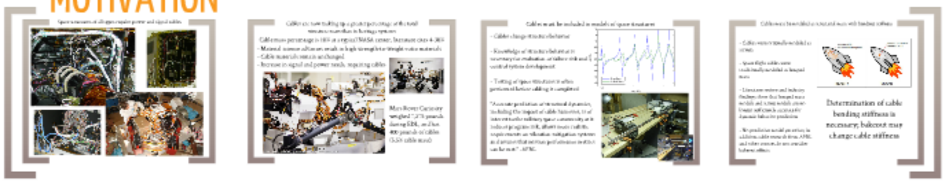
Effects of Bakeout on Space Flight Cable Stiffness

SEM Student Paper Competition ~ June 3, 2013

Kaitlin Spak

MOTIVATION

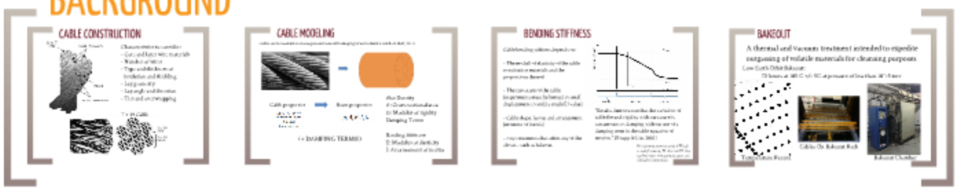


OBJECTIVES

Thus, because cables make up a significant portion of space structures and affect the structural dynamics, determining the bending stiffness of space flight cables is necessary. Since bending stiffness may be affected by the bakeout procedure, the objectives of this study are to:

- Determine whether space flight cable stiffness is indeed affected by bakeout, as evidenced by changes in dynamic response
- Observe the effects of bakeout on space flight cables and compare the cables pre- and post-bakeout
- Quantify the dynamic response effects of low Earth orbit bakeout on a variety of cable geometries by determining the changes in natural frequency and/or damping

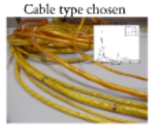
BACKGROUND



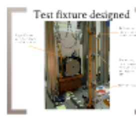
EXPERIMENTAL PROCEDURE

Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

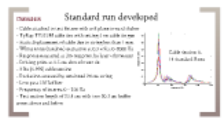
Cable type chosen



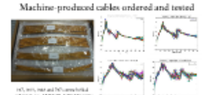
Test fixture designed



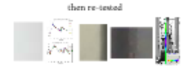
Standard run developed



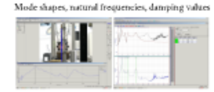
Machine-produced cables ordered and tested



Most reliable cables determined and baked out at 105C, 1E-5 torr for 72 hours, then re-tested



Results compared:
Mode shapes, natural frequencies, damping values



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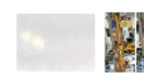
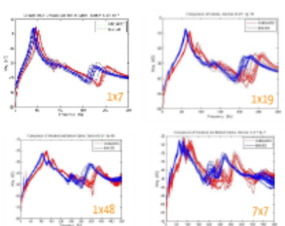
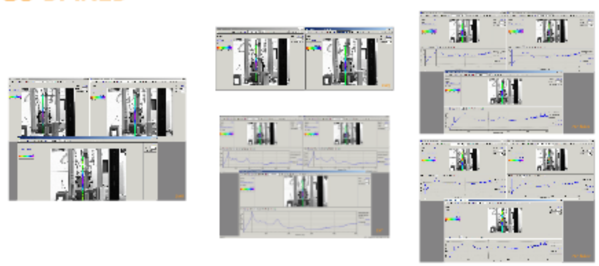
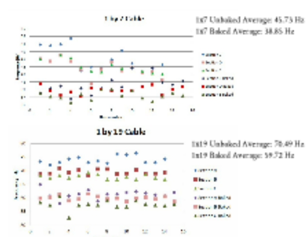


RESULTS: UNBAKED VERSUS BAKED







Baked out cables show decrease in natural frequency and increase in damping.

	LASER SCANS	VIB SCOPE	
1x7	First Frequency [Hz]	First Frequency [Hz]	% Damping
Unbaked	41.25	41.3	3.49
Baked	[illegible]	[illegible]	[illegible]
1x19			
Unbaked	68.44	68.3	4.05
Baked	57.5	57.4	5.5
1x48			
Unbaked	118.1	118	4.6
Baked	107.5	108	8.87
7x7			
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Baked	[illegible]	[illegible]	[illegible]

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1x7	7.05	7.02
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1x48	9.12	8.85
7x7	24.42	27.95

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

- No literature exists on the effect of bakeout treatment on cable stiffness;
  this work provides concrete data that bakeout does indeed change the dynamic response of space flight cables
- After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%
- After a low Earth orbit bakeout, damping values increased for all single-strand cables
  It is clear that this combination of wire type and bakeout results in a significant reduction in bending stiffness.

- Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables;
  spacecraft designers should keep this in mind if using currently published data

Future work:
- Different bakeout treatments may have different results
- Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout
- More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment

ACKNOWLEDGEMENTS

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- Virginia Space Grant Consortium
- Air Force Office of Scientific Research
- AIAA San Gabriel Valley Chapter
- Jet Propulsion Laboratory
- Virginia Tech
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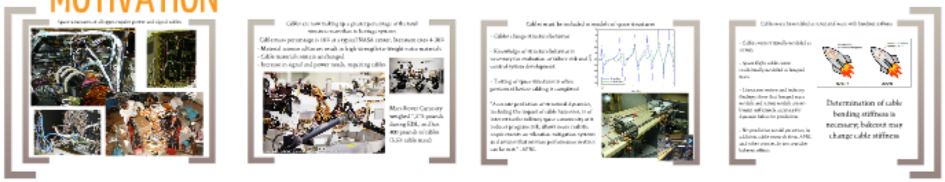

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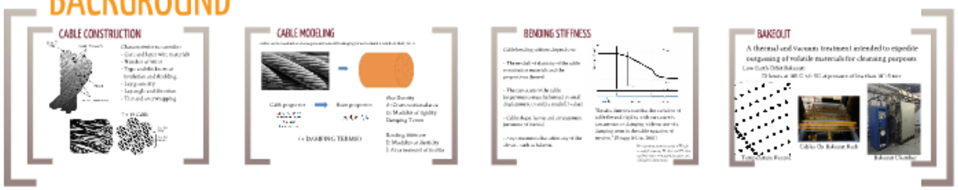

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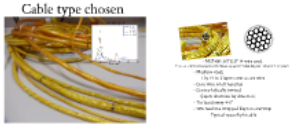

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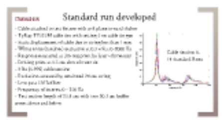

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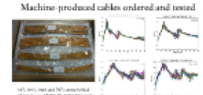

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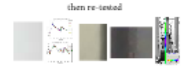

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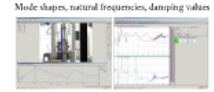

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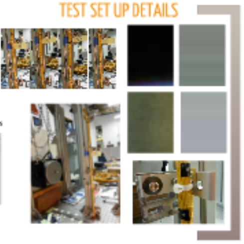

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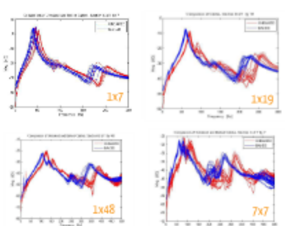

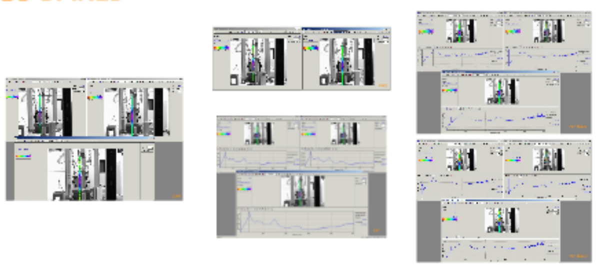

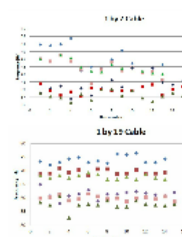

1x7 Unbaked Average: 45.73 Hz
1x7 Baked Average: 38.85 Hz

1x19 Unbaked Average: 70.49 Hz
1x19 Baked Average: 59.72 Hz

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Effects of Bakeout on S

SEM Student Paper

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MOTIVATION

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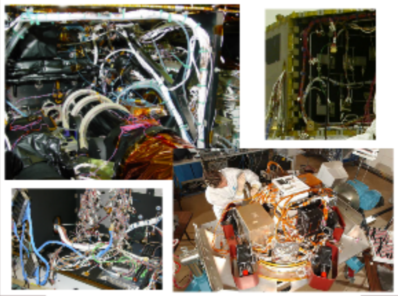

Cables are now making up a greater percentage of the total structure mass than in heritage systems

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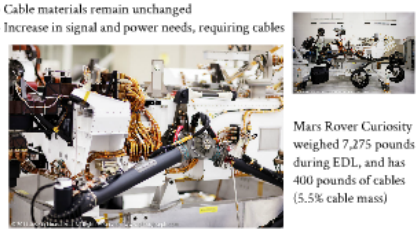

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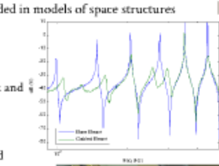

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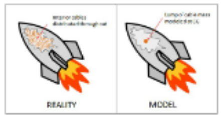

Determination of cable bending stiffness is necessary; bakeout may change cable stiffness

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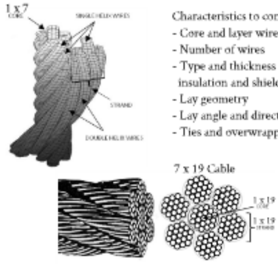
CABLE CONSTRUCTION



Characteristics to consider:
- Core and layer wire materials
- Number of wires
- Type and thickness of insulation and shielding
- Lay geometry
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- Ties and overwrapping

CABLE MODELING

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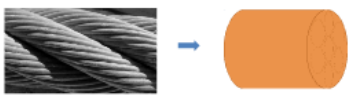

Cable properties → Beam properties

ρ, A, E, I, G

(+ DAMPING TERMS!)

rho: Density
A: Cross-sectional area
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Damping Terms

Bending Stiffness:
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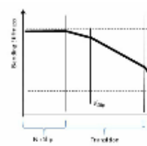

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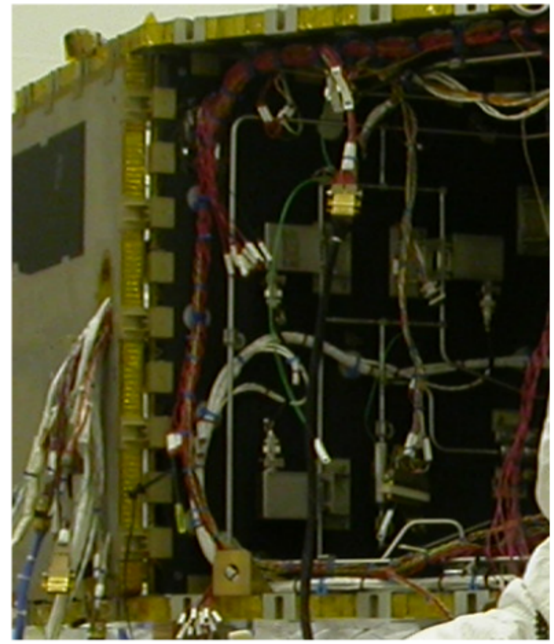

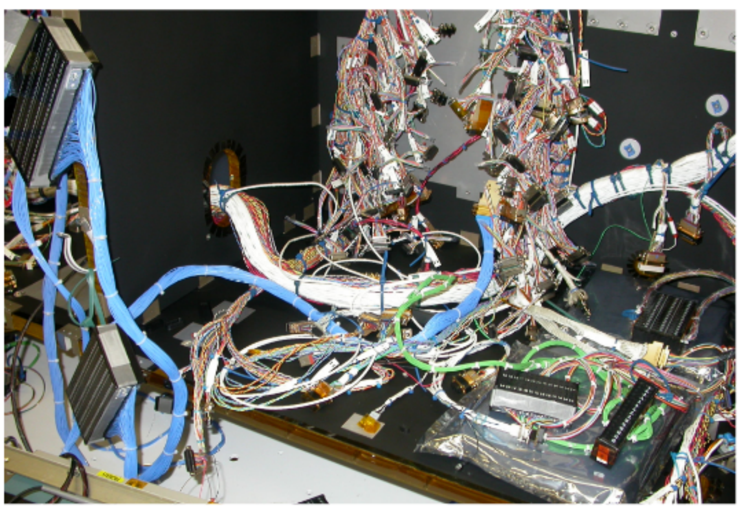

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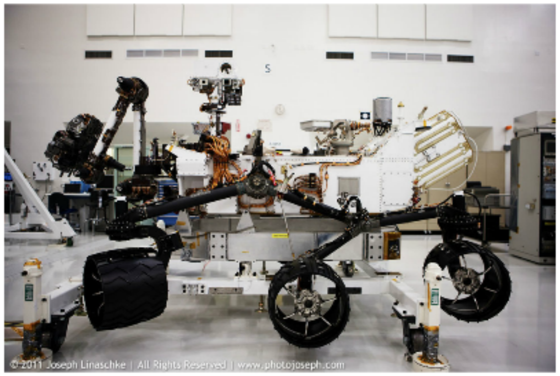

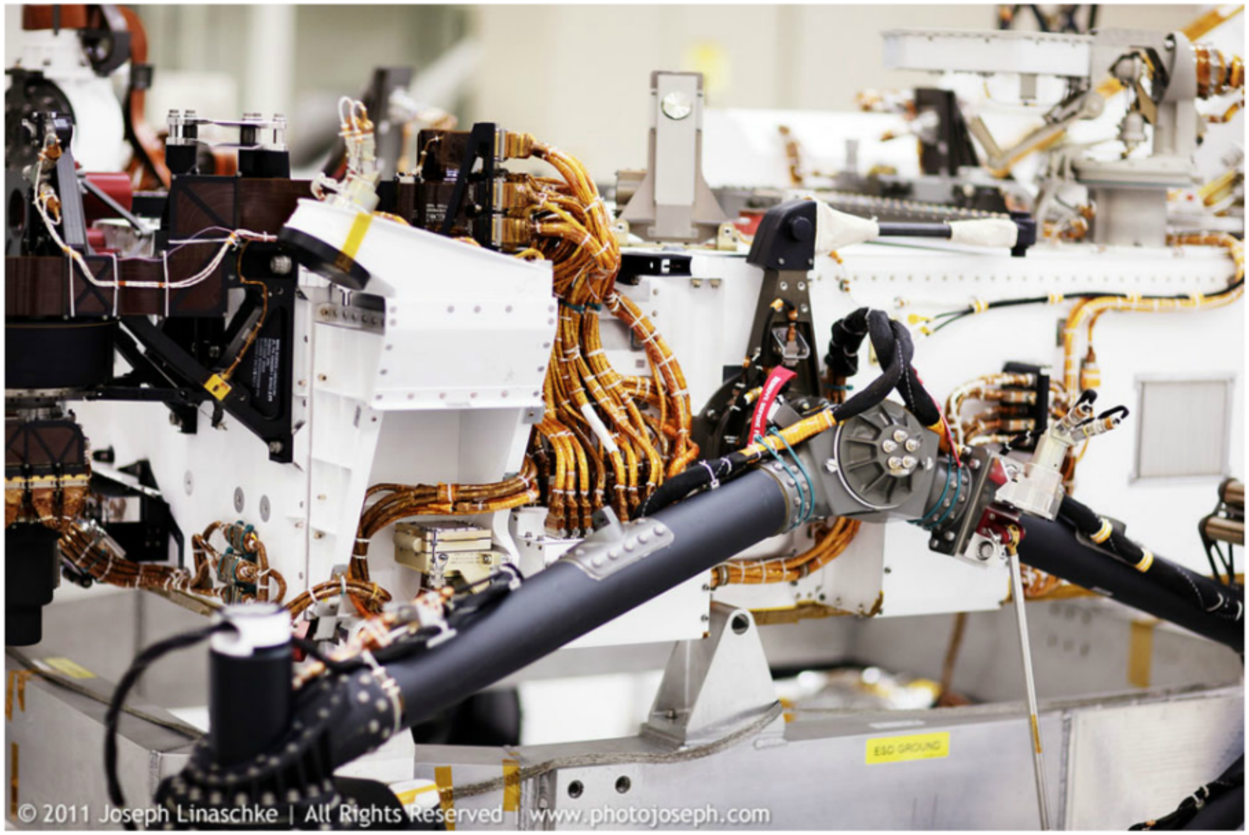

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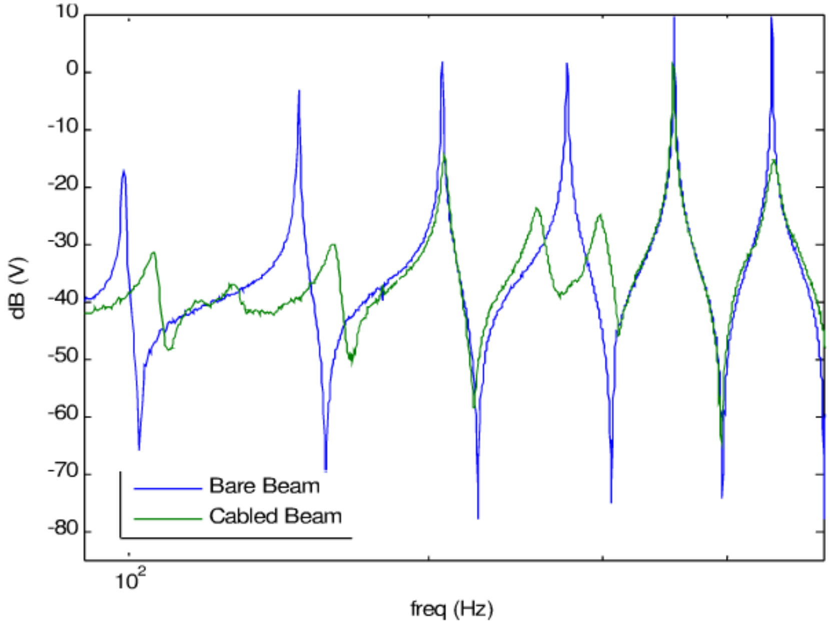

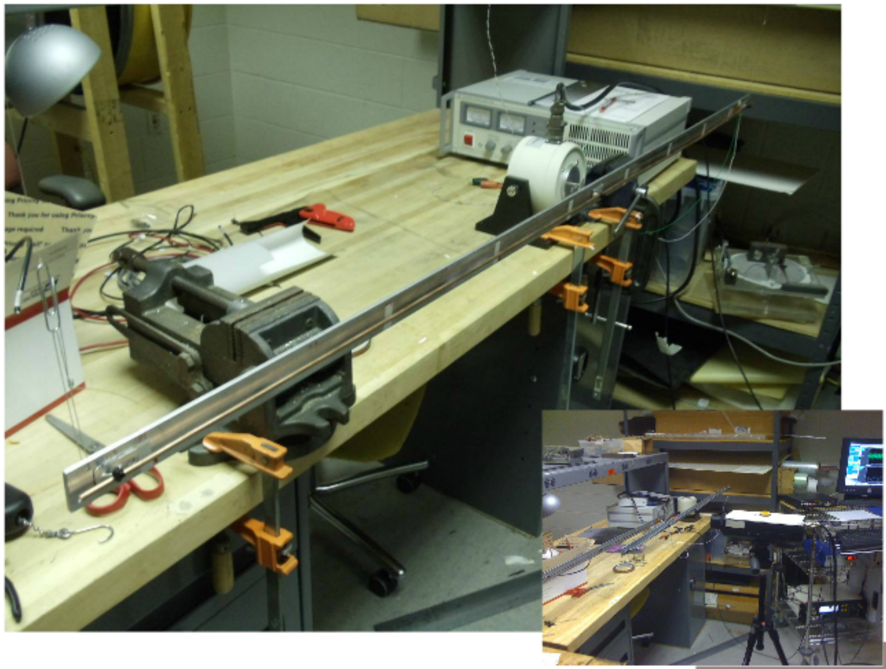

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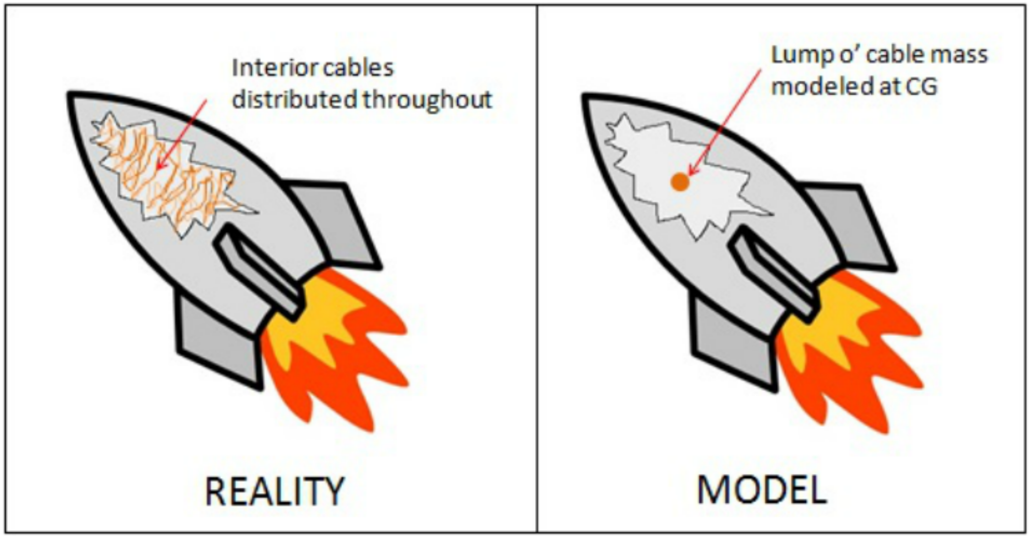

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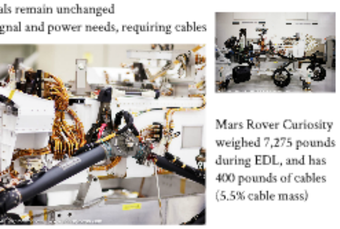

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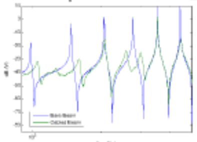

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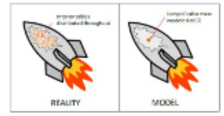

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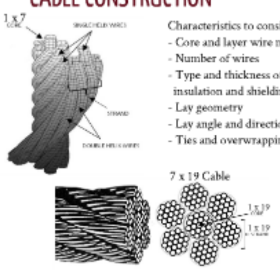

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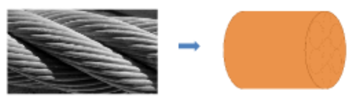

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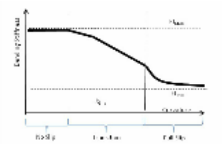


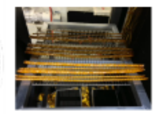
"Results demonstrate that the variation of cable flexural rigidity with curvature is tantamount to damping without use of a damping term in the cable equation of motion." (Knapp & Liu, 2005)

BAKEOUT

A thermal and vacuum treatment intended to expedite outgassing of volatile materials for cleansing purposes

Low Earth Orbit Bakeout:
72 hours at 105 C +/- 5C at pressure of less than 10^{-5} torr

Temperature Record



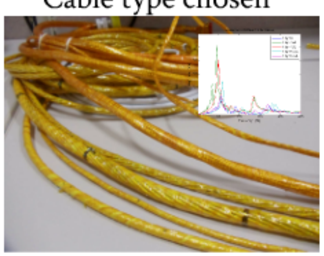
Cables On Bakeout Rack

Bakeout Chamber

EXPERIMENTAL PROCEDURE

Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

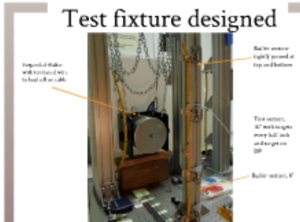
Cable type chosen



- M27500-26TG2T14 wire used
- Medium sized; 1 by 19 in 2 layers over a core wire
- Core wire is left hand lay
- Contra-helically twisted (layers alternate lay direction)
- Tie laced every 4-6"
- 50% machine wrapped Kapton overwrap

Typical space flight cable

Test fixture designed



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- Cable attached to test fixture with coil plane toward shaker
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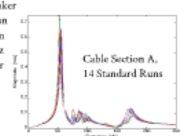
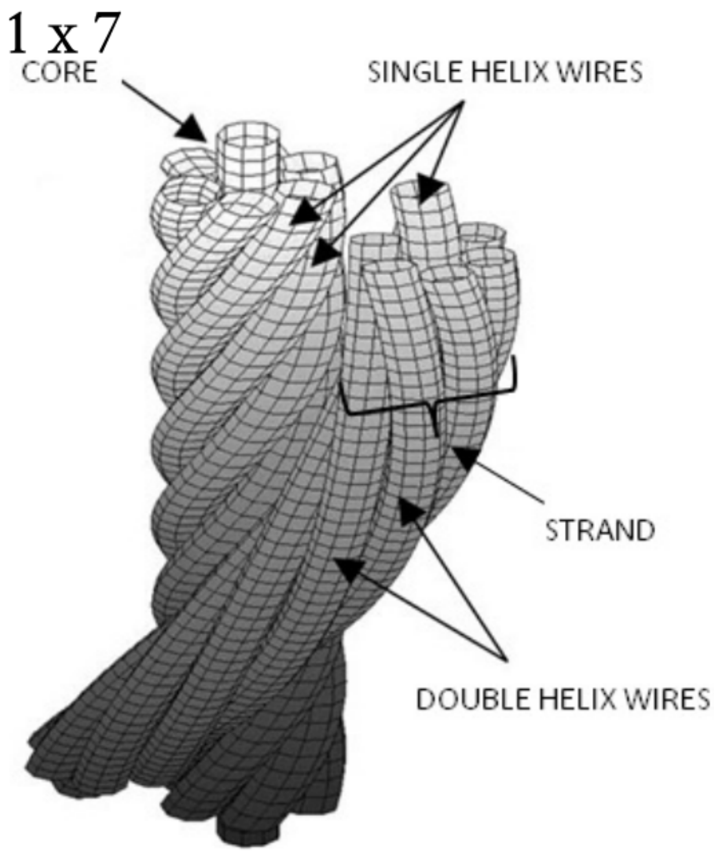


Machine-produced cab

1x7, 1x19, 1x48 and 7x7 contra-helical configurations of M27500-26TG2T14 wire

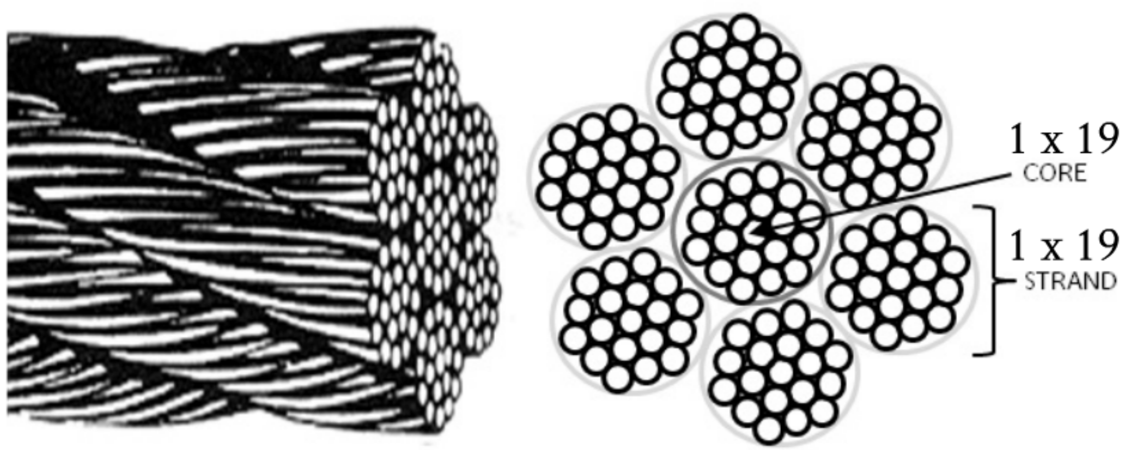
CABLE CONSTRUCTION



Characteristics to consider:

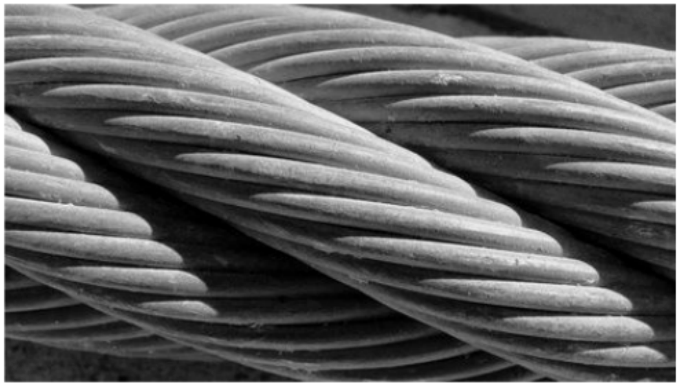
- Core and layer wire materials
- Number of wires
- Type and thickness of insulation and shielding
- Lay geometry
- Lay angle and direction
- Ties and overwrapping

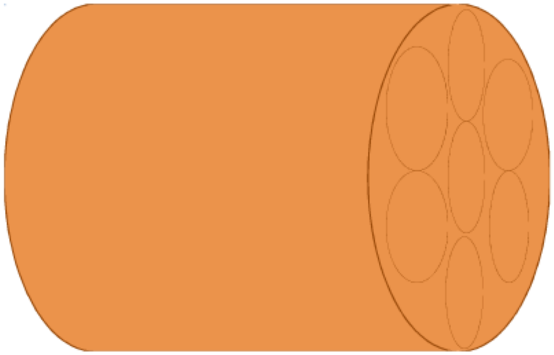
7 x 19 Cable



CABLE MODELING

Cables can be modeled as a homogeneous beam with damping terms included (Castello & Matt, 2011)





Cable properties

Number of wires
Number of layers
Wire size
Wire material

Beam properties

ρ, A, E, I, G

(+ DAMPING TERMS!)

rho: Density
A: Cross-sectional area
G: Modulus of rigidity
Damping Terms

Bending Stiffness:
E: Modulus of elasticity
I: Area moment of inertia

BENDING STIFFNESS

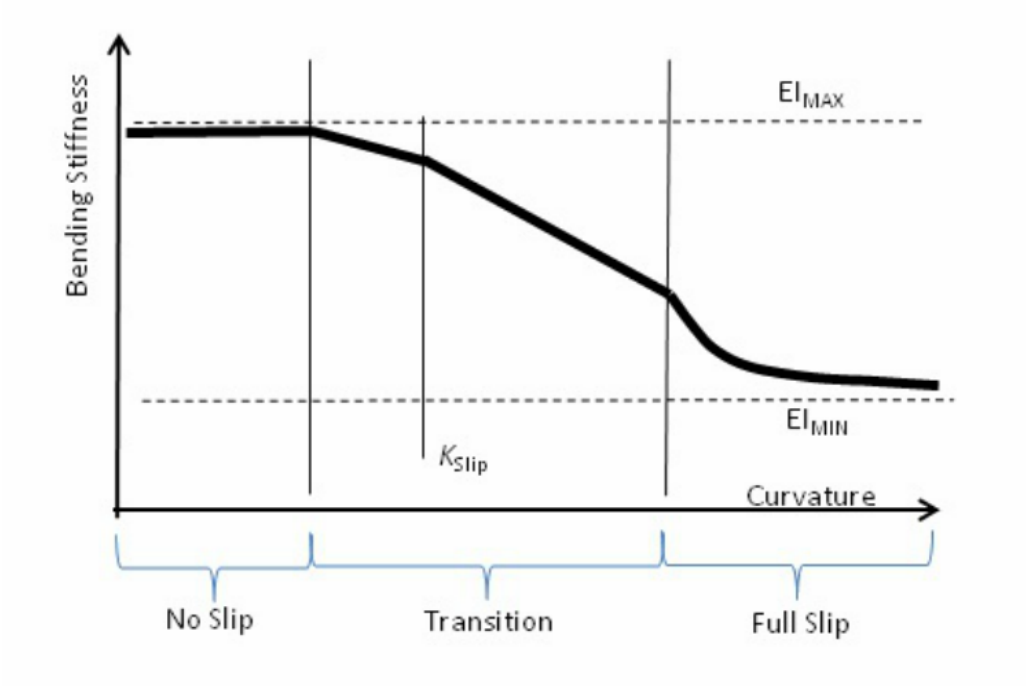
Cable bending stiffness depends on:

- The moduli of elasticity of the cable constitutive materials and the proportions thereof

- The curvature of the cable (experiments must be limited to small displacement to yield a single EI value)

- Cable shape, layout and arrangement (moment of inertia)

- Any treatments that affect any of the above... such as bakeout



"Results demonstrate that the variation of cable flexural rigidity with curvature is tantamount to damping without use of a damping term in the cable equation of motion." (Knapp & Liu, 2005)

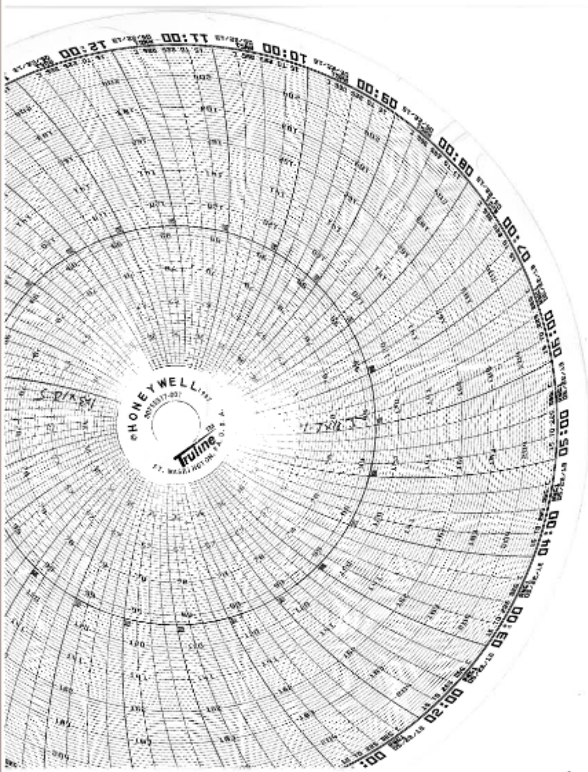
No damping term required if EI(x,t) is used; however, EI_max and EI_min can be orders of magnitude apart and difficult to determine.

BAKEOUT

A thermal and vacuum treatment intended to expedite outgassing of volatile materials for cleansing purposes

Low Earth Orbit Bakeout:

72 hours at 105 C +/- 5C at pressure of less than 10^-5 torr



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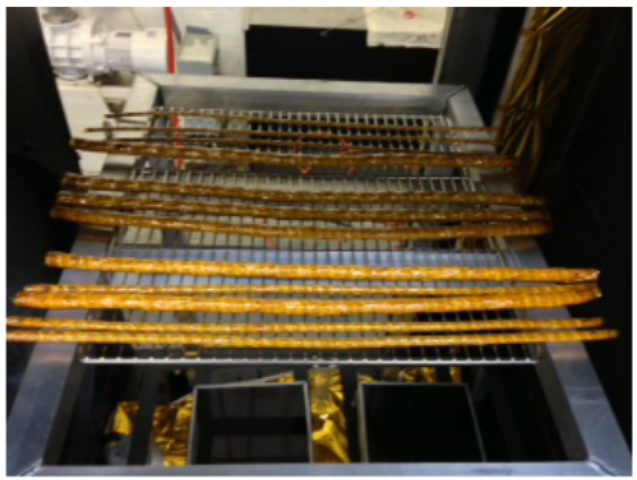


Cables On Bakeout Rack

Bakeout Chamber

OBJECTIVES

Thus, because cables make up a significant portion of space structures and affect the structural dynamics, determining the bending stiffness of space flight cables is necessary. Since bending stiffness may be affected by the bakeout procedure, the objectives of this study are to:

- Determine whether space flight cable stiffness is indeed affected by bakeout, as evidenced by changes in dynamic response

- Observe the effects of bakeout on space flight cables and compare the cables pre- and post-bakeout

- Quantify the dynamic response effects of low Earth orbit bakeout on a variety of cable geometries by determining the changes in natural frequency and/or damping

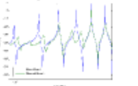
Cables must be included in models of space structures

- Cables change structure behavior

- Knowledge of structure behavior is necessary for evaluation of failure risk and control system development

- Testing of space structures is often performed before cabling is completed

"Accurate prediction of structural dynamics, including the impact of cable harnesses, is of interest to the military space community as it reduces program risk, allows more realistic requirements on vibration mitigation systems and assures that mission performance metrics can be met." -AFRL



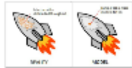
Cables must be modeled as structural mass with bending stiffness

- Cables were originally modeled as strings

- Space flight cables were traditionally modeled as lumped mass

- Literature review and industry findings show that lumped mass models and string models are no longer sufficiently accurate for dynamic behavior prediction

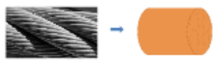
- No predictive model yet exists; in addition, cable research from AFRL and other sources do not consider bakeout effects



Determination of cable bending stiffness is necessary; bakeout may change cable stiffness

ROUND

CABLE MODELING



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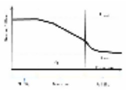

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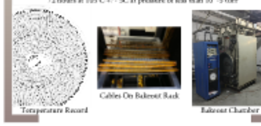

Temperature Record | Cables On Bakeout Rack | Bakeout Chamber

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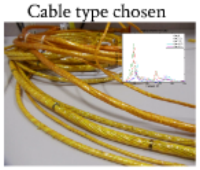

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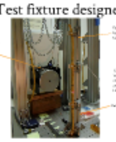
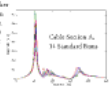
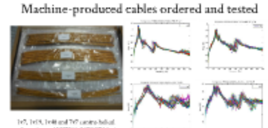


Standard run developed

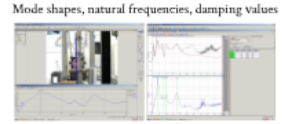


Machine-produced cables ordered and tested

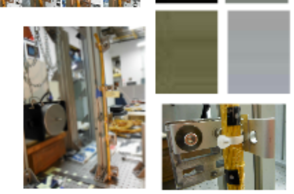


Most reliable cables determined and baked out at 105C, 1E-5 torr for 72 hours, then re-tested

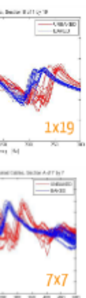
Results compared:
Mode shapes, natural frequencies, damping values

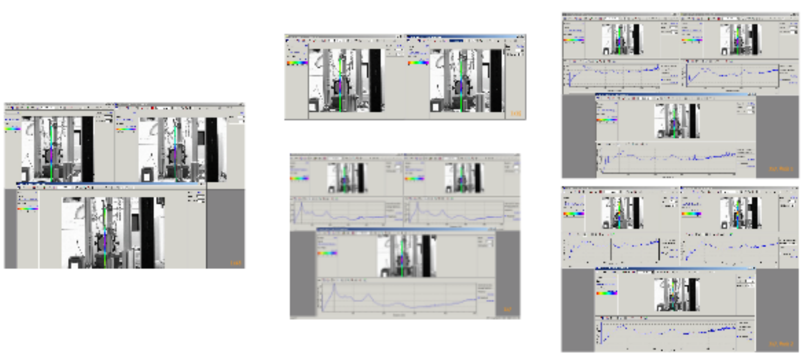


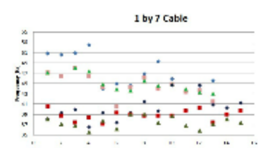
TEST SET UP DETAILS



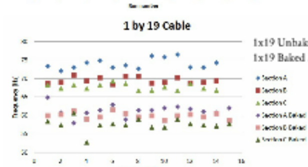
AKED VERSUS BAKED







1x7 Unbaked Average: 45.73 Hz
1x7 Baked Average: 38.85 Hz



1x19 Unbaked Average: 70.49 Hz
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Baked out cables show decrease in natural frequency and increase in damping.

	LASER SCANS	ME SCOPE	
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7x7	24.42	27.93

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

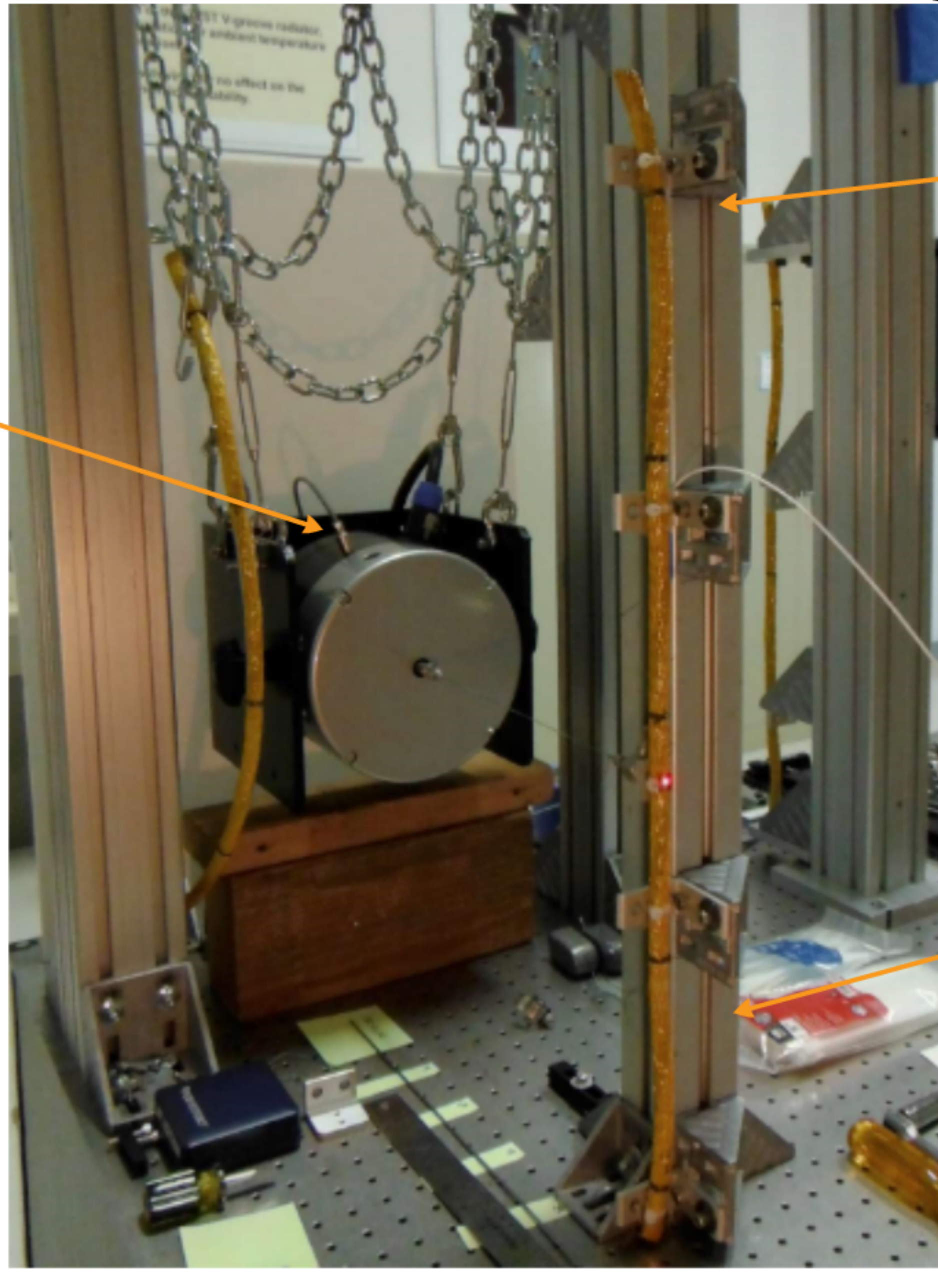
- No literature exists on the effect of bakeout treatment on cable stiffness;
this work provides concrete data that bakeout does indeed change the dynamic response of space flight cables

ACKNOWLEDGEME

Many thanks to the organizations and universities that have supported this research and provided equipment:

Test fixture designed

Suspended shaker with tensioned wire to load cell on cable



Buffer section- tightly pinned at top and bottom

Test section, 10" with targets every half inch and target on DP

Buffer section, 8"

STANDARD RUN

Standard run developed

- Cable attached to test fixture with coil plane toward shaker
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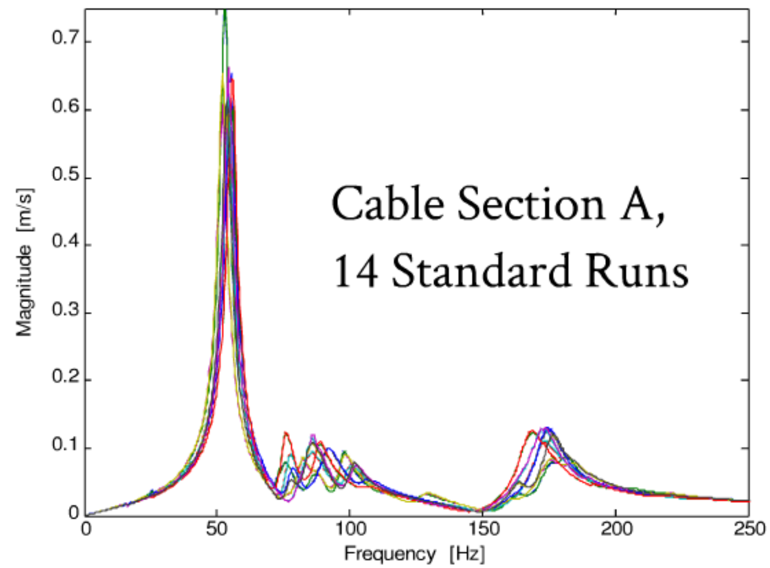

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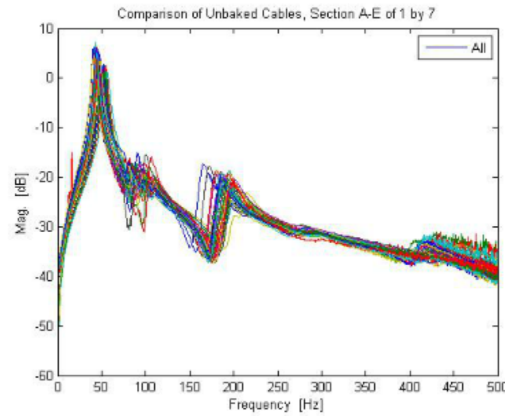

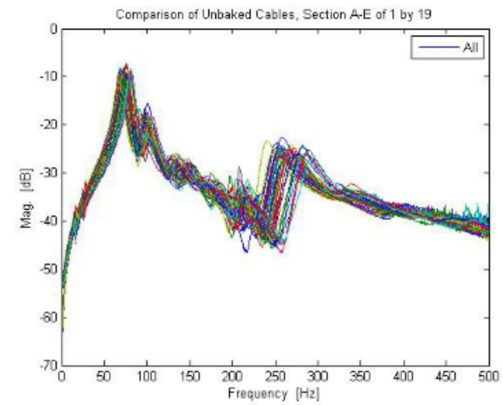

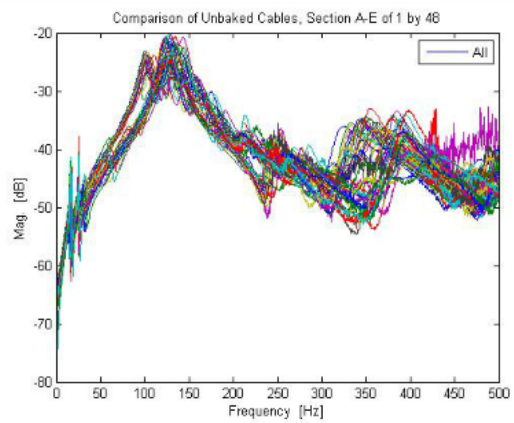

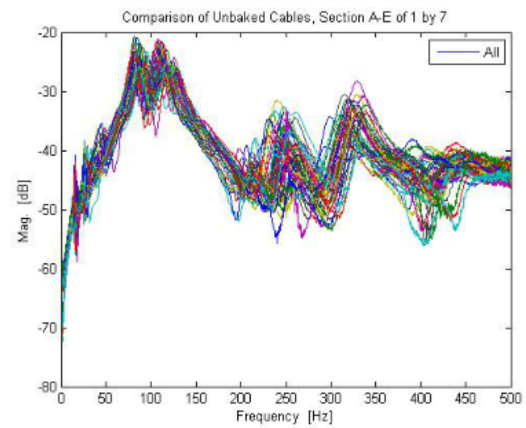

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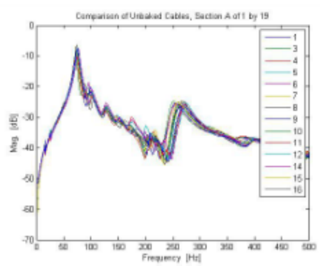

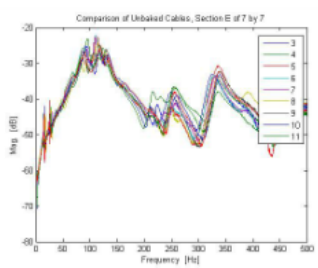

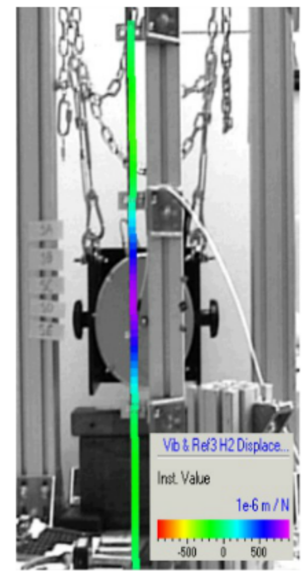

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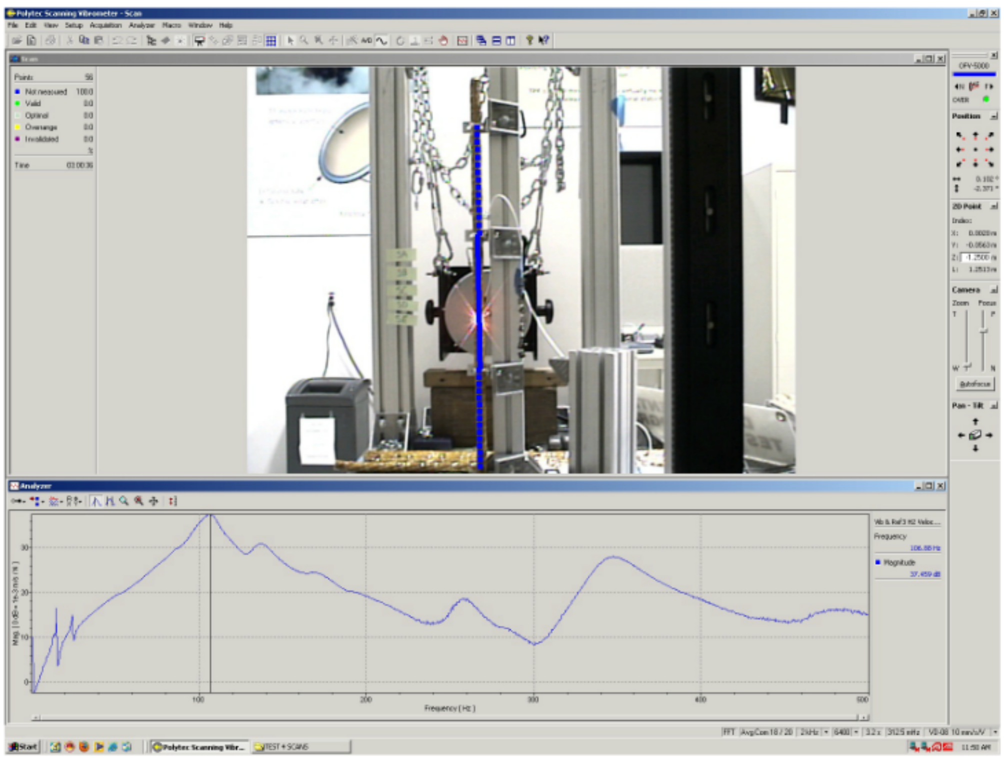

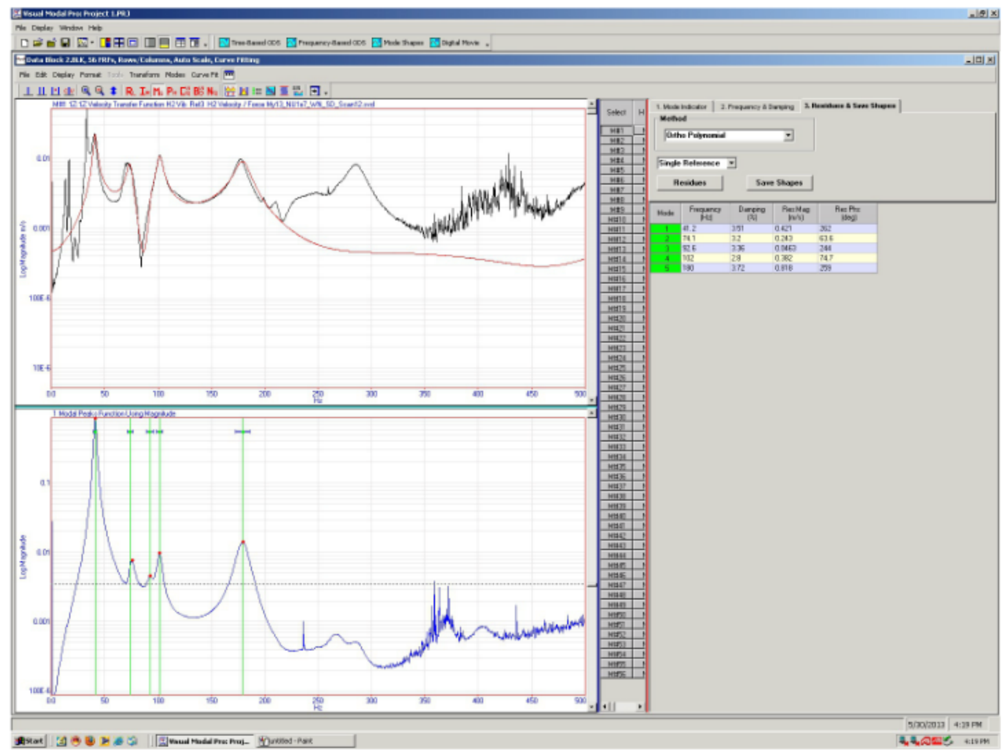

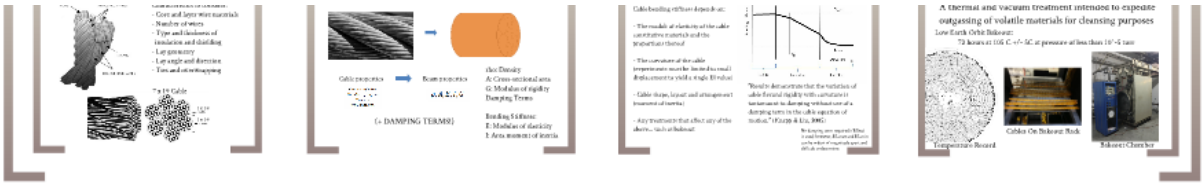

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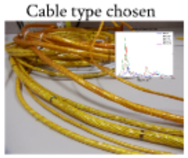

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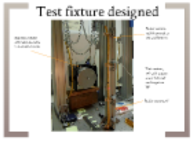

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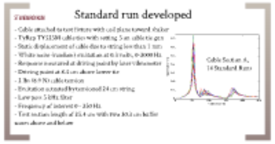

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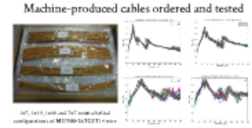

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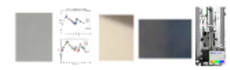

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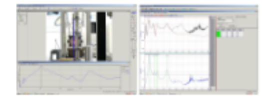
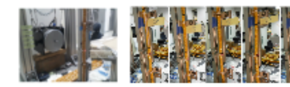
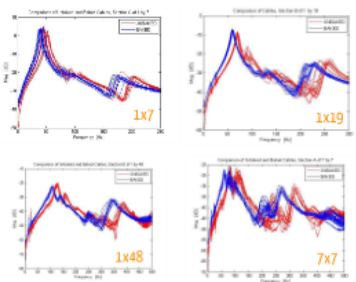
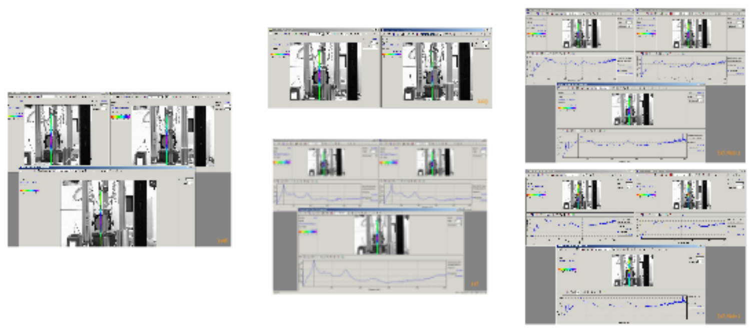


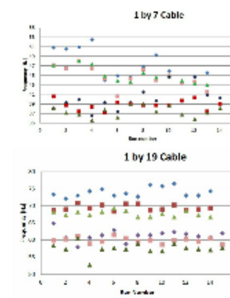
TEST S



RESULTS: UNBAKED VERSUS BAKED







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CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

- No literature exists on the effect of bakeout treatment on cable stiffness; this work provides concrete data that bakeout does indeed change the dynamic response of space flight cables
- After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%
- After a low Earth orbit bakeout, damping values increased for all single-strand cables

It is clear that this combination of wire type and bakeout results in a significant reduction in bending stiffness.

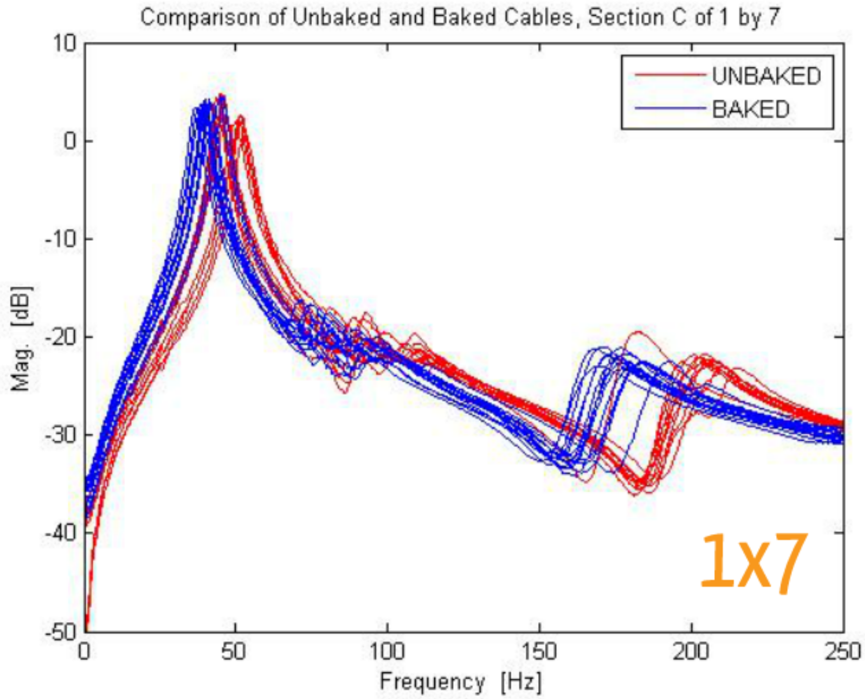
- Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables; spacecraft designers should keep this in mind if using currently published data

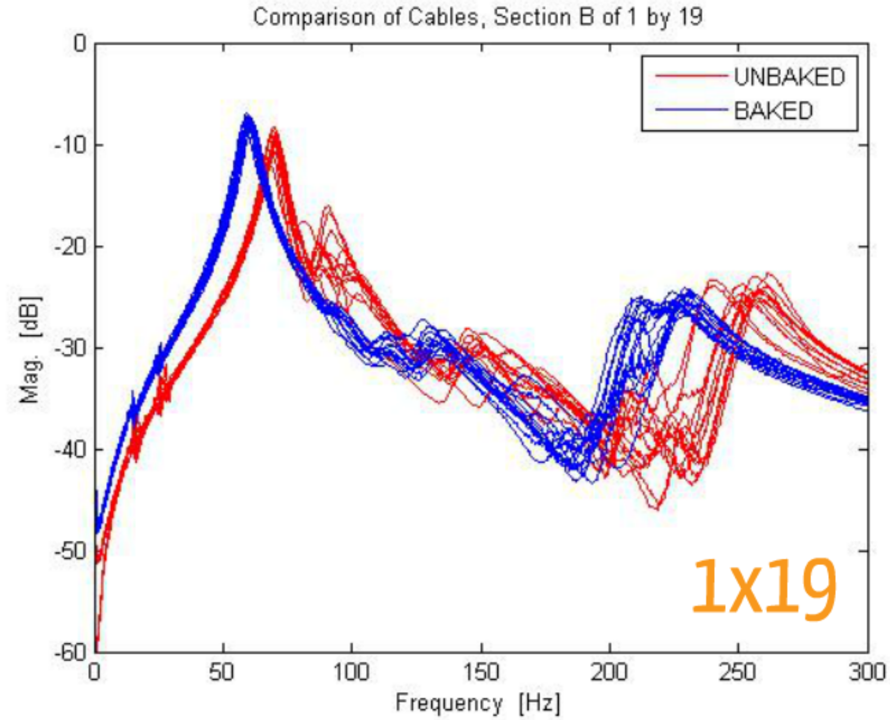
Future work:
- Different bakeout treatments may have different results
- Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout
- More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment

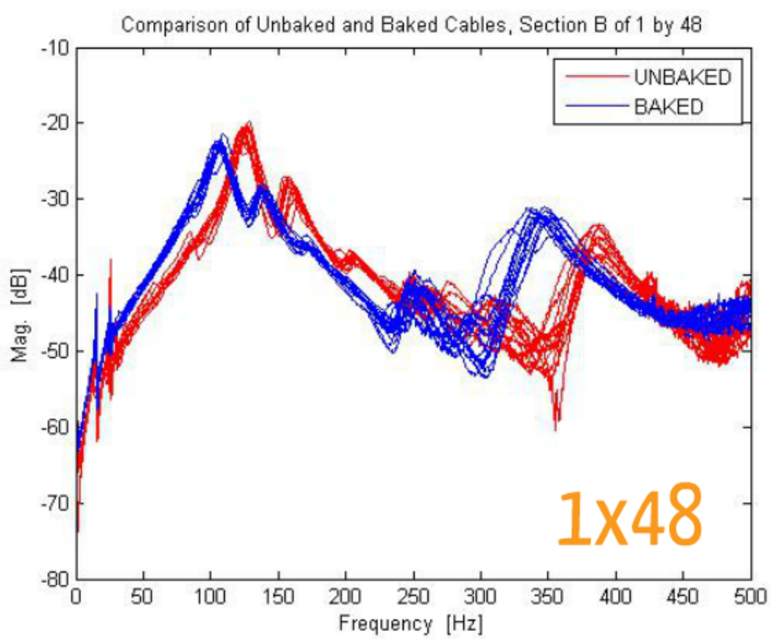
ACKNO

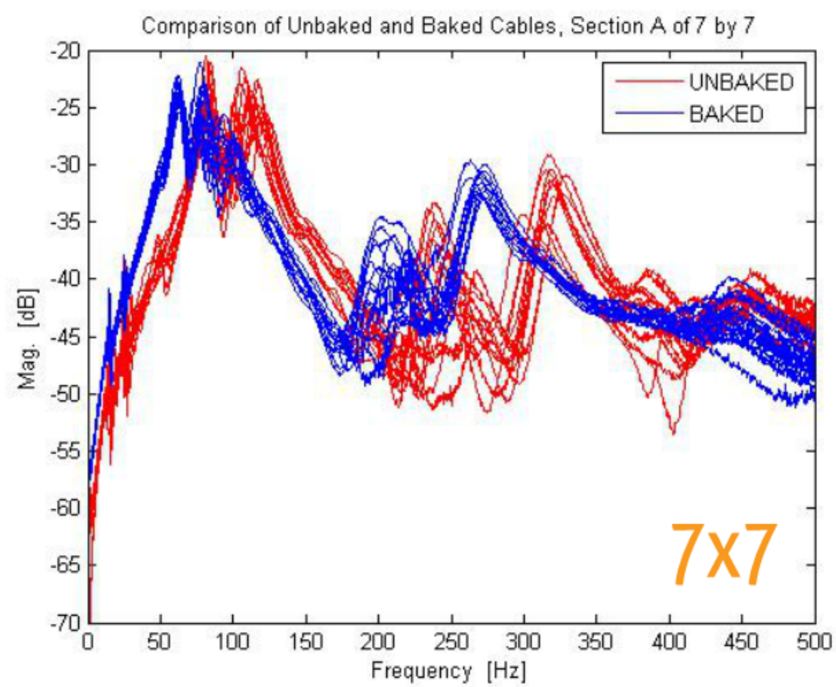
Many thanks to the
have supported thi
- NASA Spac
Fellowship
- Virginia Sp
- Air Force C
- AIAA San C
- Jet Propuls
- Virginia Te
- University
- Southern C

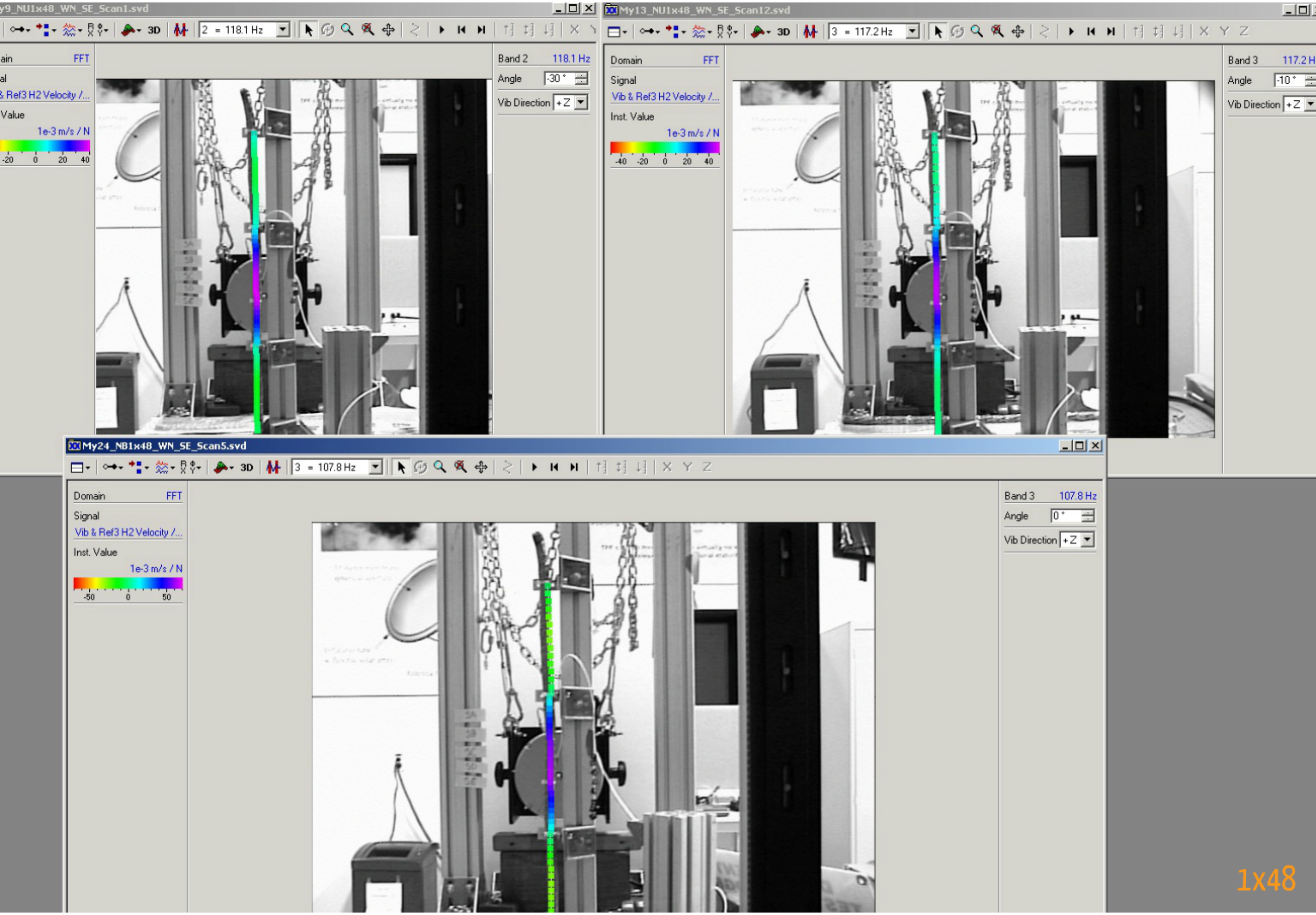
Advisor: Dr. Daniel
Mentor: Dr. Greg


Comparison of Unbaked and Baked Cables, Section C of 1 by 7
UNBAKED
BAKED
Mag. [dB]
Frequency [Hz]
1x7

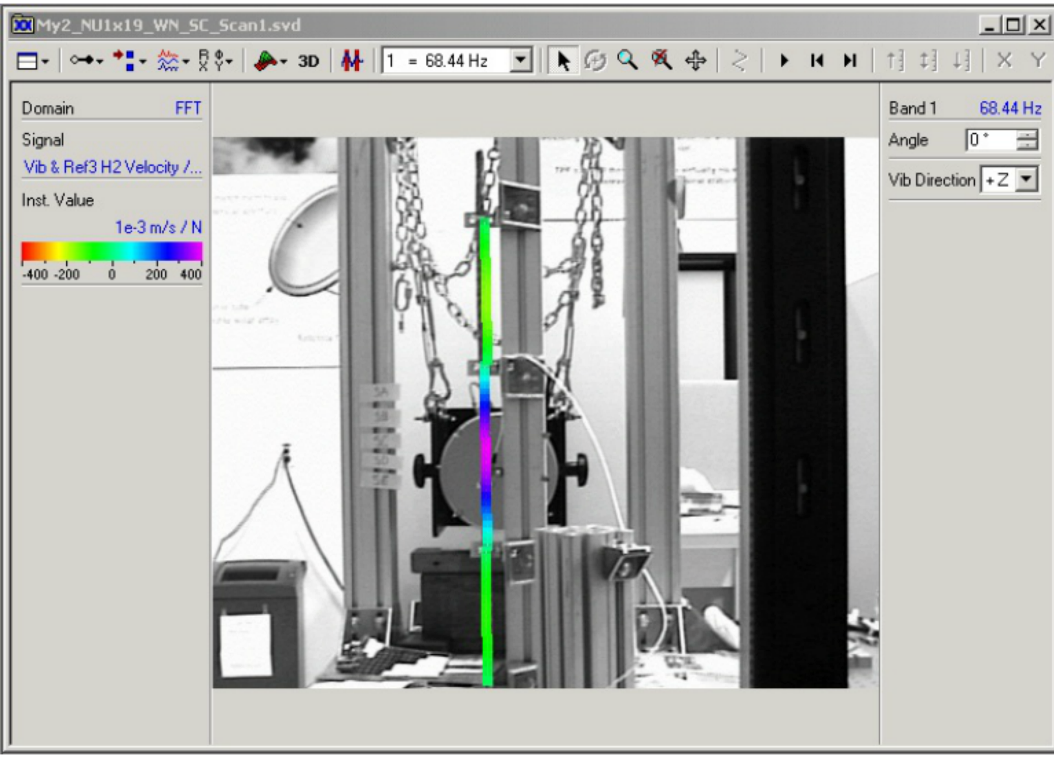

Comparison of Cables, Section B of 1 by 19
UNBAKED
BAKED
Mag. [dB]
Frequency [Hz]
1x19

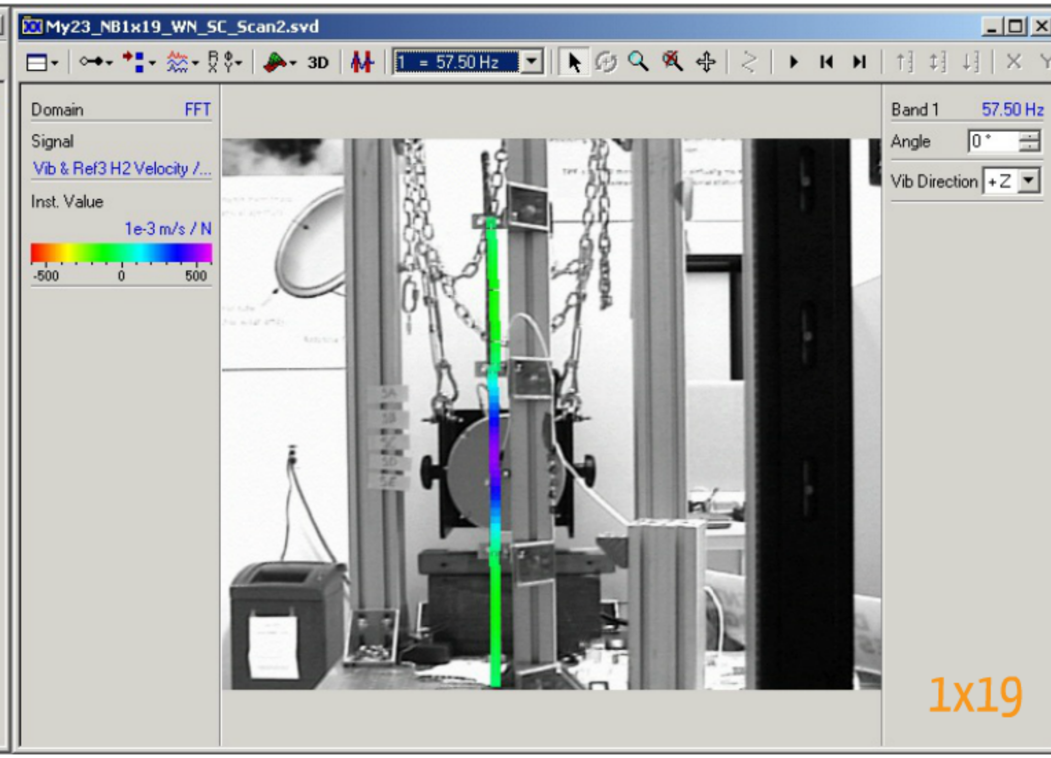

Comparison of Unbaked and Baked Cables, Section B of 1 by 48
UNBAKED
BAKED
Mag. [dB]
Frequency [Hz]
1x48


Comparison of Unbaked and Baked Cables, Section A of 7 by 7
UNBAKED
BAKED
Mag. [dB]
Frequency [Hz]
7x7



y9_NU1x48_WN_SE_Scan1.svd
2 = 118.1 Hz
Band 2 118.1 Hz
Angle -30 °
Vib Direction +Z
FFT
& Ref3 H2 Velocity /...
Value
1e-3 m/s / N
-20 0 20 40
My13_NU1x48_WN_SE_Scan12.svd
3 = 117.2 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
-40 -20 0 20 40
Band 3 117.2 H
Angle -10 °
Vib Direction +Z
My24_NB1x48_WN_SE_Scan5.svd
3 = 107.8 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
-50 0 50
Band 3 107.8 Hz
Angle 0 °
Vib Direction +Z
1x48

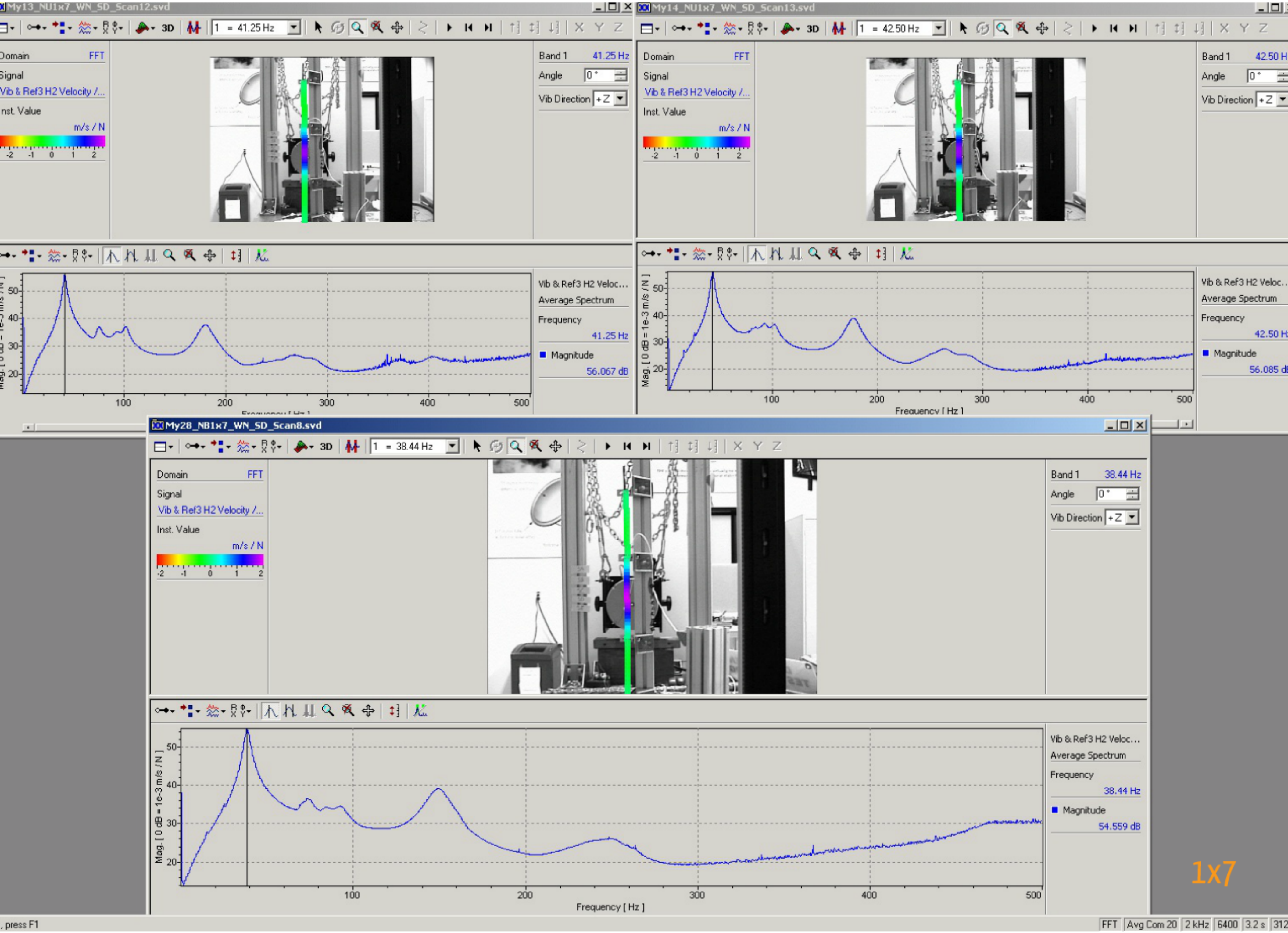

My2_NU1x19_WN_SC_Scan1.svd
1 = 68.44 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
-400 -200 0 200 400
Band 1 68.44 Hz
Angle 0 °
Vib Direction +Z

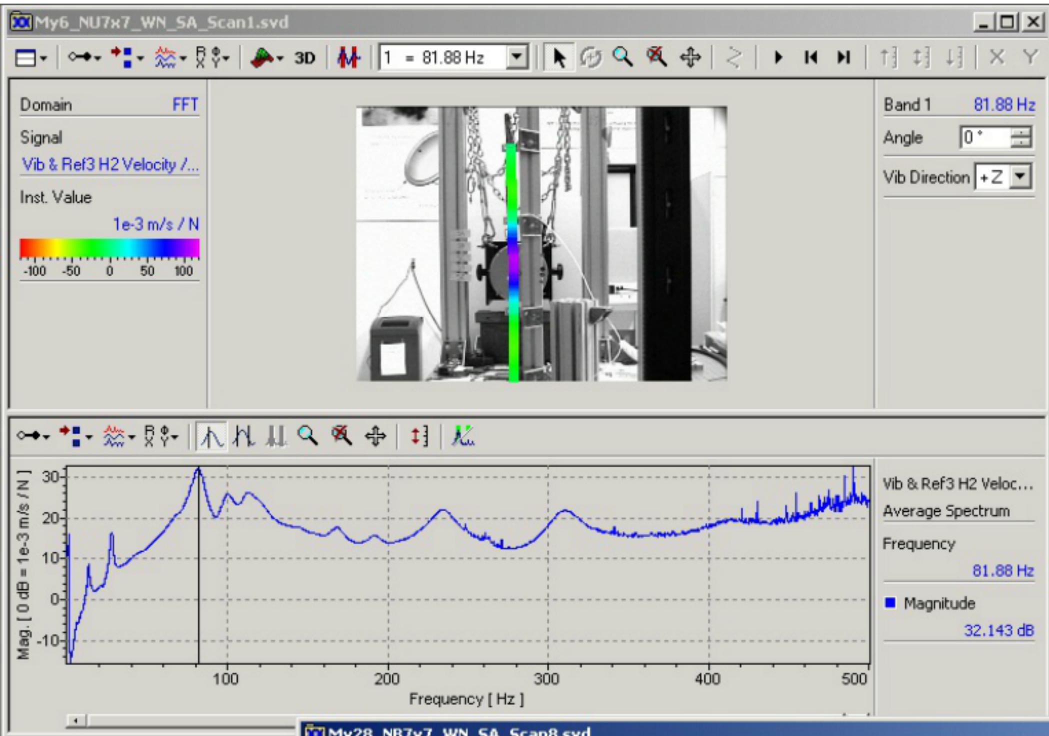

My23_NB1x19_WN_SC_Scan2.svd
1 = 57.50 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
-500 0 500
Band 1 57.50 Hz
Angle 0 °
Vib Direction +Z

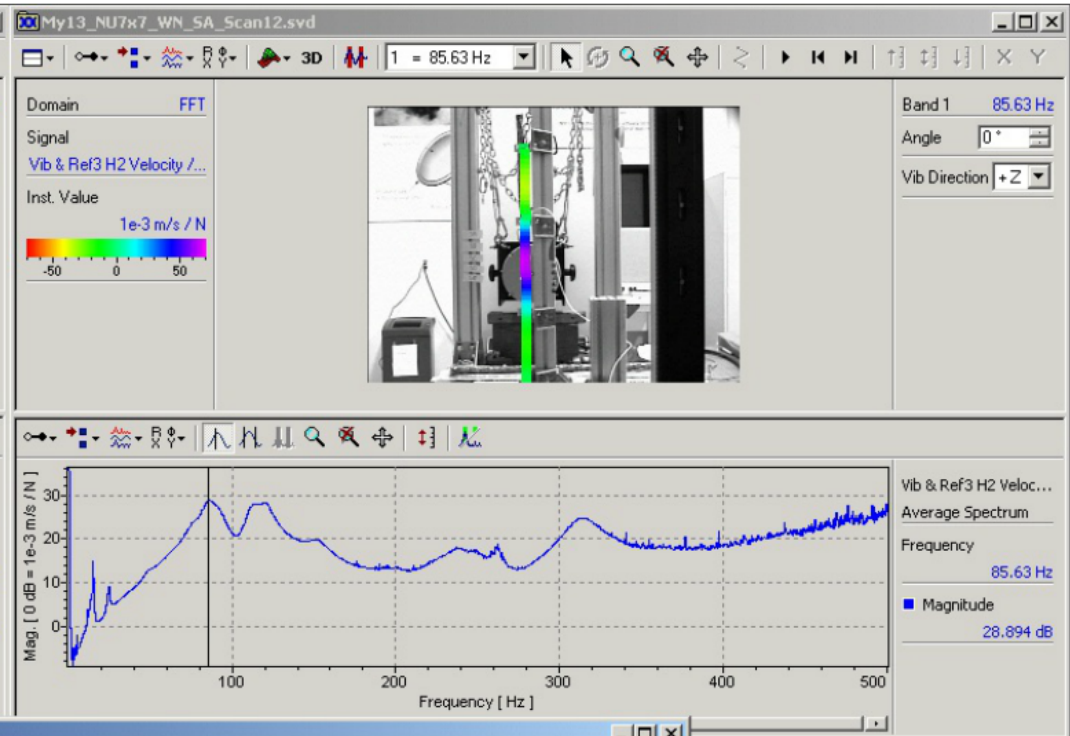
1x19

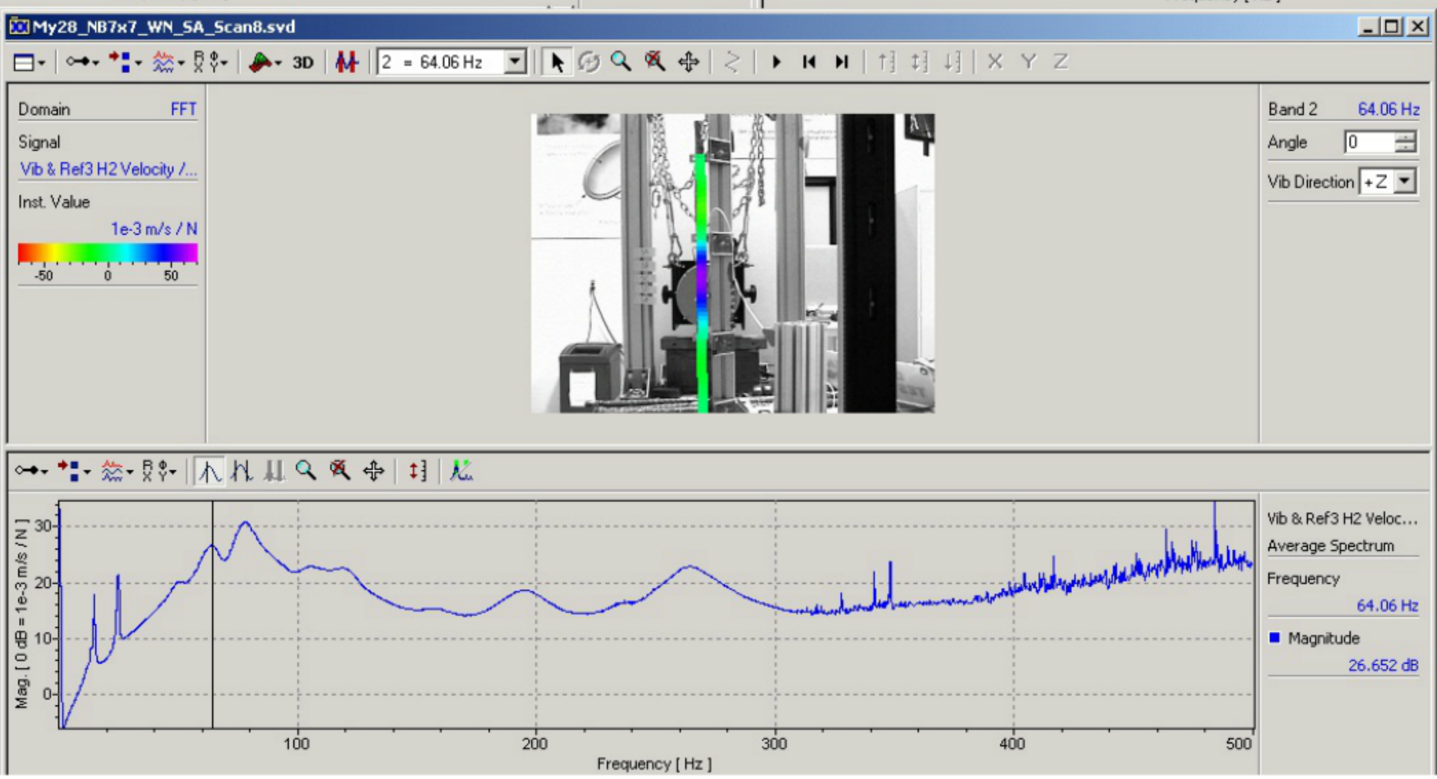

My13_NU1x7_WN_SD_Scan12.svd
1 = 41.25 Hz
Domain FFT
Band 1 41.25 Hz
Angle 0 °


My14_NU1x7_WN_SD_Scan13.svd
1 = 42.50 Hz
Domain FFT
Band 1

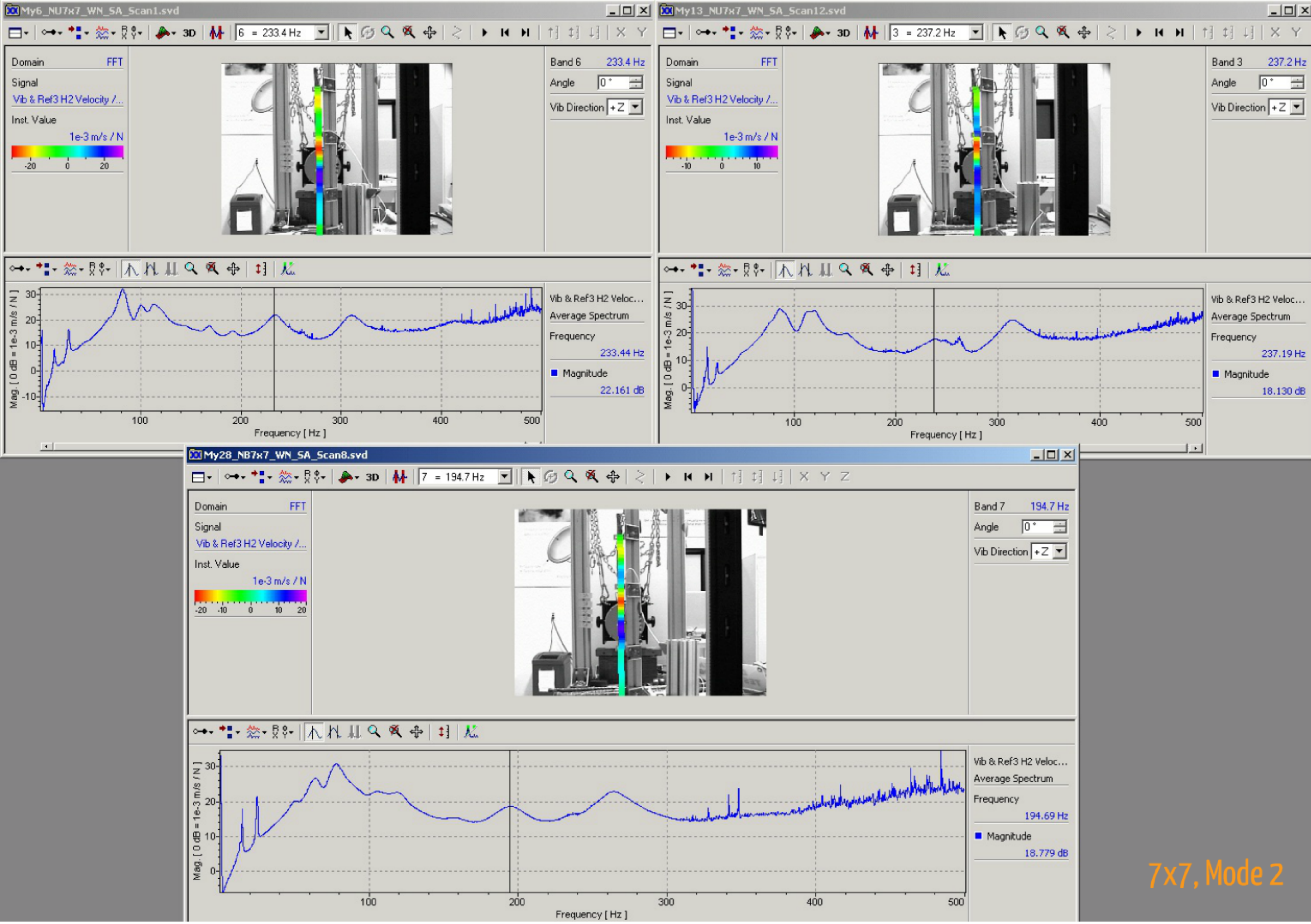

My13_NU1x7_WN_SD_Scan12.svd
My14_NU1x7_WN_SD_Scan13.svd
My28_NB1x7_WN_SD_Scan8.svd
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
m/s / N
Band 1 41.25 Hz
Band 1 42.50 Hz
Band 1 38.44 Hz
Angle 0°
Vib Direction +Z
Vib & Ref3 H2 Veloc...
Average Spectrum
Frequency
41.25 Hz
42.50 Hz
38.44 Hz
Magnitude
56.067 dB
56.085 dB
54.559 dB
Mag. [0 dB = 1e-3 m/s / N]
Frequency [Hz]
, press F1
FFT
Avg Com 20
2 kHz
6400
3.2 s
1x7


My6_NU7x7_WN_SA_Scan1.svd
1 = 81.88 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
-100 -50 0 50 100
Band 1 81.88 Hz
Angle 0 °
Vib Direction +Z
Mag. [0 dB = 1e-3 m/s / N]
Frequency [Hz]
Vib & Ref3 H2 Veloc...
Average Spectrum
Frequency
81.88 Hz
Magnitude
32.143 dB

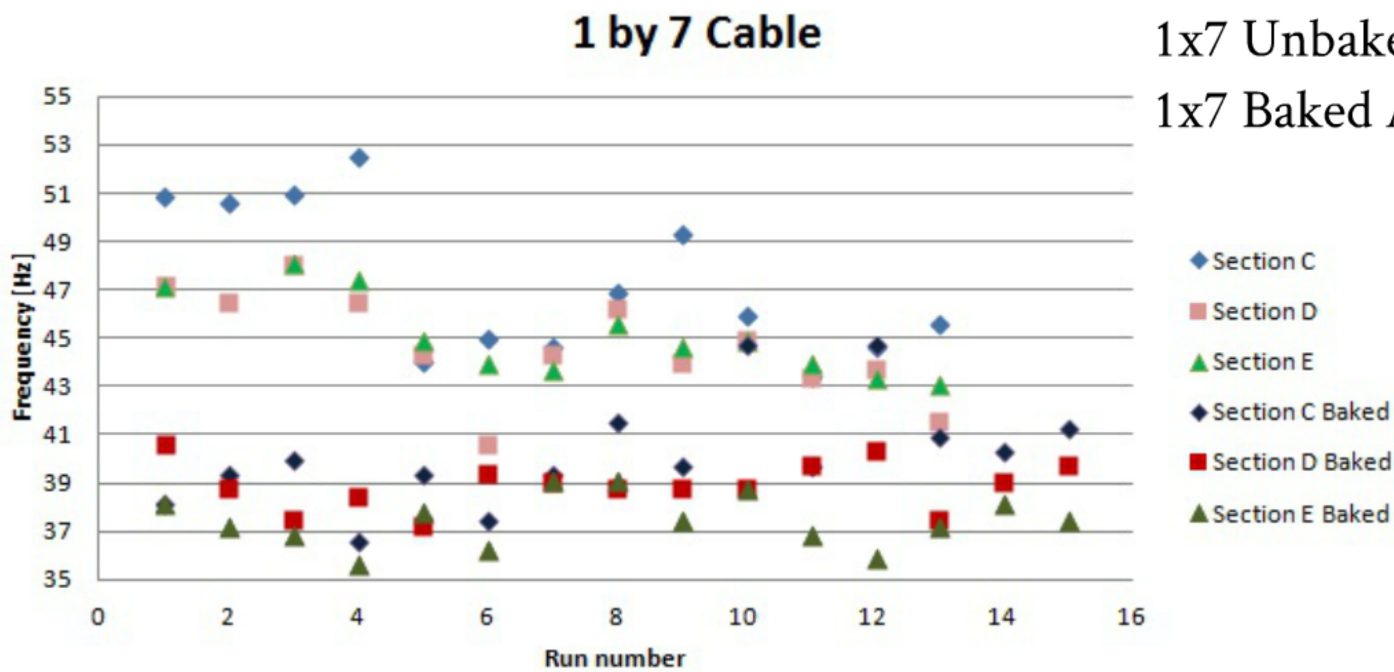

My13_NU7x7_WN_SA_Scan12.svd
1 = 85.63 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
-50 0 50
Band 1 85.63 Hz
Angle 0 °
Vib Direction +Z
Mag. [0 dB = 1e-3 m/s / N]
Frequency [Hz]
Vib & Ref3 H2 Veloc...
Average Spectrum
Frequency
85.63 Hz
Magnitude
28.894 dB


My28_NB7x7_WN_SA_Scan8.svd
2 = 64.06 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
-50 0 50
Band 2 64.06 Hz
Angle 0
Vib Direction +Z
Mag. [0 dB = 1e-3 m/s / N]
Frequency [Hz]
Vib & Ref3 H2 Veloc...
Average Spectrum
Frequency
64.06 Hz
Magnitude
26.652 dB

7x7, Mode 1

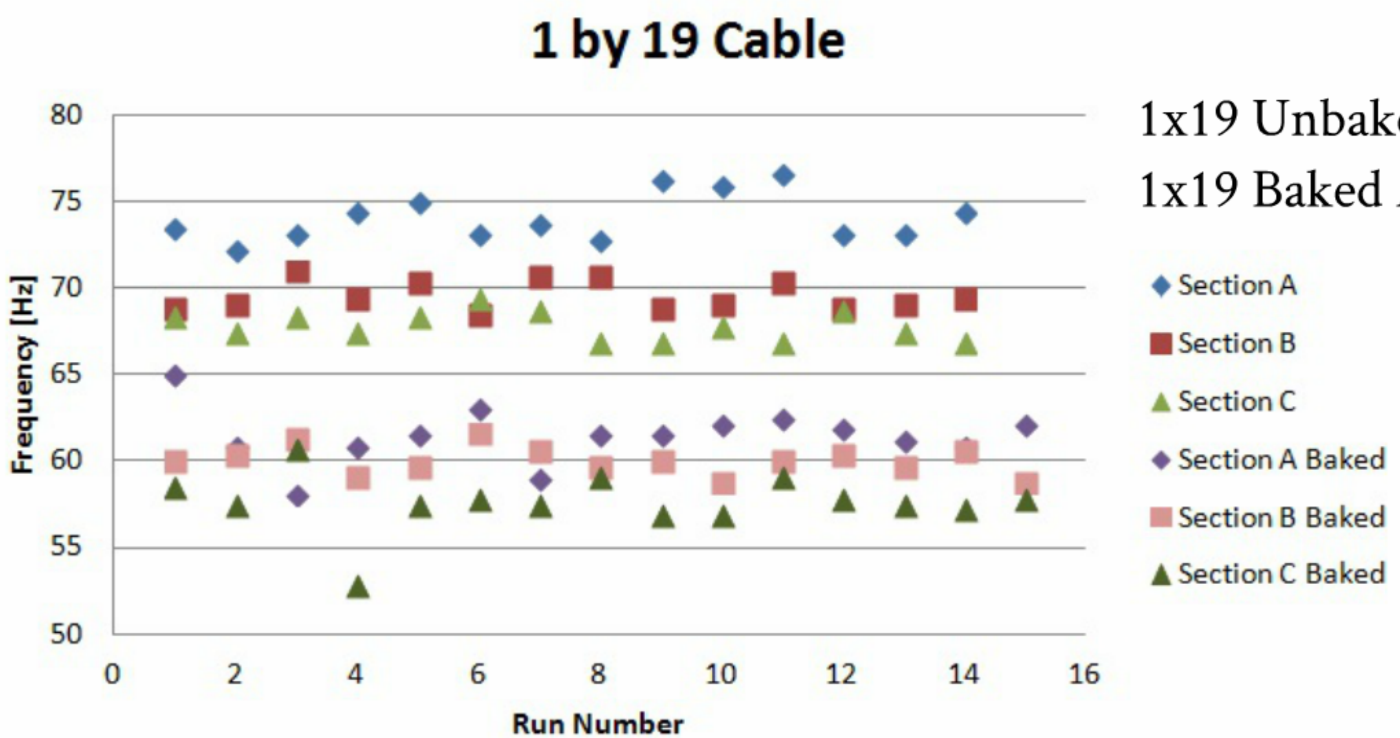

My6_NU7x7_WN_SA_Scan1.svd
6 = 233.4 Hz
Domain FFT
Signal
Vib & Ref3 H2 Velocity /...
Inst. Value
1e-3 m/s / N
Band 6 233.4 Hz
Angle 0 °
Vib Direction +Z
Mag. [0 dB = 1e-3 m/s / N]
Frequency [Hz]
Vib & Ref3 H2 Veloc...
Average Spectrum
Frequency
233.44 Hz
Magnitude
22.161 dB
My13_NU7x7_WN_SA_Scan12.svd
3 = 237.2 Hz
Band 3 237.2 Hz
Frequency
237.19 Hz
Magnitude
18.130 dB
My28_NB7x7_WN_SA_Scan8.svd
7 = 194.7 Hz
Band 7 194.7 Hz
Frequency
194.69 Hz
Magnitude
18.779 dB

7x7, Mode 2



1x7 Unbaked Average: 45.73 Hz

1x7 Baked Average: 38.85 Hz



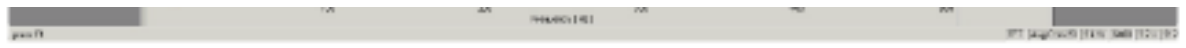
1x19 Unbaked Average: 70.49 Hz

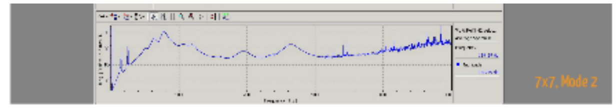
1x19 Baked Average: 59.72 Hz

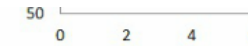
Baked out cables show decrease in natural frequency and increase in damping.

	LASER SCANS	ME SCOPE	
1x7	First Frequency [Hz]	First Frequency [Hz]	% Damping
Unbaked	41.25	41.3	3.49
Baked	38.44	38.5	4.25
1x19			
Unbaked	68.44	68.3	4.65
Baked	57.5	57.4	5.5
1x48			
Unbaked	118.1	118	4.6
Baked	107.8	108	6.87
7x7			
Unbaked	81.88	86.5	8.45
Baked	64.06	65.3	5.55

	% Difference Scan	% Difference Scope
1x7	7.05	7.02
1x19	17.37	17.34
1x48	9.12	8.85
7x7	24.42	27.93







NCLUSIONS, CONTRIBUTIONS, AND FUTURE WO

- No literature exists on the effect of bakeout treatment on cable stiffness;
  this work provides concrete data that bakeout does indeed change the dynamic response of space flight cables
- After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%
- After a low Earth orbit bakeout, damping values increased for all single-strand cables

It is clear that this combination of wire type and bakeout results in a significant reduction in bending stiffness.

- Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables;
  spacecraft designers should keep this in mind if using currently published data

Future work:

- Different bakeout treatments may have different results
- Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout
- More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment

Many thanks to the organizations and universities that have supported this research and provided equipment:

- NASA Space Technology Research Fellowship Program
- Virginia Space Grant Consortium
- Air Force Office of Scientific Research
- AIAA San Gabriel Valley Chapter
- Jet Propulsion Laboratory
- Virginia Tech
- University of Michigan
- Southern California Braiding Co.

Advisor: Dr. Daniel Inman, Univ. of Michigan

Mentor: Dr. Greg Agnes, JPL

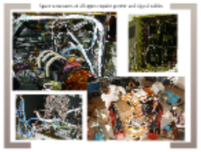
VirginiaTech

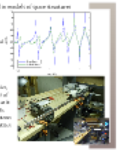
Effects of Bakeout on Space Flight Cable Stiffness

SEM Student Paper Competition ~ June 3, 2013

Kaitlin Spak

MOTIVATION





Determination of cable bending stiffness is necessary; bakeout may change cable stiffness

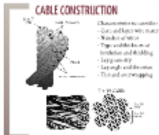
OBJECTIVES

Thus, because cables make up a significant portion of space structures and affect the structural dynamics, determining the bending stiffness of space flight cables is necessary. Since bending stiffness may be affected by the bakeout procedure, the objectives of this study are to:

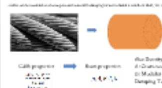
- Determine whether space flight cable stiffness is indeed affected by bakeout, as evidenced by changes in dynamic response
- Observe the effects of bakeout on space flight cables and compare the cables pre- and post-bakeout
- Quantify the dynamic response effects of low Earth orbit bakeout on a variety of cable geometries by determining the changes in natural frequency and/or damping

BACKGROUND

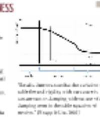
CABLE CONSTRUCTION



CABLE MODELING

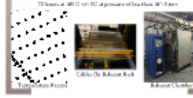


BENDING STIFFNESS



BAKEOUT

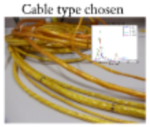
A thermal and vacuum treatment intended to expedite outgassing of volatile materials for cleaning purposes



EXPERIMENTAL PROCEDURE

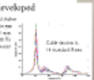
Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

Cable type chosen

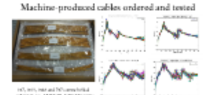


Test fixture designed

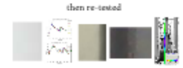
Standard run developed



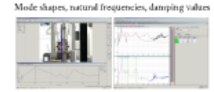
Machine-produced cables ordered and tested



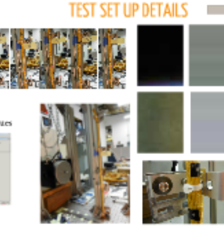
Most reliable cables determined and baked out at 105C, 1E-5 torr for 72 hours, then re-tested



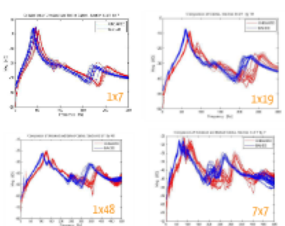
Results compared:
Mode shapes, natural frequencies, damping values

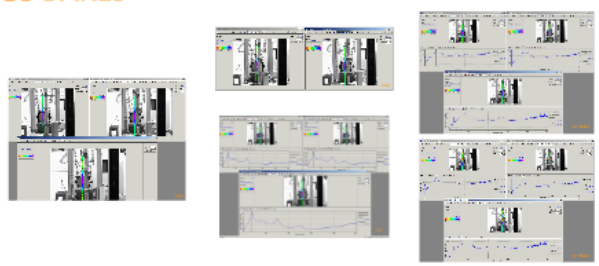


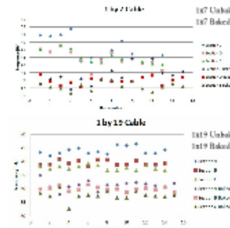
TEST SET UP DETAILS



RESULTS: UNBAKED VERSUS BAKED







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Baked	[illegible]	[illegible]	[illegible]
1x19			
Unbaked	68.44	68.3	4.05
Baked	57.8	57.4	[illegible]
1x48			
Unbaked	[illegible]	118	4.6
Baked	[illegible]	108	[illegible]
7x7			
Unbaked	[illegible]	66.5	[illegible]
Baked	[illegible]	[illegible]	[illegible]

	% Difference Scan	% Difference Scope
1x7	7.05	7.02
1x19	17.37	17.34
1x48	9.12	8.85
7x7	24.42	27.95

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REFERENCES

ACKNOWLEDGEMENTS

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- Air Force Office of Scientific Research
- AIAA San Gabriel Valley Chapter
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