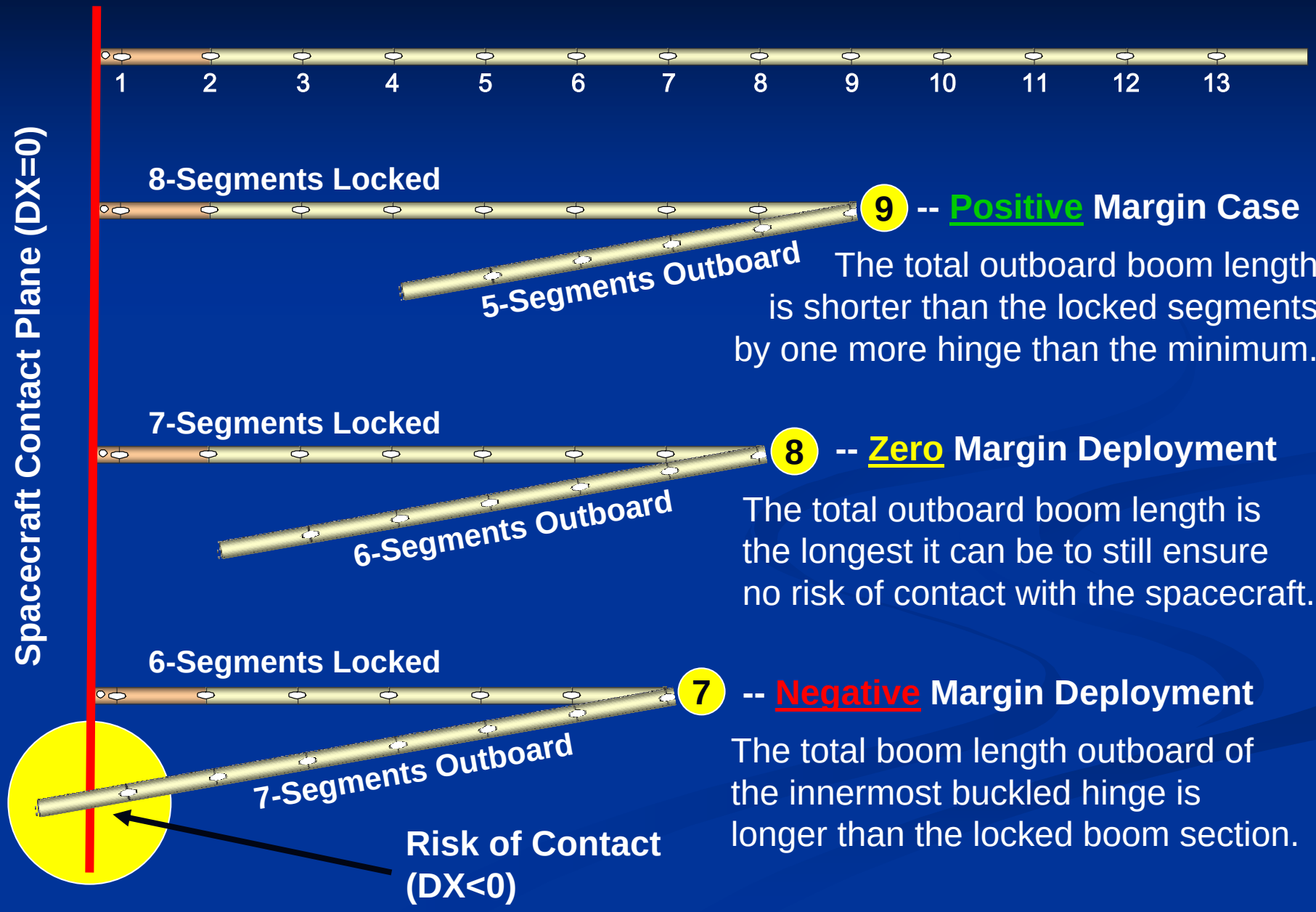


60-sec Example (Run 725)



1 Buckle 2 Buckles 3 Buckles 4+ Buckles

Single Buckled Hinge Geometric Margin



9 -- Positive Margin Case

The total outboard boom length is shorter than the locked segments by one more hinge than the minimum.

8 -- Zero Margin Deployment

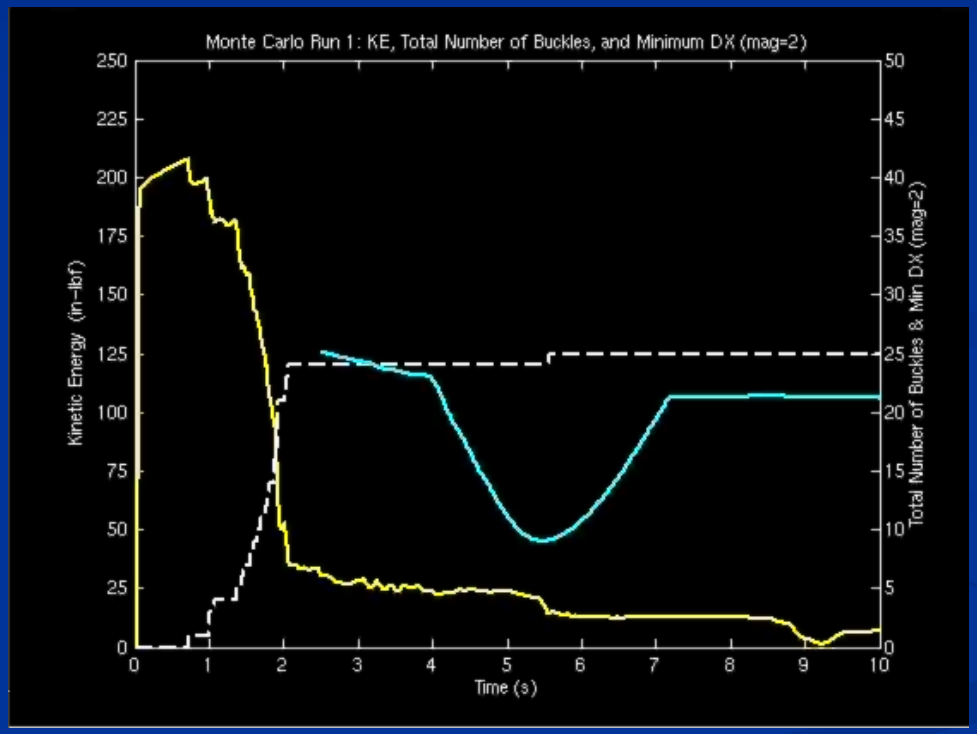
The total outboard boom length is the longest it can be to still ensure no risk of contact with the spacecraft.

7 -- Negative Margin Deployment

The total boom length outboard of the innermost buckled hinge is longer than the locked boom section.

Aggregate Monte Carlo KE, Buckling, and Tip Deflection Results

- The simulations show fairly high repeatability in KE and hinge buckling events but chaotic results for boom closest approach



Click to Animate!

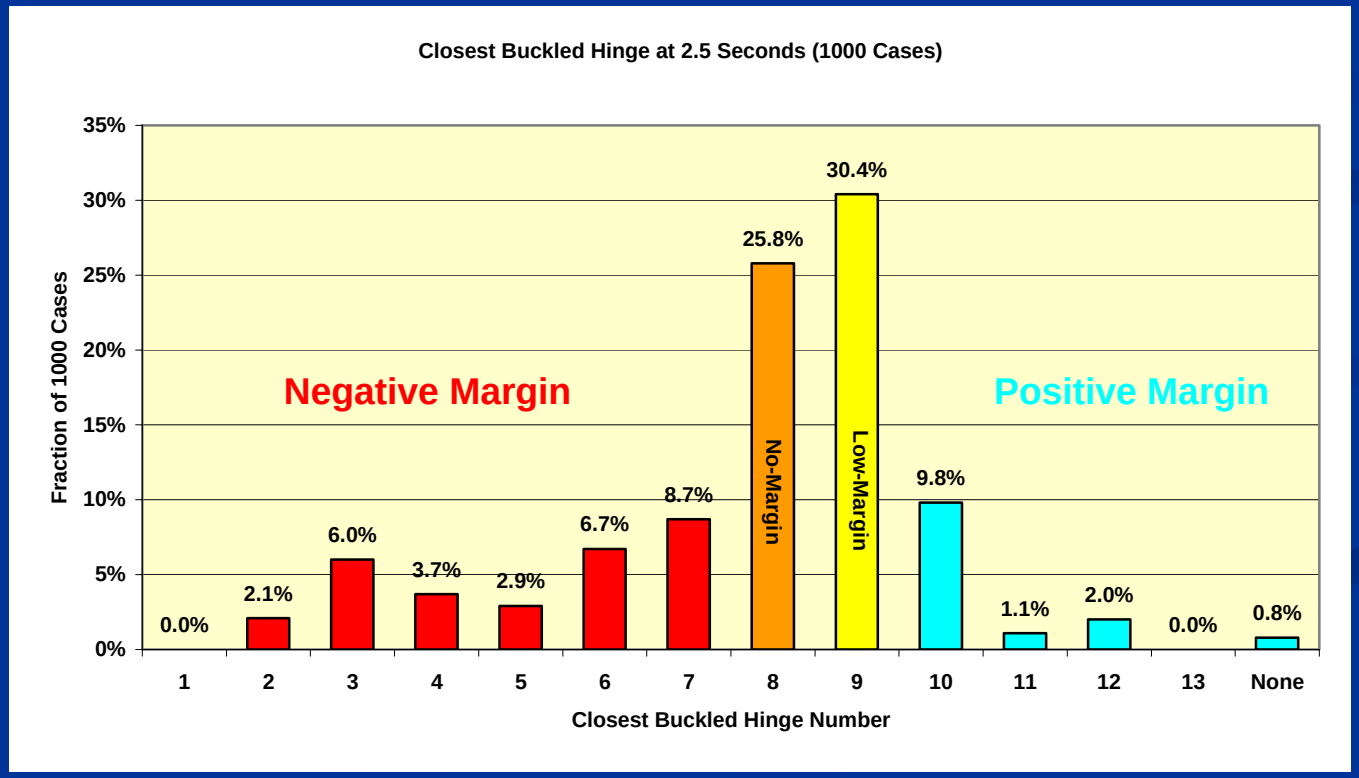
- **Total Boom Kinetic Energy (in-lbf)**
- **Total number of hinge buckling events**
- **Closest approach of any point outside of the innermost buckled hinge (m)(×2)**
  (DX<0 indicates crossing the YZ plane and a risk of contact with the spacecraft)

Monte Carlo Conclusions

- Significant probability of contact with the spacecraft
- No reliable means of predicting the location of contact
- Relatively low real risk to the s/c health (e.g., high-gain antenna)

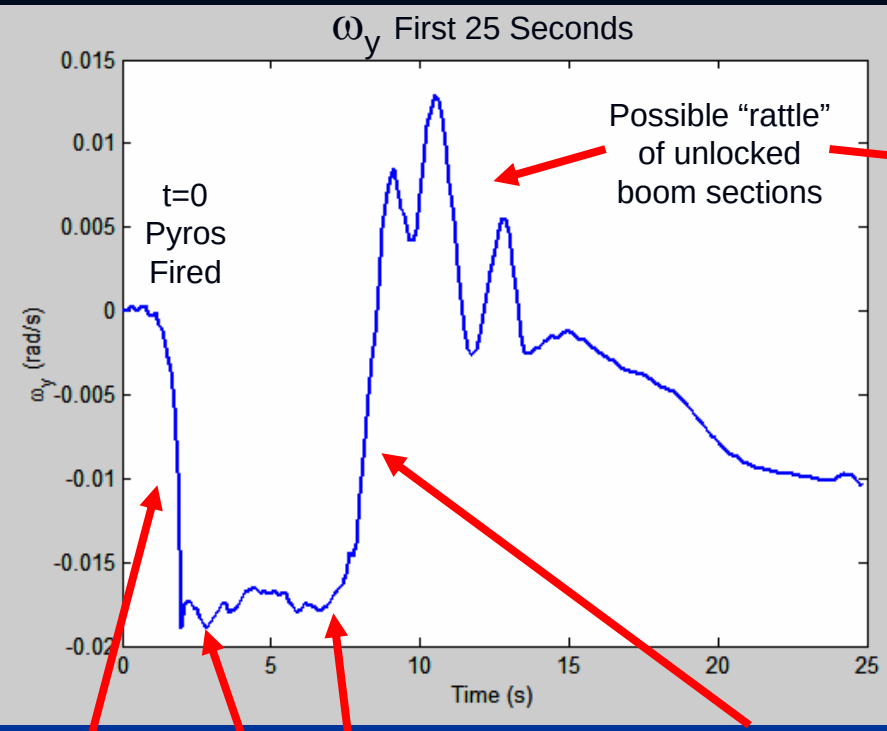
	Contact Cases	Slap Cases	Fold Cases	Cradle Cases
Boom 1	26%	15%	8%	3%
Boom 2	24%	13%	9%	2%

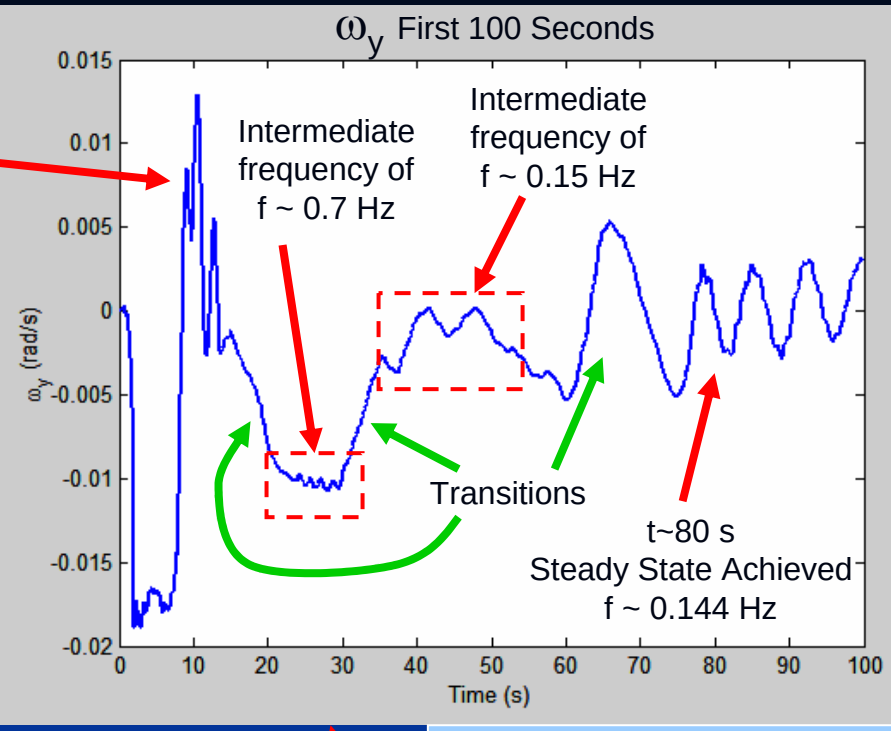
Contact – total % of contact risk cases
Slap – lateral contact with s/c
Fold – 2 or more buckled hinges when crossing X=0 plane
Cradle – recontacts cradle



Dipole-1 Deployment

- Dipole-1 was deployed on May 4, 2005
- The spacecraft recovered and was stable
- However, telemetry returned from the spacecraft indicated two anomalies in the deployment
  - The deployment dynamics were outside of the Monte Carlo simulations
  - The spacecraft inertia and measured natural frequencies both indicated that the boom had not completely locked into place
- Careful correlation between the measured spacecraft inertias and frequencies showed that hinge-10 had stalled at 40° from full deployment





Both plots show the s/c ω_y rates which is about the min. inertia axis and is the axis where most of the boom dynamics are observable.

t~2 sec
Initial snatch torque.

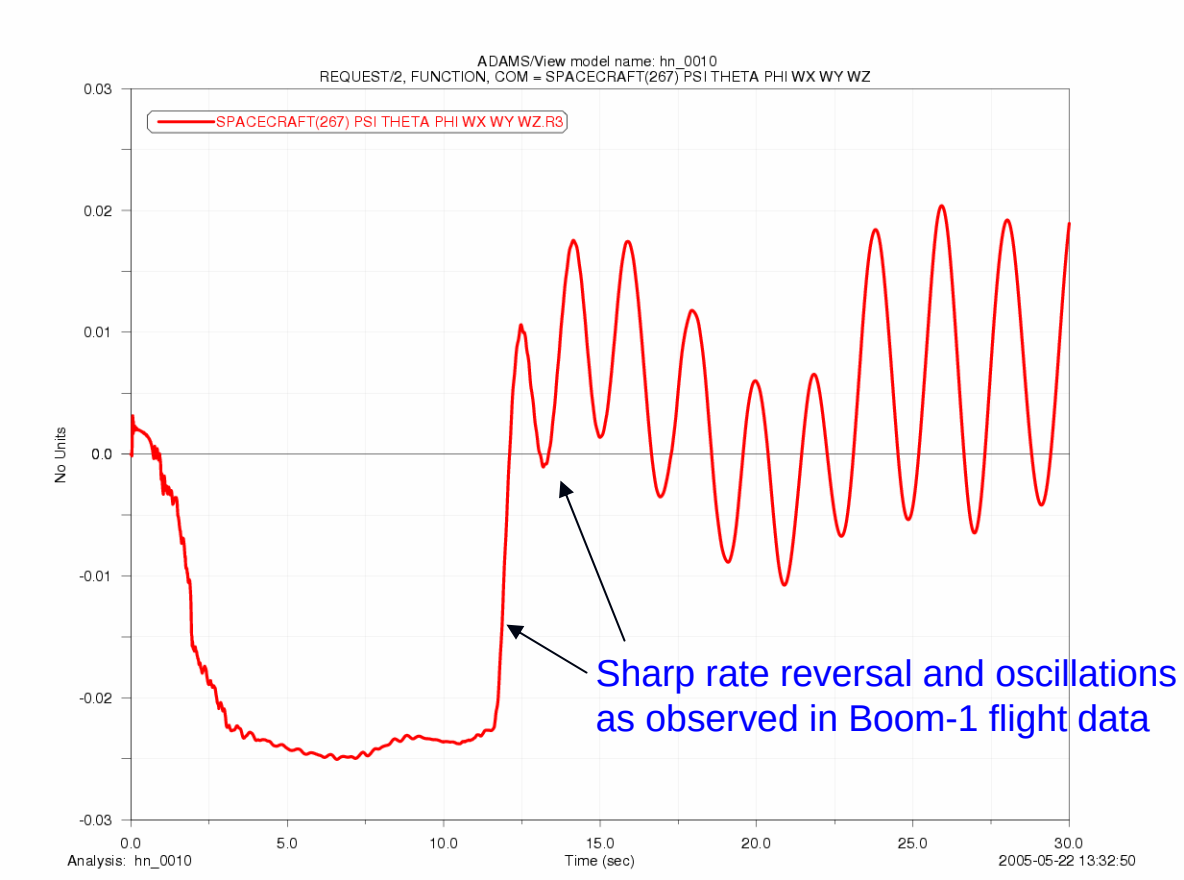
t~7 sec
Possible snatch or twang event.
The rapid nulling and slight reversal of the spacecraft angular rate suggests a change in angular momentum on the same order as the initial snatch event.

t~2-7 sec
Nearly constant spacecraft rate suggests that the boom may have multiple buckled hinges with the boom cg following a linear path.

During the subsequent time several intermediate frequencies are observed that likely indicate partially locked boom segments. There were at least 4 individual hinge locking or buckling events following the initial deployment phase (including hinge-10).

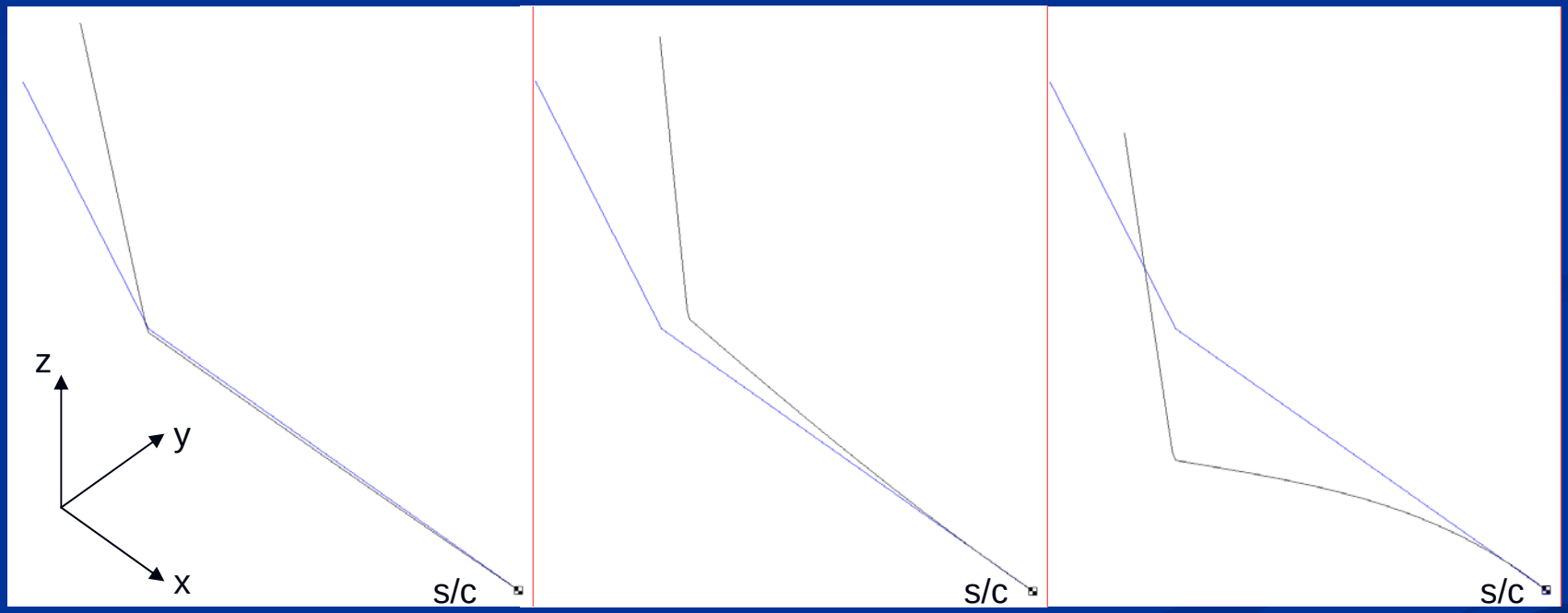
Modified ADAMS Spacecraft ω_y Rates

- ADAMS simulation with 0.8% damping and increased strength in hinges 1 and 2 has produced a similar response to what was observed in flight
- This calculation is outside the scope of the original Monte Carlo analysis
  - Damping was originally varied from 2%-5% based on available data
  - Hinges 1 & 2 were originally assigned the same strength ranges as the outer hinges in order to conservatively assess the risk of spacecraft contact



First Three Boom-1 Modes with Hinge-10 Unlocked

- Expected only two modes near 0.1 Hz for a nominal deployment
- Flight data indicated three modes:



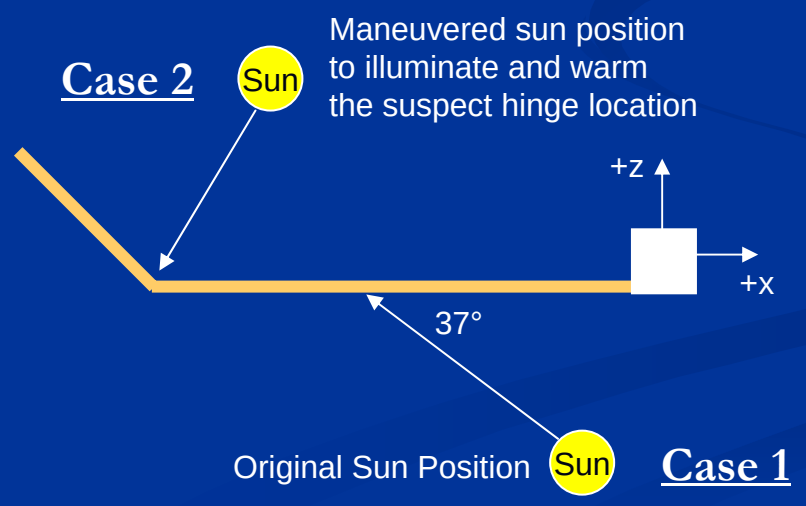
Mode 1: 0.043 Hz
Articulation of Hinge-10
in the XZ plane.

Mode 2: 0.076 Hz
Swinging and rotation
About the Z-axis.

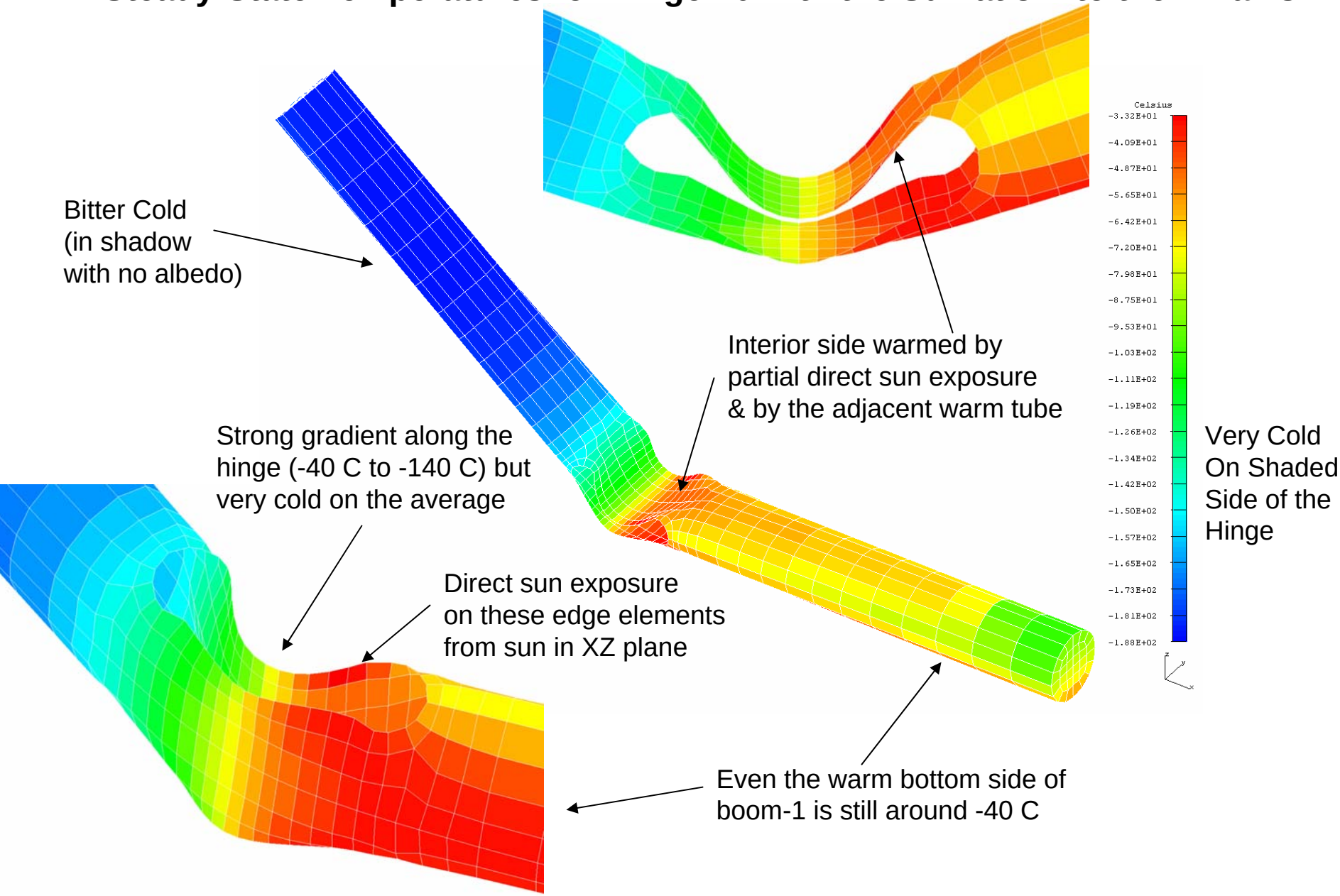
Mode 3: 0.146 Hz
Cantilever mode in
The XZ plane.

Dipole-1 Recommended Actions

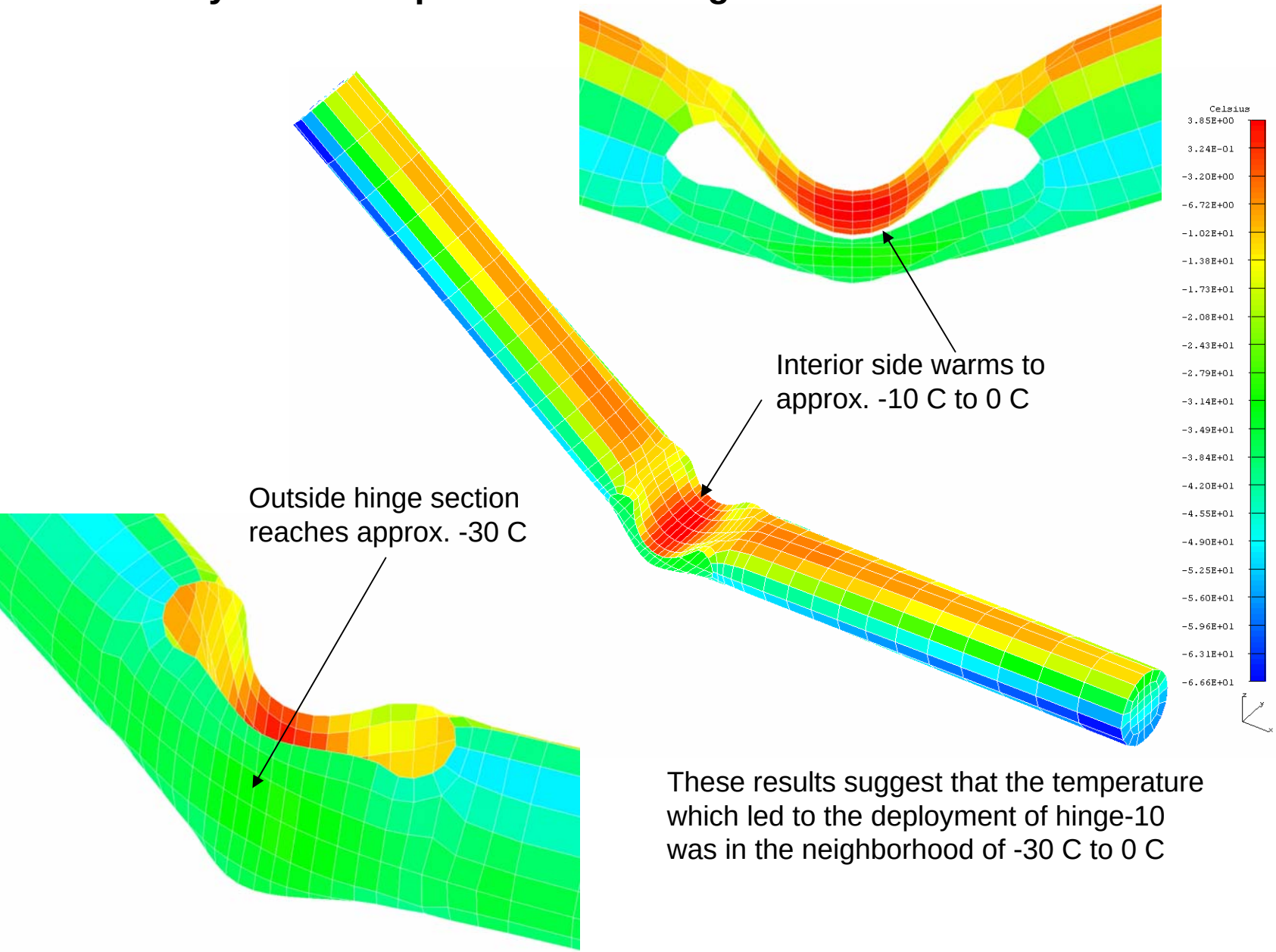
- After careful analysis of the observed s/c inertia and frequencies a maneuver to illuminate the +Z side of the antenna was recommended
  - The stall characteristic of the hinge is known to exist only at cold temperatures and warming the hinge could cause it to lock into position
- More aggressive maneuvers combining thruster pulses with optimal heating of hinge-10 were also planned



Case 1
Steady-State Temperatures for Hinge-10 with the Sun at 37° to the +X-axis



Case 2
Steady-State Temperatures for Hinge-10 with the Sun at -70° to the +X-axis

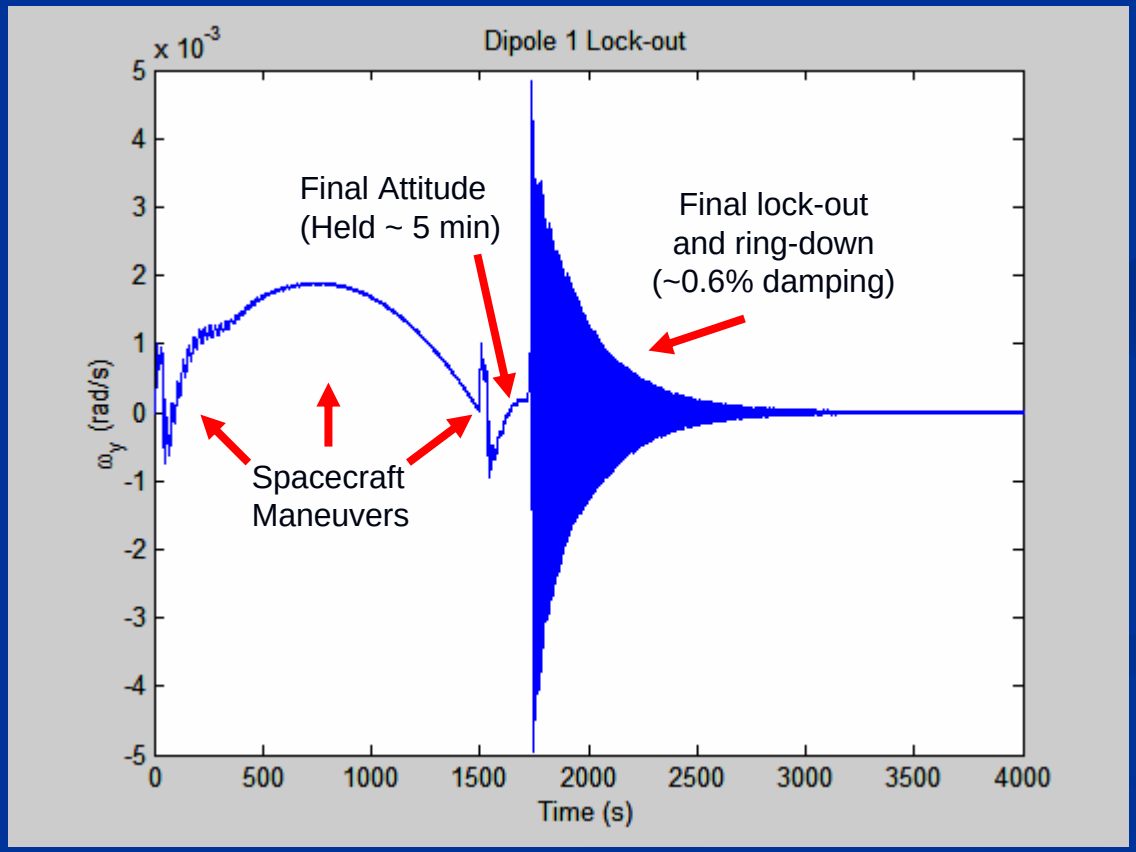


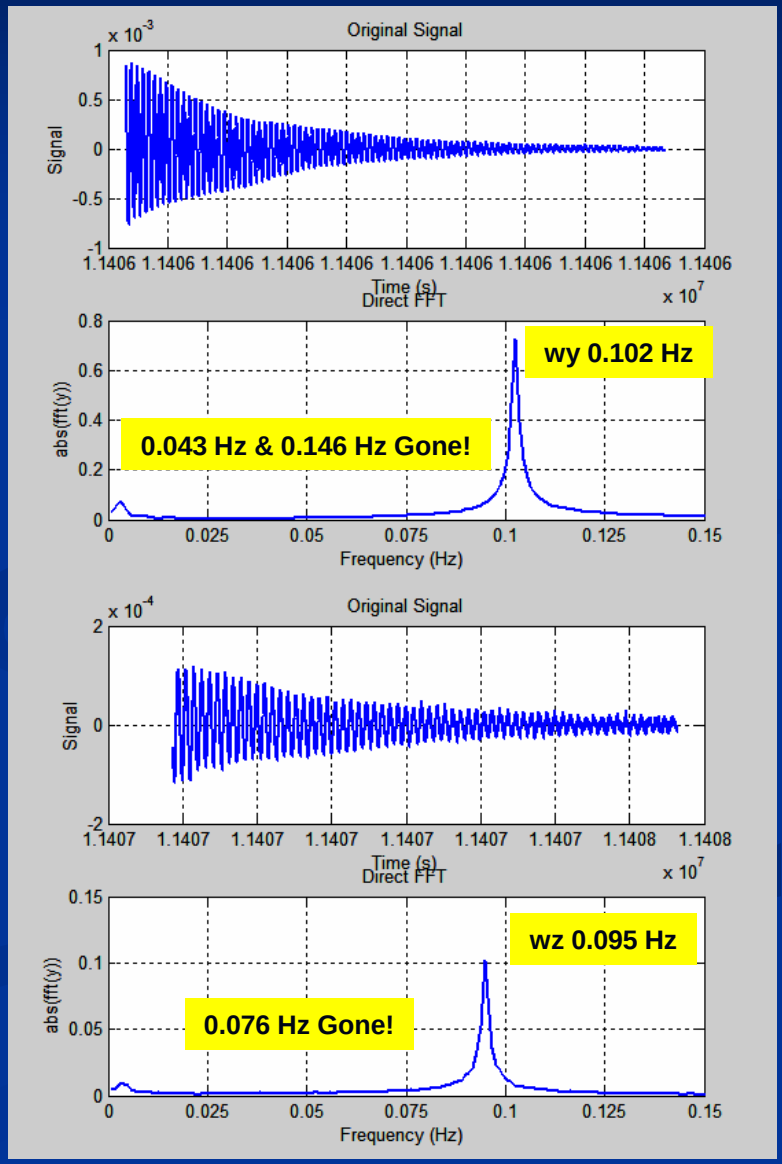
These results suggest that the temperature which led to the deployment of hinge-10 was in the neighborhood of -30 C to 0 C

Success!

Dipole-1 Locks Into Position!

- The hinge warming maneuver was performed on May 11, 2005 and resulted in the successful and full lock-out of dipole-1





Summary of Relevant Measured vs. Expected Data from the Partial Deploy Mode for Boom-1

	EXPECTED	MEASURED	HINGE-10 LOCKOUT
Change in s/c Inertia:	0 -9 -5 -9 +139 0 -5 0 +139	0 -11 +6 -11 +132 +1 +6 +1 +132 *Δlxz has wrong sign* *Δlyy & Δlzz < expected*	-4 -11 -2 -11 +138 +1 -2 +1 +139
Damping:	3.5%	<1.0%	<1.0%
Flexible Modes:	x None y ~0.1 Hz z ~0.1 Hz	x None y 0.043 Hz** y 0.146 Hz z 0.076 Hz	x None y 0.102 Hz z 0.095 Hz

*****The 0.043 Hz mode was excited by eclipse and solar array rotations***
Note that 0.043 Hz was inside the spacecraft controller's bandwidth of 0.05 Hz!

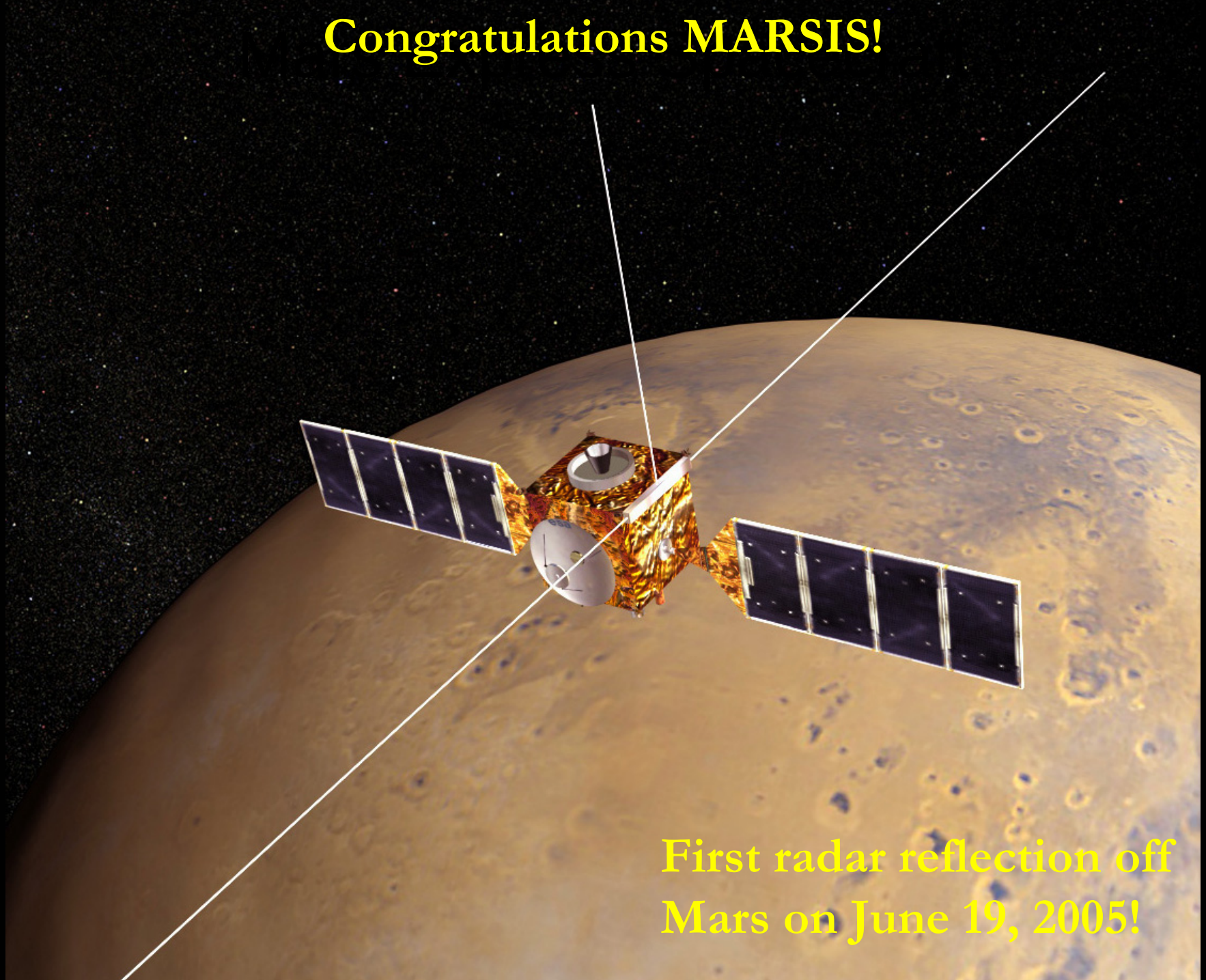
Dipole-2 and the Monopole

- Several possible mitigating actions were identified for the dipole-2 deployment sequence
  - ☑ The previously planned shading maneuver should not be done
  - ☑ Leave the PCB heaters on and at their warmest nominal setting
  - ☑ Maintain solar illumination of the external hinges prior to deployment
  - ☒ Deploying at a low altitude would take advantage of the Mars albedo (not feasible)
  - ☒ Illuminating the boom-1 cavity may increase the enclosed hinge temperatures ~5 C
    - This option is not recommended because it introduces additional unknowns with only a minimal improvement in temperature
  - ☑ Desirable for the coldest (even) hinges to receive maximum solar flux on their inner (folded) side immediately after deployment
    - The dipole-2 deployment was executed with an uncontrolled 0.1°/s roll about the y-axis for a period of 30 minutes to ensure warming of the even numbered hinges
- **Dipole-2 was uneventfully and successfully deployed on June 14**
- **The monopole was subsequently deployed on June 17**
  - Due to its very low mass and inertia it is currently uncertain whether it fully locked into place

Conclusions & Lessons Learned

- Do not take lenticular (carpenter tape) structures for granted
  - The mechanisms and sensitivities of these joints are complex
  - The use of multiple hinges greatly amplifies the modeling challenges
- Material selection and construction can have subtle effects on the hinge behavior
- If possible the hinges should be test verified to have a positive torque margin throughout their range of motion
  - These tests should closely approximate the flight conditions
- The total stowed energy should be optimized (not to high or low)
  - The tube compression energy should be low enough to prevent the back-buckling phenomenon
  - The hinge energy needs to be high enough to produce positive torque
- These types of booms are extremely lightweight and, once deployed, are very easily modeled and accounted for on the spacecraft

Congratulations MARSIS!



First radar reflection off Mars on June 19, 2005!