CPAS Main Parachute Cluster Asymmetry: A Second Look

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COMMERCIAL CREW PROGRAM

Pre-Decisional

Bottom Line Up Front

- **This presentation will walk through a brief revisit of the data presented in 'Load Asymmetry Observed During Orion Main Parachute Inflation'**
  - Ref. AIAA 2011-2611

- **The original paper showed a first look at the Crew Exploration Vehicle Parachute Assembly System (CPAS) measured asymmetry**
  - Three tests were performed with highly reefed Ringsail parachutes with individually instrumented Bridles

- **The purpose for revisiting the data was twofold**
  - Perform a deeper interrogation of the available data
  - To follow up on the goal of the original paper, which was "*…to open a dialogue regarding asymmetrical parachute inflation load factors.*"

- **Results of the original paper and the revisit are in agreement**
  - The industry-wide asymmetry value of 1.1 is insufficient for accurately assessing the structural margins of highly reefed parachutes operating in a cluster

Refresher: Legacy Margins Methodology

- **Margin of Safety (MoS) is calculated based upon four independent variables**

$$MoS = \left(\frac{ES \cdot NP}{TDF \cdot AL}\right) - 1$$

- **Element Strength (ES) and Number of Plies (NP)**
  - All values are empirically derived for joint and element-specific applications
- **Total Design Factor (TDF)**
  - Each material degradation load factor for the joint/element is multiplied to get total load factor
    - Asymmetry (s), Dynamic (m), and Convergence (c)
  - Each material degradation loss factor for the joint/element is multiplied to get total loss factor
    - Abrasion (e), Fatigue (k), Aging (a), Contamination (o), Thermal (t), and Joint (u)

$$TDF = SF\,\frac{m \cdot s \cdot c}{u \cdot e \cdot k \cdot o \cdot t \cdot a} = SF\,\frac{(Amplification\ Factor)}{(Degradation\ Factor)}$$

- **Applied Load (AL)**
  - Peak predicted dynamic pressures are applied throughout drag surfaces, on a per-stage basis
  - Peak predicted riser loads are translated throughout structural grid to determine loads at each element (focus)

What is Asymmetry?

- **What is asymmetry?**
  - Asymmetry is the manifestation of unsymmetrical load distribution among elements

- **What does asymmetry look like?**

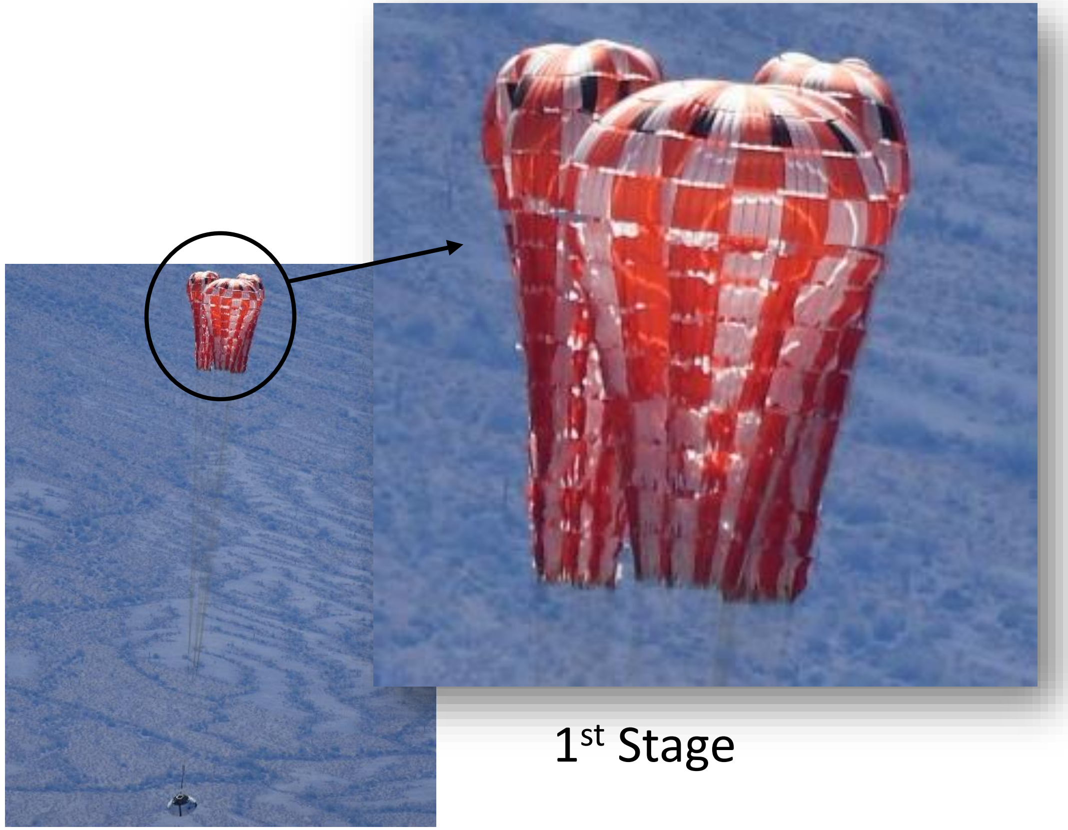
CPAS CDT-2-3 Disreef to 2nd Stage

CPAS CDT-2-2 mid-1st Stage Inflation

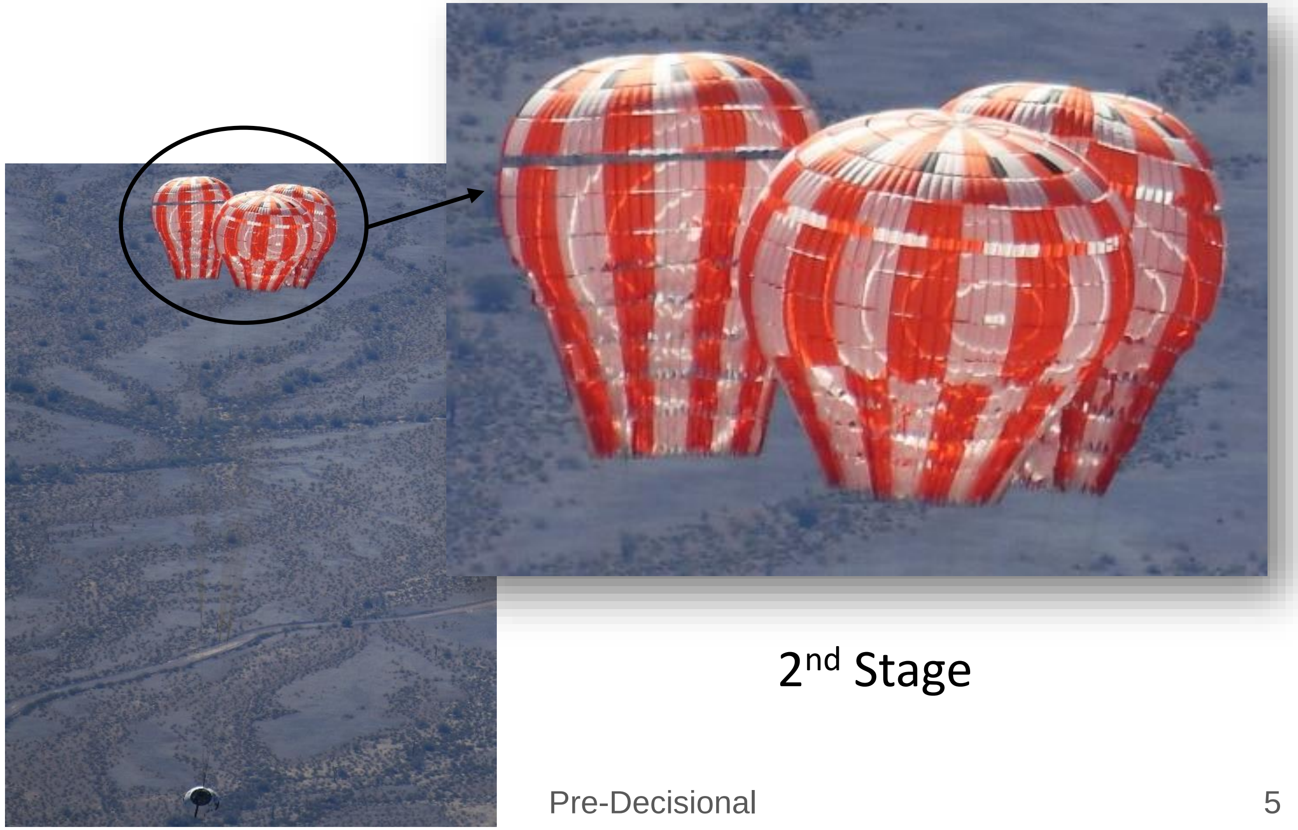
CPAS CDT-2-1 Skipped 2nd Stage

- **What causes asymmetry?**
  - Multiple likely contributing causes, though primarily believed to be the interaction between interference aerodynamics and canopy pressurization

- **CQT-4-3**



1st Stage



2nd Stage

Asymmetry Factor vs Amplification Factor

- **Per ARES Internal Asymmetry Paper**
  - Canopy Shape: "*An oval or kidney shaped canopy mouth has asymmetric loading above that of a circular shaped canopy. This shape would be best seen by cameras on the payload looking back at the parachute*"
  - Canopy Position: "*Riser loads are affected by where the canopy is located radially and tangentially in relation to the deck fittings.*"
  - Suspension System Geometry: "*Routing of the lines and deck fitting attachment location may have an effect on the asymmetry in the risers. The fact that neighboring suspension lines may go to different riser bundles could also cause increased asymmetry at the skirt band*."
  - Other: "*Riser-to-riser asymmetry that would exist in a round parachute under ideal conditions (like in single parachute drop tests with the JDTV). Also any dynamic loads due to localized portions of the parachute rapidly inflating or waves (vibrations) or other transients traveling through the structure*."

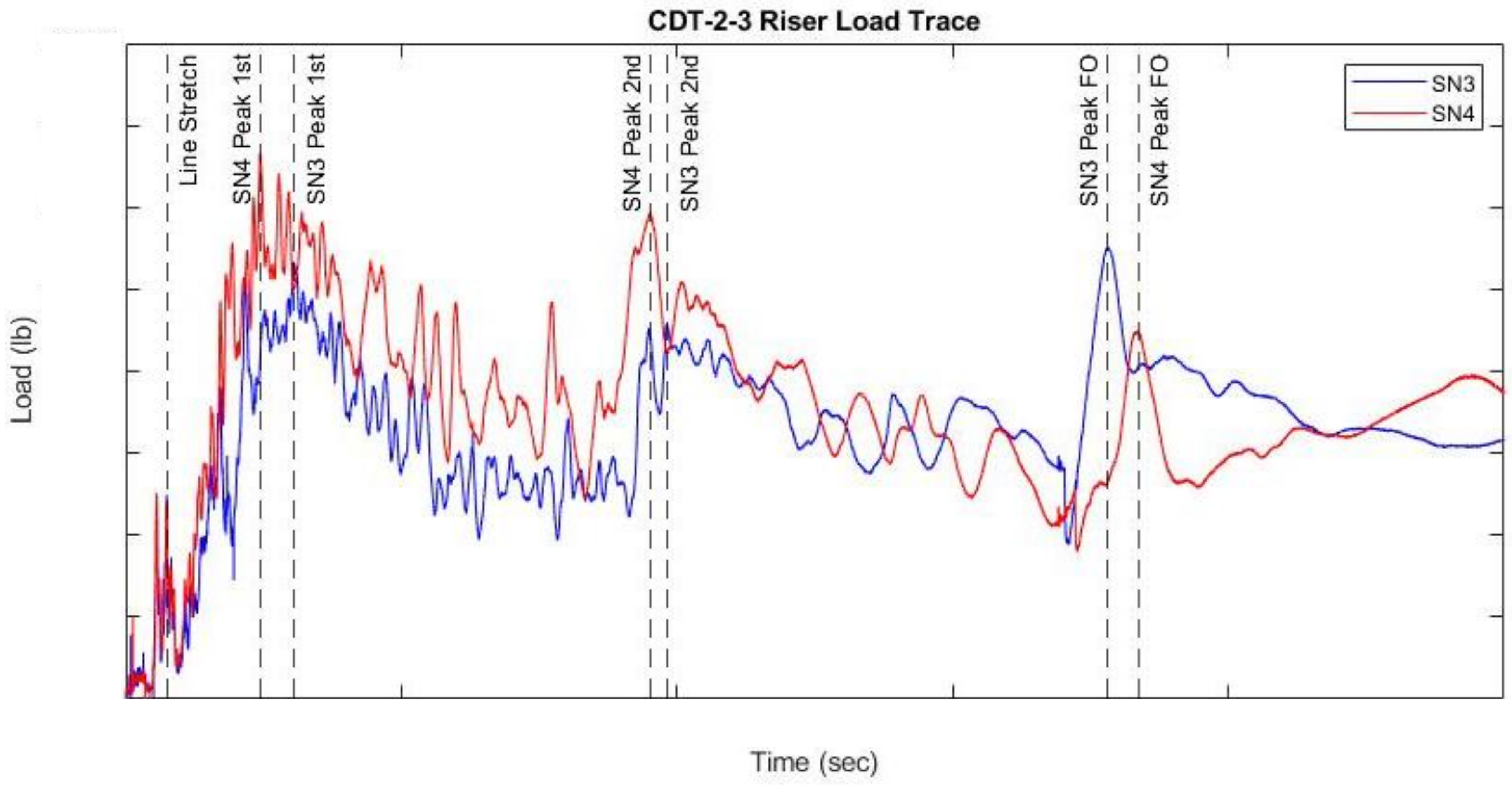
- **Load measurements capture most element-level amplifications in localized load**
  - Cannot capture dynamics that are taking place at a higher frequency than instrumentation capability

- **Based upon load path, load at the Bridle includes convergence, dynamic, and asymmetry**

- **For the purpose of this discussion, the remainder of this presentation will reference a single amplification factor, AMP**
  - This includes asymmetry, convergence, and dynamic

Main Risers Load Trace

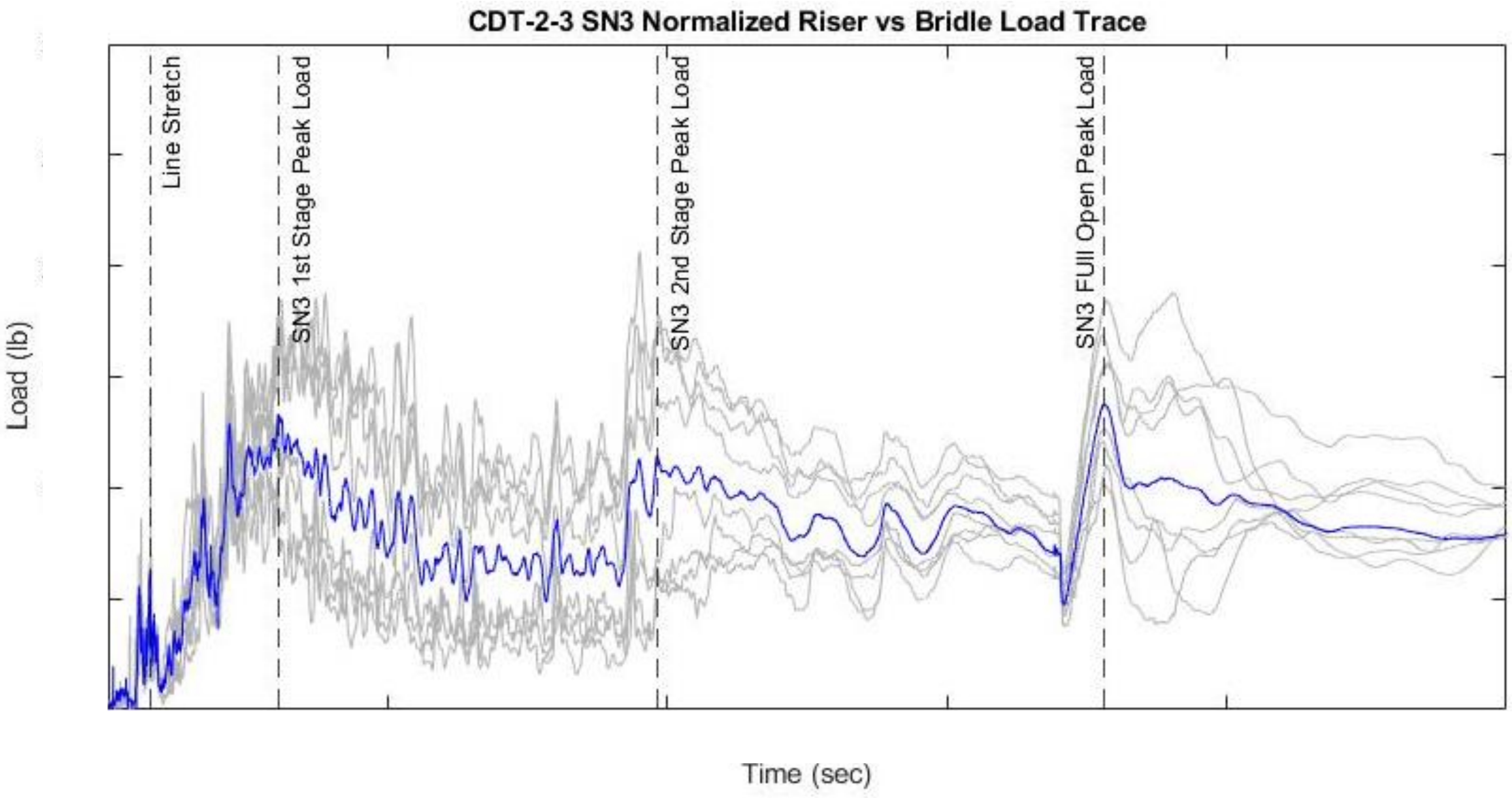
- **CDT-2-3 Main Riser load trace zoomed in on time range of interest**
  - Major events called out with vertical lines



Main Riser vs Bridle Load Trace

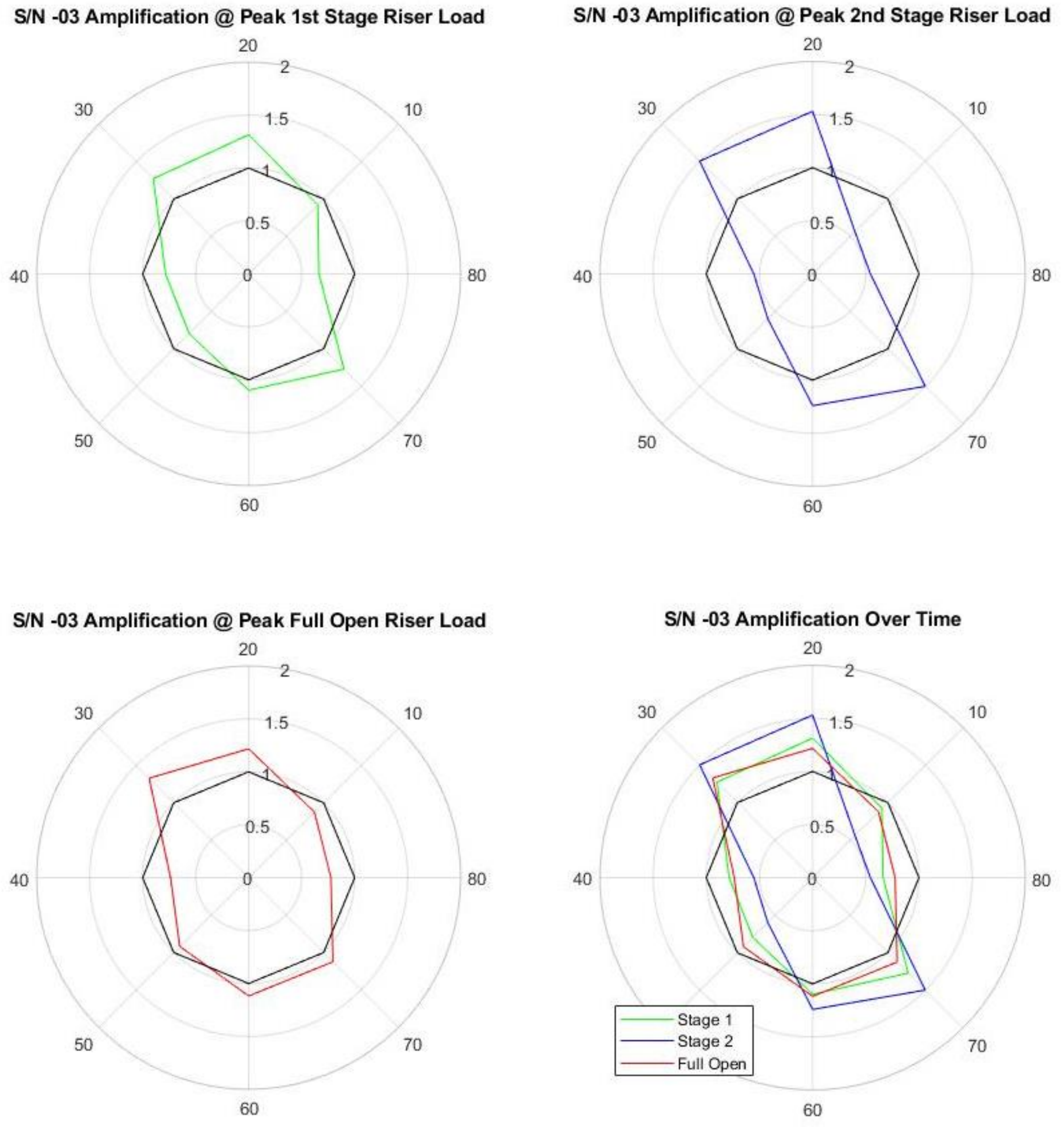
- **CDT-2-3 SN3 Main Riser load trace (dark blue) normalized to Bridle-level resolution**
  - Eight bridles, so Main Riser load was divided by eight (i.e. normalized)
- **Normalization allows for direct determination of amplification factor (AMP)**

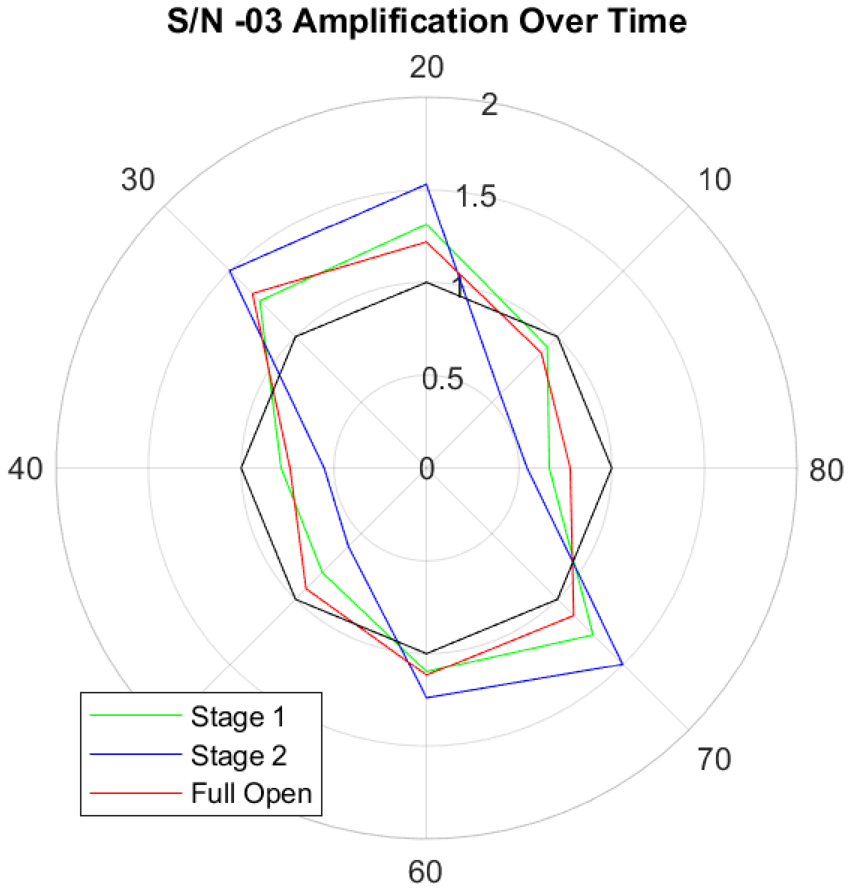
$$AMP = \frac{Load_{Bridle}}{(Load_{Riser}) * \left(\frac{1}{8}\right)}$$



Polar Plots @ Peak Riser Load

- **Polar plots show instantaneous amplification at peak Riser load for each stage**
  - Bridle-level amplification @ 1st stage peak Riser load is ~1.31
  - Bridle-level amplification @ 2nd stage peak Riser load is ~1.53
  - Bridle-level amplification @ full open peak Riser load is ~1.33





Summary: Amplification Factor @ Peak Riser Load

Stage	CDT-2-3			CDT-2-2		CDT-2-1	
	SN3	SN4	SN5	SN4	SN5	SN1	SN2
1st Stage	1.31	**1.35**	N/A	N/A	**1.35**	1.55	**1.86**
2nd Stage	1.53	**1.26**	N/A	N/A	**1.67**	N/A	**1.14**
Full Open	1.33	1.55	**N/A**	N/A	**1.52**	N/A	**1.26**

- **Leading chute for each drop test is bolded**
- **CDT-2-2 SN4 amplification not shown**
  - Bridle measurements are suspect
- **CDT-2-1 SN1 amplification not shown**
  - Pancaked by SN2 (inadvertent skipped stage)

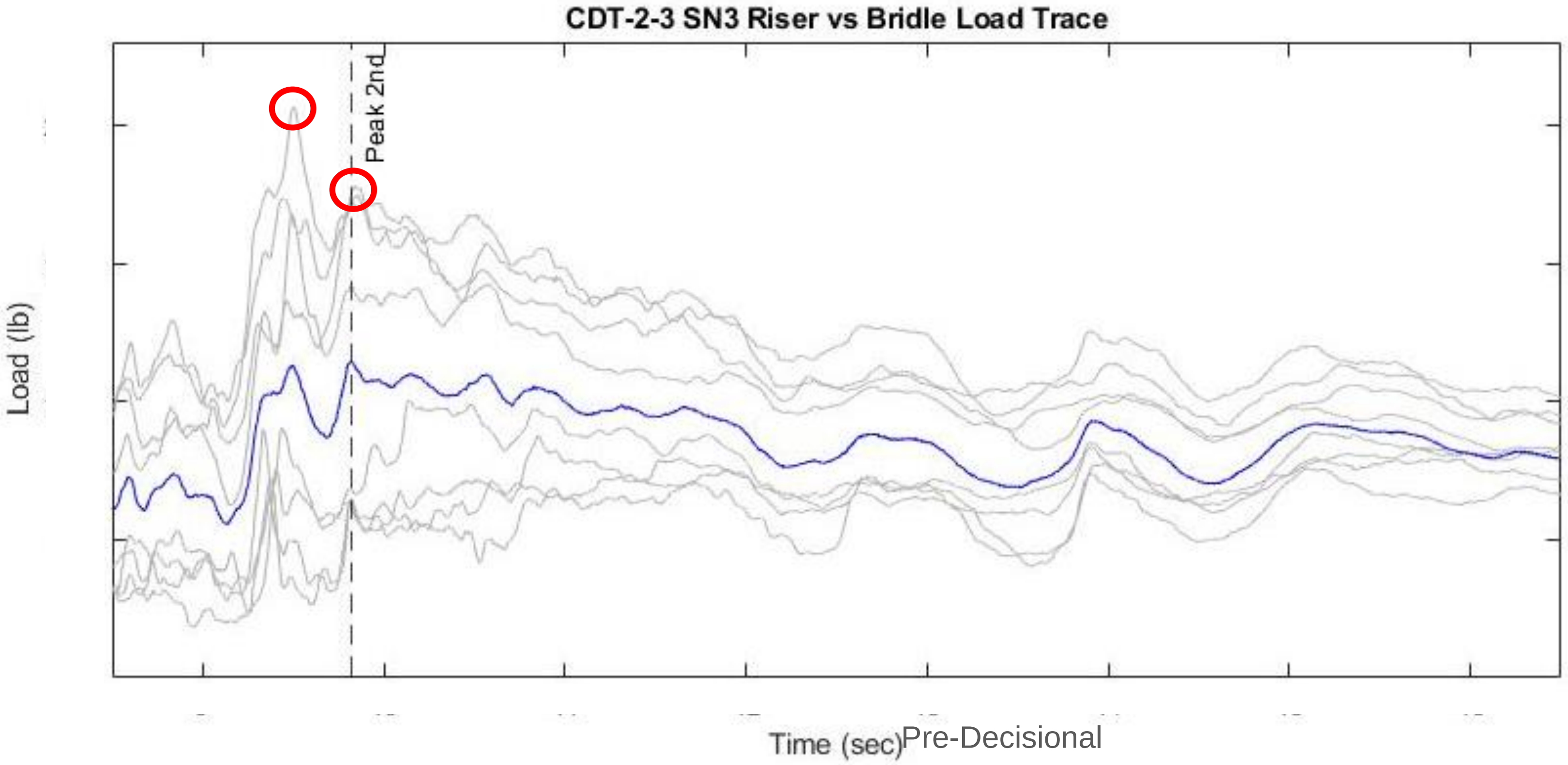
Amplification Phasing (1/2)

- **Heritage margins methodology method assumes that the peak applied load (element level) occurs coincident with peak Riser tension**
  - Models/simulations have been designed to output peak Riser load for margins assessment

- **Figure shows normalized Riser vs Bridle load trace for CDT-2-3 SN3 2nd stage**

- **Visual inspection shows peak Bridle load occurs prior to peak riser load**

- **Indicates that driving load case does not always occur coincident with peak Riser load**
  - Applies to structural elements at, and north of, Bridle element

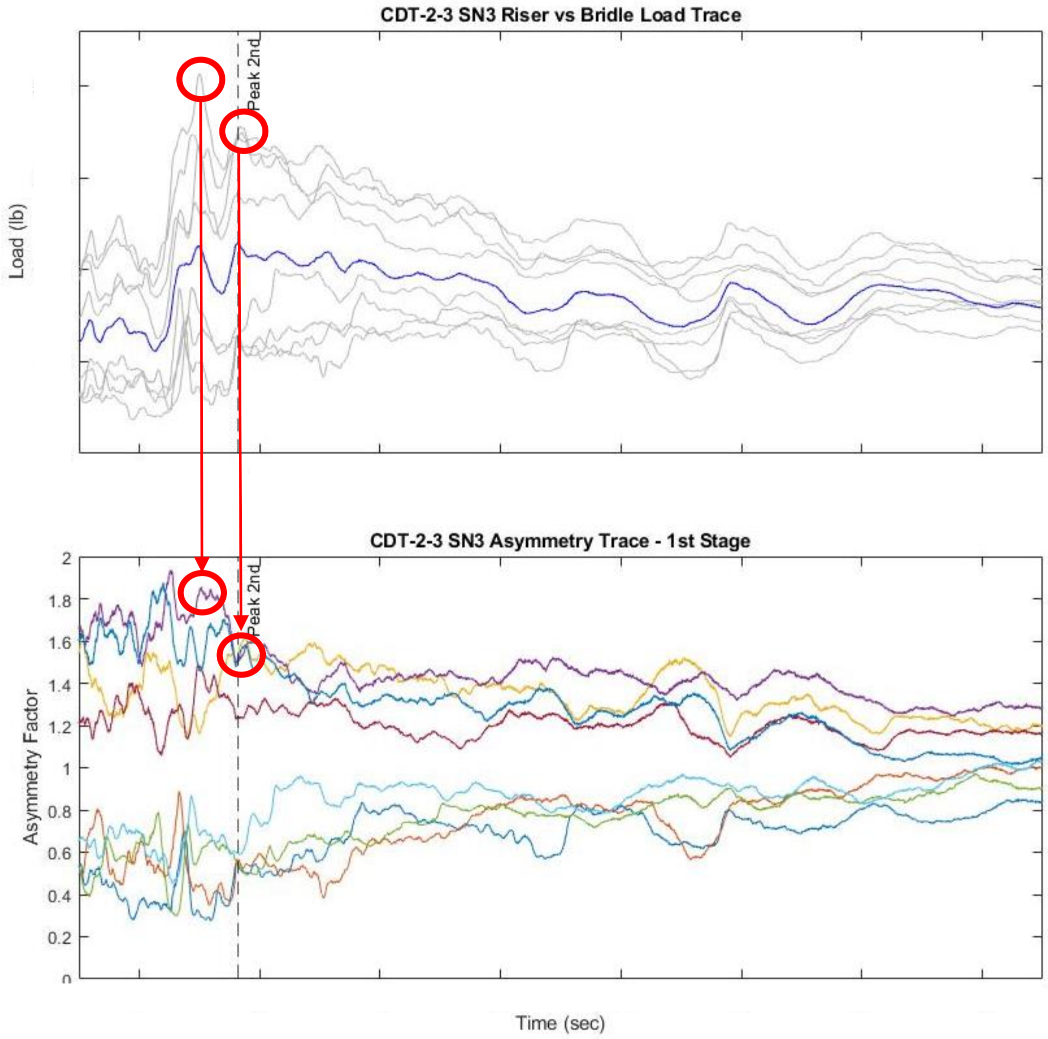


Amplification Phasing (2/2)

- **Quantifying magnitude of load under prediction per heritage method**

- **Driving Load Amplification Case Study**
  - Driving Load = (Normalized Riser load)*(AMP)

- **Corresponds with ~22% under prediction of structural loads at Bridles**



CPAS Amplification Results

Mean		Max		Time Phasing	Resulting Bridle (AMP)	
3-Main	2-Main	3-Main	2-Main		3-Main	2-Main
1.33	1.59	1.35	1.86	+31%	**1.77**	**2.44**
1.40	1.41	1.53	1.67	+22%	**1.87**	**2.04**
1.44	1.39	1.55	1.52	+5%	**1.63**	**1.60**

- **Resulting amplification may be conservative**
  - Parachute clusters have worked for decades
  - Appears like cluster parachutes have been operating with reduced margin
- **Additional testing required to increase confidence in assumptions**
  - Will likely require Suspension Line level resolution to ensure an overly conservative assumption does not need to be applied

Conclusion

- **The industry standard design factor for asymmetrical loading is 1.1**
- **CPAS performed a series of parachute drop tests, which measured asymmetry values well in excess of 1.1**
- **Conclusion drawn is that parachutes have been dipping further into their safety factor than originally appreciated**
- **When compared against other similar measurements across the industry, the common trend appears to be present in clusters of highly reefed parachutes**
  - Common across Ringsail and Ribbon parachutes
- **It is recommended that all highly reefed parachutes should measure loads at the suspension line level, so as to determine an appropriate asymmetry factor on a per-design basis**
  - Blanket application of the industry standard 1.1 no longer appears appropriate
- **Ongoing work at NASA JSC to further understand this phenomenon**

Backup

Element Strength and Number of Plies

- **Number of Plies (NP)**
  - Direct function of parachute construction
    - Example 1: An outer Radial element would have 1 ply since there is one layer
    - Example 2: A Soft Link element would have # number of plies that corresponds with the number of turns

$$MoS = \left(\frac{ES \cdot NP}{TDF \cdot AL}\right) - 1$$

- **Element Strength (ES)**
  - Legacy method of assessing element strength typically leverages spec strength of material lot
    - Lots typically come in above spec strength so as not to be rejected
      - Can be between 5-30% increase in actual material capability
  - This 'hidden margin' in the material capability is typically left untouched

$$MoS = \left(\frac{ES \cdot NP}{TDF \cdot AL}\right) - 1$$

Degradation Factor (1/2)

- **Total Design Factor (TDF): The degradation factor is a product of each individual material knockdown factor**
  - Abrasion (e): "…*Accounts for the loss of strength between elements due to element-to-element abrasion, as well as abrasion on the vehicle*." – CPAS
    - Knacke Primary Manned Vehicle Recovery: 1.0

$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

  - Fatigue (k): "…*Strength loss caused by multiple uses, high pressure packing, or a combination of both*." – Knacke
    - Knacke Primary Manned Vehicle Recovery: 1.0

$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

  - Aging (a): "…*Degradation in strength due to longer-term hardware storage subject to environmental cycling*." – CPAS
    - Knacke Primary Manned Vehicle Recovery: N/A

$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

  - Contamination (o): "…Multiple uses or exposed to sunlight, water, vacuum, and other environment conditions will suffer a loss in strength." – Knacke
    - Knacke Primary Manned Vehicle Recovery: 0.95

$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

  - Thermal (t): "All natural and man-made fibers lose strength and melt, burn, or decompose when subjected to high temperatures." – Knacke
    - Knacke Primary Manned Vehicle Recovery: N/A

$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

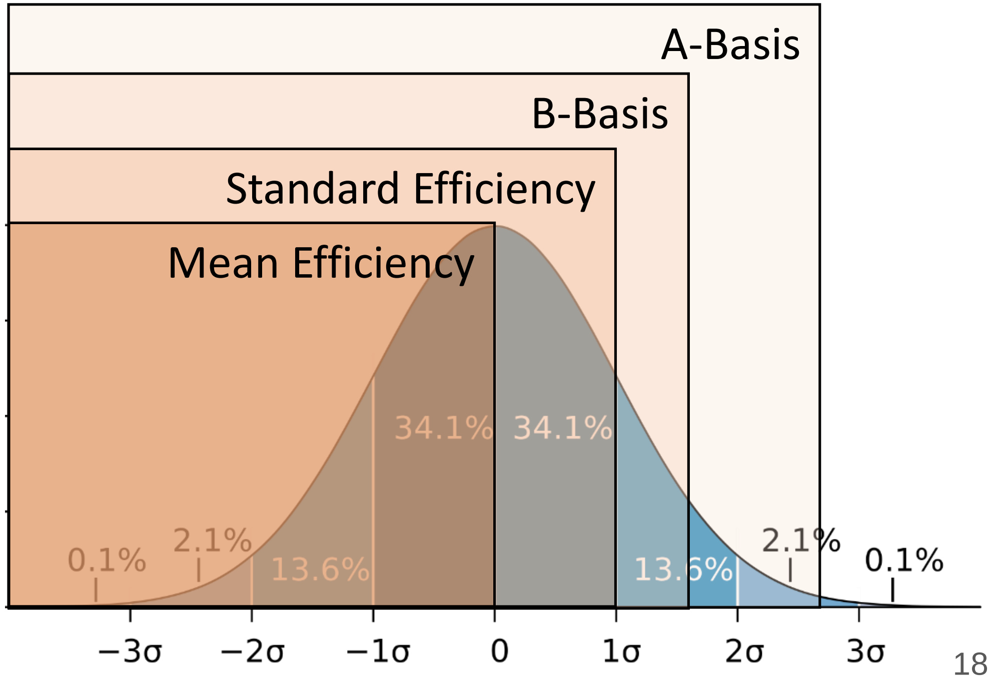
*Application specific values may vary

Degradation Factor (2/2)

- **Total Design Factor (TDF): The degradation factor is a product of each individual material knockdown factor**

$$TDF = SF \frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

  – <u>Joint (u)</u>: "Whenever textiles are connected to each other or to metals, a loss in joint strength occurs relative to the basic material strength." – Knacke
    ▪ Typical Industry Application: Joint-specific
    ▪ Knacke Primary Manned Vehicle Recovery: 0.8*
  – This value has been historically calculated via mean efficiency or standard efficiency of empirically derived samples
    ▪ Typically 3-10 joints samples and 2-5 raw element samples
    ▪ Standard efficiency captures ~84% of elements
    ▪ Mean efficiency captures ~50% of elements
  – Sensitivity study on the application of A or B-Basis
    ▪ B-Basis captures 90% of elements with 95% confidence
    ▪ A-Basis captures 99% of elements with 95% confidence



*Application specific values may vary

Amplification Factor

- **Total Design Factor (TDF): The amplification factor is a product of each individual load amplification factor**
  - Dynamic (m): "*…Used for hard-to-determine loads*" – Knacke
    - Knacke Primary Manned Vehicle Recovery: 1.0

$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

  - Convergence (c): "*The suspension lines run at an angle to this axis, thereby experiencing a slightly higher load.*" – Knacke
    - Knacke Primary Manned Vehicle Recovery: 1.0

$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

  - Asymmetry (s): "*A general assumption is that on circular parachutes, the parachute force is evenly distributed among the suspension lines. Although this assumption may not be correct, past experience has shown it to be acceptable for both reefed and full open canopies. **If force measurements on suspension lines or uneven canopy deployment suggest an uneven load distribution, an appropriate factor should be used**.*" – Knacke
    - Knacke Primary Manned Vehicle Recovery: 1.0

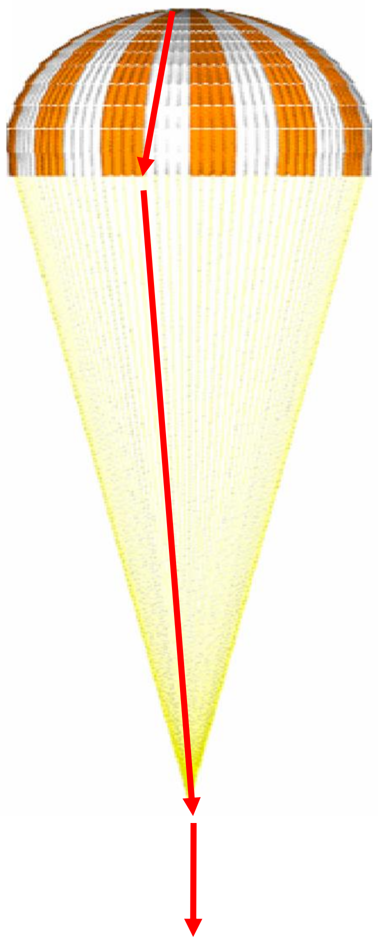
$$TDF = SF\frac{m \cdot s \cdot c}{e \cdot k \cdot o \cdot t \cdot a \cdot u}$$

*Application specific values may vary

Applied Loads

- **Applied Loads (AL)**
  - Heritage method predicts peak dynamic pressure and peak Riser tension
    - Starts with the development of a fundamental physics model based on literature, the parachute community, and NASA experience
    - Test data is reconstructed to find free parameters for the physical model
    - These free parameters are applied to the dispersions of Monte Carlo simulations, used to predict dynamic pressure and Riser loads
  - Heritage method assumes that the driving load case occurs at peak Riser tension (structural grid elements) and peak dynamic pressure (drag surface elements)

$$MoS = \left(\frac{ES \cdot NP}{TDF \cdot AL}\right) - 1$$



History of Asymmetry (1/2)

- June 1968
  - Unpublished AFFDL report by Stone measured and compared asymmetry of single canopy vs cluster
  - Medium diameter parachutes (i.e. ~48 feet) saw **average bridle-level asymmetry around ~1.5**
- December 1978
  - Yellow Book (i.e. AFFDL-TR-78-151) references unpublished AFFDL report
  - A catch-all asymmetry factor was not recommended, noting instead "***Evaluate asymmetrical unequal loading when significant***" (ref. Pg. 414)
- July 2010
  - Ares published an internal technical paper on asymmetry (EA-CLV-AR-00960-2010)
  - **Bridle-level asymmetry was measured as high as ~2.0** (1st and 2nd stage peak) and ~1.8 (full open) at each individual peak Riser load
  - Final recommendation to apply a **factor of 1.5 to Mains** and 1.2 for Drogue inflation (1.1 for Drogue disreef)
- May 2011
  - Ares published technical paper on asymmetry (AIAA 2011-2575), with the following notable quotes:
    - "*The result of numerous drop tests and a development flight test reveal that* ***rather large asymmetries are present in parachutes****.*"
    - "*This is* ***particularly true of parachutes in a cluster, where asymmetries were found to be several times greater than in single-parachute configurations***."
    - "*Finally,* ***caution should be used before blindly applying new asymmetry factors to old design techniques****.*"

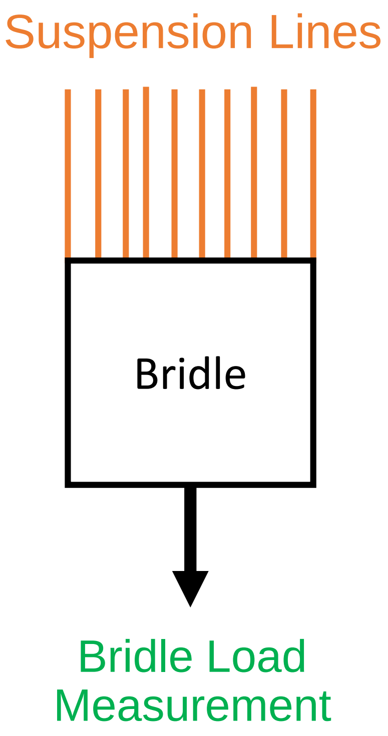
History of Asymmetry (2/2)

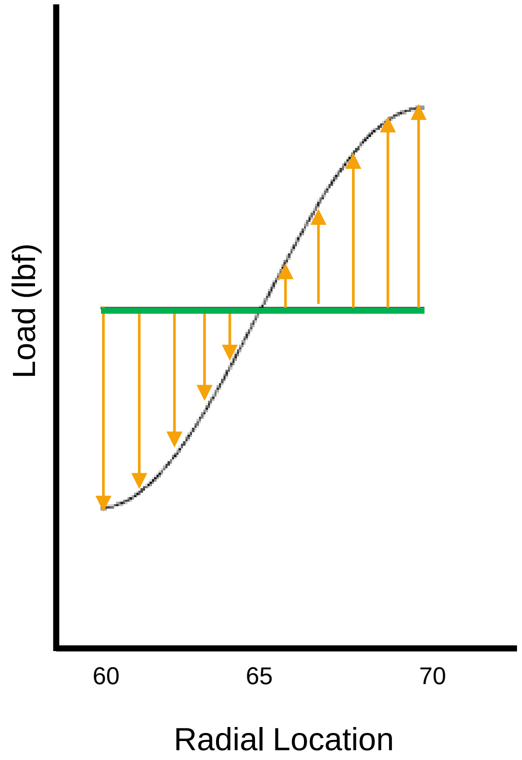
- May 2011 (continued)
  - CPAS published a technical paper on asymmetry (AIAA 2011-2611) at the same AIAA conference, with the following notable quotes:
    - "*It is apparent that* ***the asymmetrical load factors exhibited on the CPAS Main parachutes are much greater than current literature and design guides would indicate****…*"
    - "***These values suggest reconsidering the historical asymmetrical load factor of 1.1 commonly quoted in parachute literature***."
    - "*However,* ***caution is advised in implementing this load factor****.*"
    - "*Therefore,* ***parachute asymmetrical loading merits further measurements and discussion by the parachute technical community***."

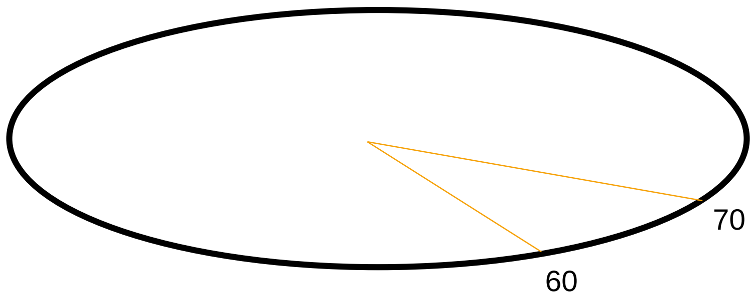
Source	Year	Diameter/Type	Structural Grid Material	Sensor Location	Tests	Cluster Size	Asymmetry @ Peak Load
AFFDL	1968	48' Ribbon	Nylon	Bridle (6x8)	10*	3	~1.5 (average)
Ares	2011	68' Ribbon Drogue 150' Ribbon Main	Kevlar Kevlar	Bridle (6x12) Bridle (8x10)	4 2	1 3	~1.2 ~2.0
CPAS	2011	*116' Ringsail Main*	Kevlar	Bridle (8x10)	1 2	3 2	~1.6 ~1.9

CPAS Measurement Technique (1/2)

- **Load measurements at the Bridle directly measure loads at the Bridle, but fail to capture the higher resolution load share happening at the Suspension Line level**







Bridle vs Suspension Line Load Example

- Green line shows the measured Bridle load per TMS instrumentation
  - Sum of 10 Suspension Lines
- Orange arrows indicate a possible gradient of Suspension Line loads
  - Applied load for Suspension Line and Radial margins assessment

CPAS Measurement Technique (3/3)

- **Sources of potential error**
  - Twist of Bridle and/or Suspension Line elements
  - Insufficient/ineffective calibration of hardware before/after testing
  - Poor quality hardware
  - Transient load environment (i.e. flutter)
  - Incorrect time synchronization of measurements (critical)
  - Sample rate

CPAS Amplification Background

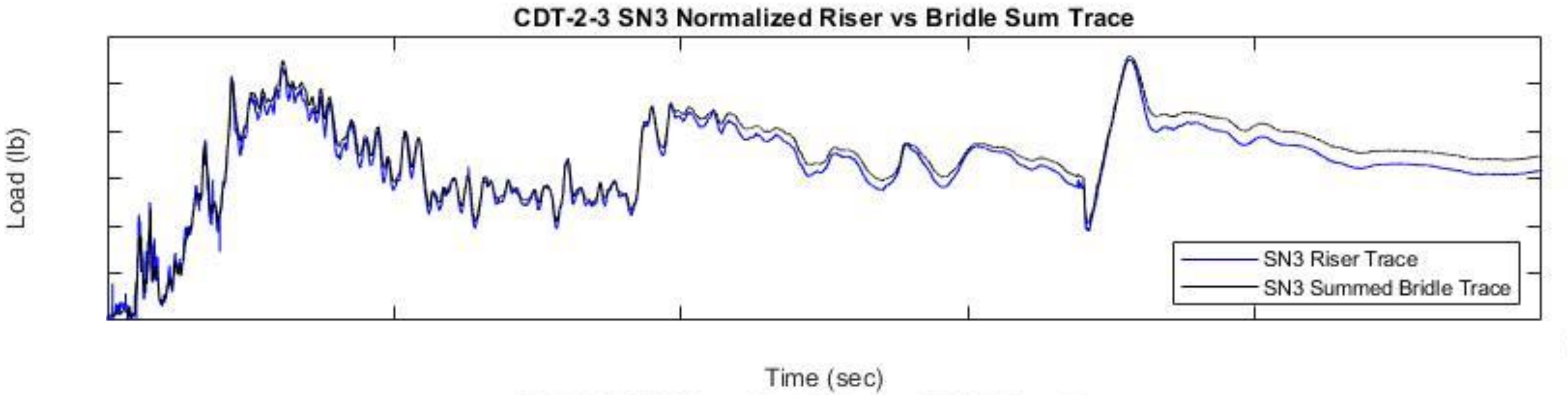
- **CPAS measured bridle-level amplification on three development parachute drop tests with the Gen II Main parachute design**
  - CDT-2-1 (Two-Main config)
    - Apollo style Riser length and Main Line Length ratio
  - CDT-2-2 (Two-Main config) and CDT-2-3 (Three-Main config)
    - Longer Riser and reduced Main Line Length ratio

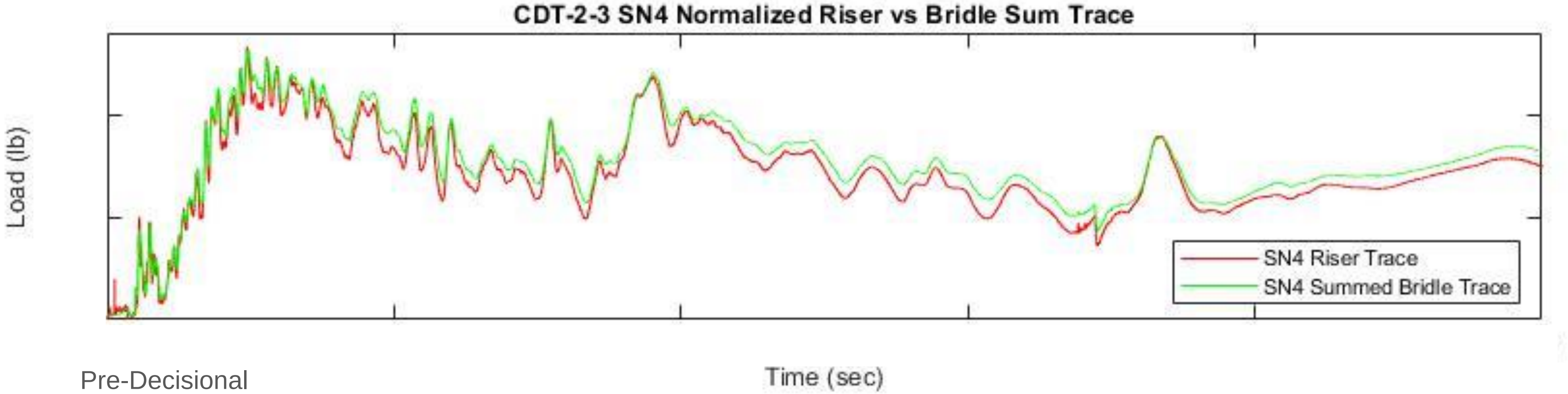
Test	Config	TMS Capture Rate		
		Main 1	Main 2	Main 3
CDT-2-3	3-Main	8 of 8	7 of 8	Not instrumented
CDT-2-2	2-Main	6 of 8*	7 of 8	N/A
CDT-2-1	2-Main	8 of 8	7 of 8	N/A

*Low confidence in data collected

Main Riser vs Bridle Sum Load Trace

- **CDT-2-3 Main Riser load trace vs Bridle load sum**
  - S/N-03 had 8 of 8 Bridle load measurements (no additional post-processing required)
  - S/N-04 had 7 of 8 Bridle load measurements (sum of 7 Bridle measurements was multiplied by (8/7))
- **Results provide confidences in TMS measurements**

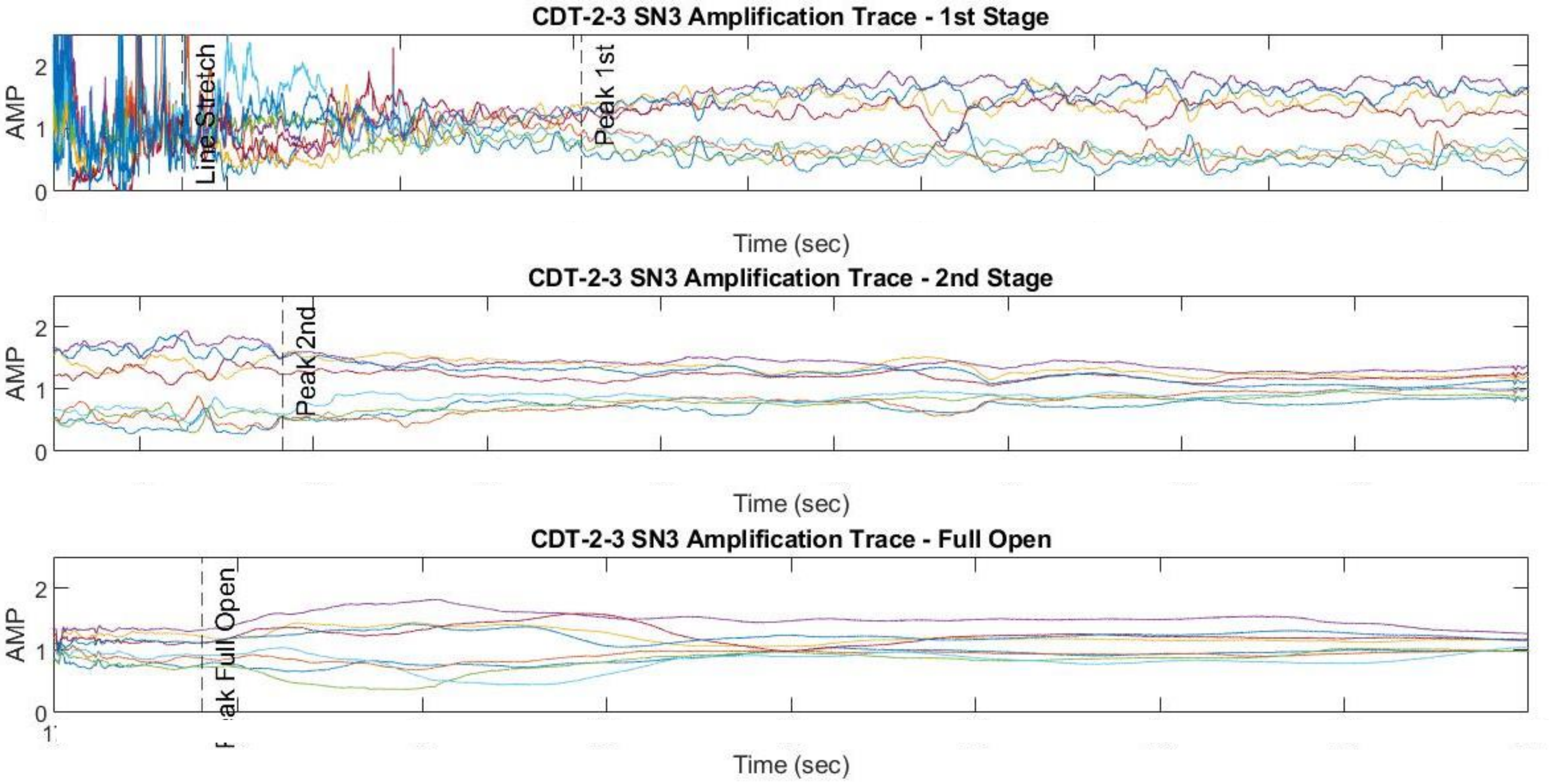




Amplification Factor Time History

- **Leveraging the AMP equation, a bridle-level amplification factor was assessed at every timestamp**
  - So 8 AMP traces are visible for each time segment, with peak Riser load called out with vertical lines

$$AMP = \frac{Load_{Bridle}}{(Load_{Riser}) * \left(\frac{1}{8}\right)}$$



Amplification Factor w/ Current Models

- **Current models/simulations predict dynamic pressure and Riser load, with post-processing required to assess applied load at all upstream elements**

- **In order to continue leveraging current models, propose incorporating the following preliminary relationships**
  - Following discussion with NESC statistician, a simple empirically based method was selected
    - Incorporates largest amplification factor, per configuration and stage
    - Require additional data in order to leverage a more statistically intensive method
  - Considering the very limited sample size of available data, 2-Main and 3-Main phasing differences cannot currently be distinguished
    - Will incorporate largest amplification phasing value identified per stage
  - Forward work to determine the resolution difference between Bridle loads (i.e. average of 10 Suspension Lines) vs Suspension Line loads

Summary: Amplification Phasing

- **Amplification phasing appears chaotic and unrepeatable**
  - 1st stage phasing appears coincident with or after peak Riser load
  - 2nd stage phasing does not appear to have phasing consistency
    - Occurs before, after, and coincident with peak Riser load
  - Full open phasing appears coincident with or after peak Riser load
- **More data is needed to determine whether phasing can be empirically characterized**
- **Insufficient data to distinguish between 2-Main and 3-Main phasing differences**

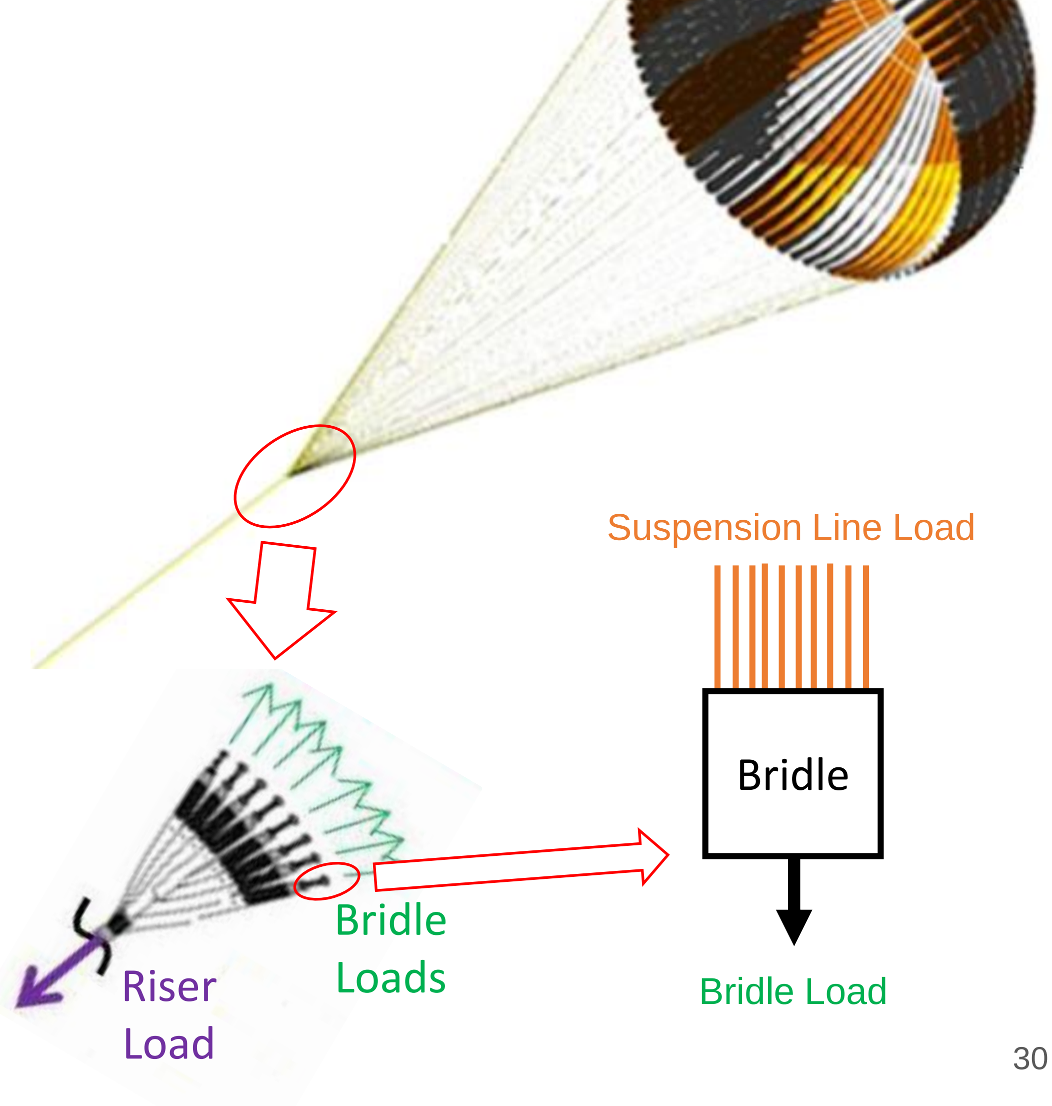
Test	Config	Chute	Per-Stage Load Phasing					
			1st Stage		2nd Stage		Full Open	
CDT-2-3	3-Main	S/N-03	+10%	After	+22%	Before	+5%	After
		S/N-04	+17%	After	+3%	After	In Phase	
		S/N-05	N/A		N/A		N/A	
CDT-2-2	2-Main	S/N-04	N/A		N/A		N/A	
		S/N-05	+31%	After	In Phase		In Phase	
CDT-2-1	2-Main	S/N-01	+4%	After	In Phase		In Phase	
		S/N-02	N/A		+9%	Before	N/A	

- **Legend**
  - Before = Before peak riser tension
  - After = After peak riser tension

Influence of Asymmetry on Element Loads

- **Margins Methodology**
  - Monte Carlos predict range of potential Riser loads
  - Post-processing evenly distributes Riser loads throughout the structural grid
    - Each Bridle sees 1/8th of total Riser load
      - Eight Bridles per Riser
    - Each Suspension Line sees 1/10th of total Bridle load
      - 10 Suspension Lines per Bridle
    - Each Radial sees the same load as each Suspension Line
    - Each Vent Line sees the same load as each Radial
  - Design factors for material degradation and load amplification are then applied

$$asym = \frac{Load_{Bridle}}{(Load_{Riser}) * \left(\frac{1}{8}\right)}$$



- **Legacy assumptions required for this methodology**
  - The same asymmetry is seen at all structural elements, no matter the location of loading method
    - Incorrect assumption: Measuring at the Bridle looses resolution of load gradient in the Suspension Lines, since they are upstream to the Bridle(s)
  - All peak element loads occur coincident with peak Riser load
    - Incorrect assumption: Peak Bridle load can occur before or after Peak Riser load

Visualization of Design Factors

- **Parachute margins are a function of element capability, knockdowns, and applied loads**

$$\text{MoS} = \frac{(Element\ Capability)}{(\ Knockdowns) * (Applied\ Loads)} - 1$$

- **Visualization was developed to show margins vs asymmetry**
  - Intent: Show the impact to safety factor (SF) when adjusting the asymmetry factor (s)
  - Assume: Design was baselined with SF=1.6 and s=1.1
    - Color Legend
      - Asymmetry: Brown
      - Safety Factor: Sky Blue
- **Asymmetry factor of 1.1**
  - Dotted line denotes fully mass-optimized Main parachute design
  - Full Safety Factor of 1.6 above ultimate strength is maintained
- **Asymmetry factor of 1.6**
  - Minimal Safety Factor above ultimate strength is maintained (SF=~1.1)
- **Asymmetry factor of 2.0**
  - Ultimate strength is exceeded (SF<1)