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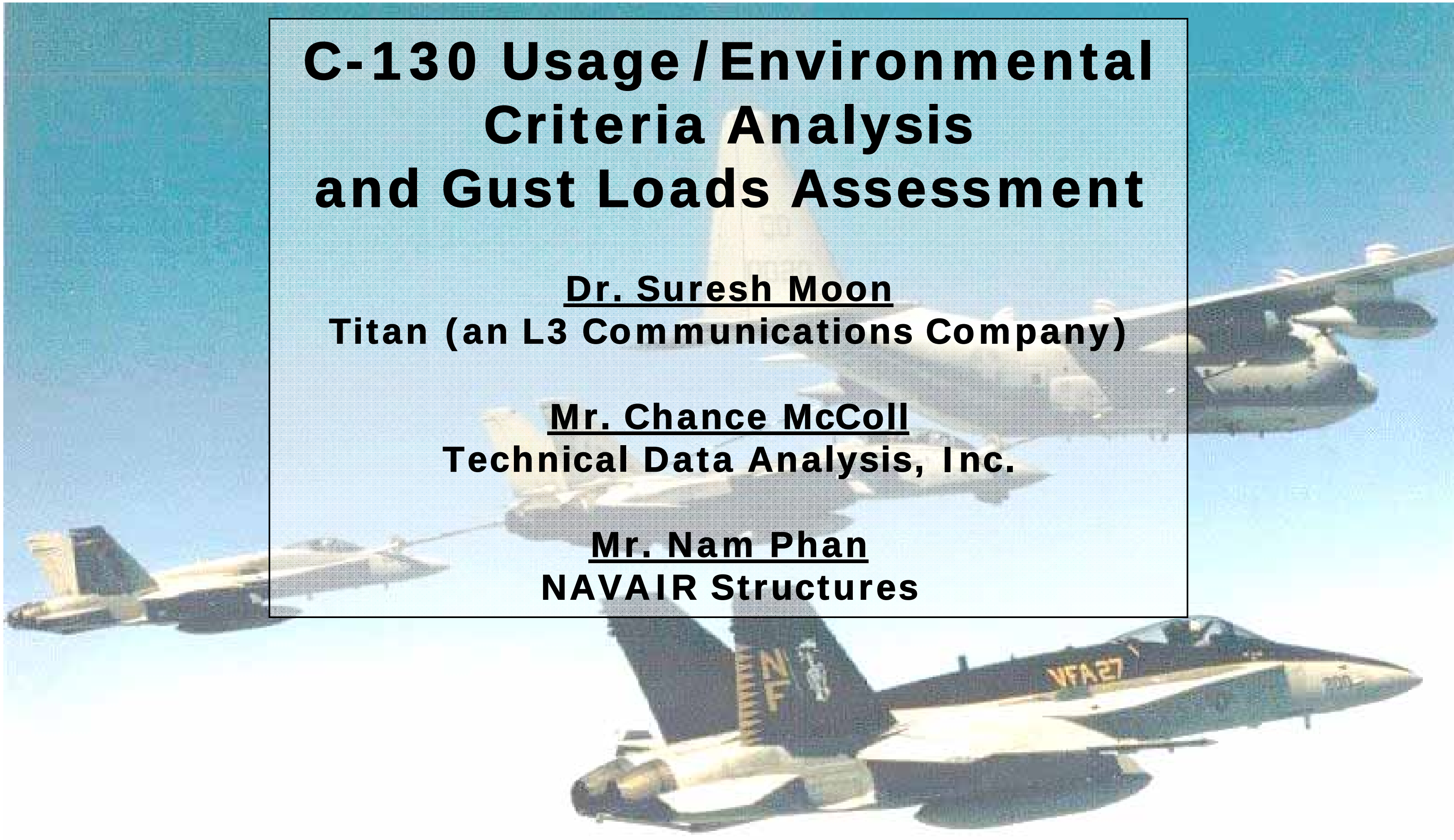

C-130 Usage/Environmental Criteria Analysis and Gust Loads Assessment

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NAVAIR Structures

Outline

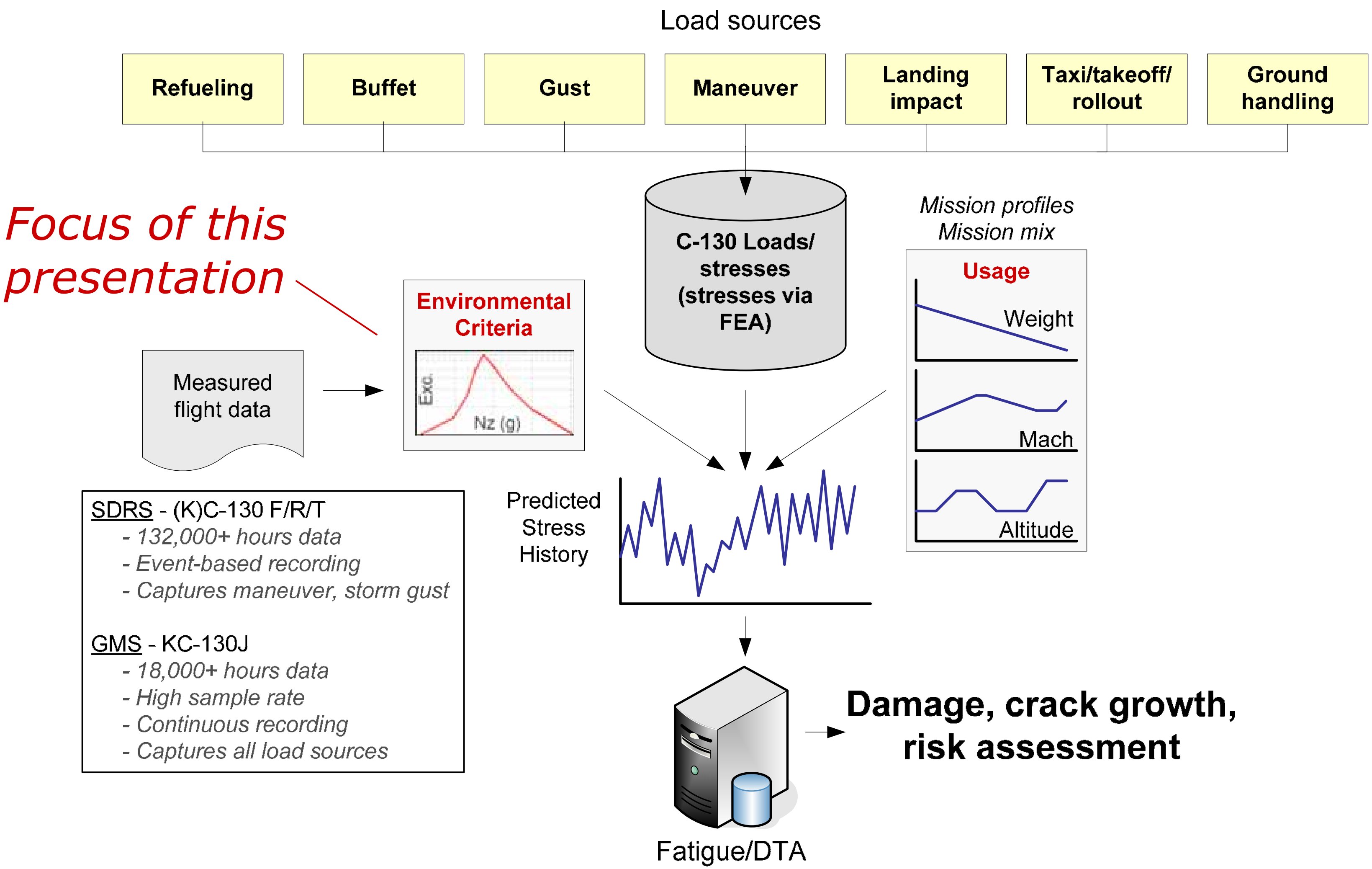
- C-130 SLAP Background, Requirements, and Objectives
- Gust Clustering Effects (Mr. McColl)
- Environmental Criteria Development (Dr. Moon)
  – Maneuver
  – Gust
  – Taxi
  – Landing Impact
- Conclusions

US Navy C-130 Service Life Assessment (SLAP)

Why perform a SLAP for the C-130?

- Inspections reveal fatigue cracking at various locations
- Grounded (or potentially grounded) aircraft
- C-130 usage continues to change and evolve
- Effects due to individual aircraft usage
- Limited aircraft resources and increased demand requires optimized fleet management and aircraft life assessments
- These requirements dictate the need for the following:
  - More refined representations of fleet usage/environmental criteria
    - Analyze (K)C-130F/R/T/J recorded data to create Nz maneuver, Nz gust, VGH-VH, mission mix, mission profile, maneuver sequence (with time, weight, fuel, cargo, velocity, and altitude), and landing impact/ground maneuver criteria
  - Structural integrity assessments
- The focus of this presentation is environmental criteria – specifically the most critical load sources (gust and maneuver); ground and landing impact are addressed as well

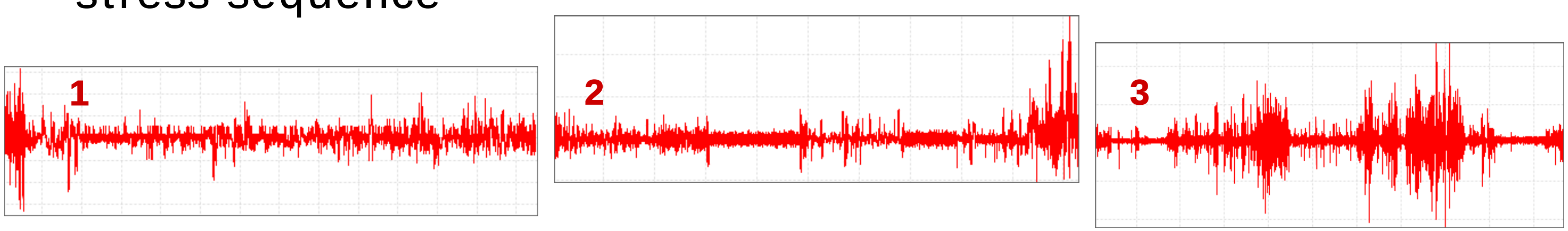
SLAP: Areas of Interest



Gust Cycle Clustering Effects

Gust Cycle Clustering Effects

- Aircraft fatigue and damage tolerance analyses are highly sensitive to the placement of large amplitude cycles within the underlying stress sequence (spectra)
- Large amplitude cycles occurring near the beginning[1] of the stress sequence can potentially result in large residual stresses and, subsequently, slower crack growth or even crack retardation
- Conversely, large amplitude cycles occurring near the end[2] of the stress sequence can result in faster crack growth due to the absence of large residual stresses earlier in the spectrum
- A variety of intermediate effects can be achieved by more uniform distributions[3] of large amplitude cycles throughout the stress sequence



Gust Cycle Clustering Effects

- For aircraft instrumented with high sample rate data recorders where fatigue is tracked on a flight-by-flight basis, these large amplitude cycles can be measured and applied in analysis exactly where/when they occur
  - KC-130J GMS recorder
- For other aircraft, such information may not be directly known
  - Also, for more generalized fleet-wide studies (i.e., mission analysis or airframe fatigue test spectra generation), such information may also not be directly known
- Where should cycles be placed?
  - Pilot-induced maneuvers: typically distributed evenly across such a spectrum (based on mission type/flight segment)
  - Gust-induced cycles (e.g., MIL-based power spectral density (PSD) gust): typically formulated based purely on altitude and time-in-segment, with no known information provided as to where to explicitly place cycles across the sequence

Gust Cycle Clustering Effects

- Typical gust cycle placement
  - Evenly distribute large amplitude gust cycles across the sequence
    - Inconsistent with the randomness of turbulence (a random process should display no pattern or regularity)
  - Group them in a subset of flights in some random fashion
    - Wide variation in crack growth rates can result based on where the high amplitude cycles were randomly placed
- KC-130J measured flight data was examined to better model the placement of gust cycles across a sequence
- Two objectives
  - Examine the distribution of the number of gust cycles per flight
  - Examine the gust cycle clustering effects, wherein high amplitude gust cycles tend to congregate together in a subset of flights across the spectrum
    - Significant in that it provides insight into how to better model the random nature of turbulence when developing spectra for fatigue and damage tolerance analysis

Gust Cycle Clustering Effects

- Previous work by Bullen* states

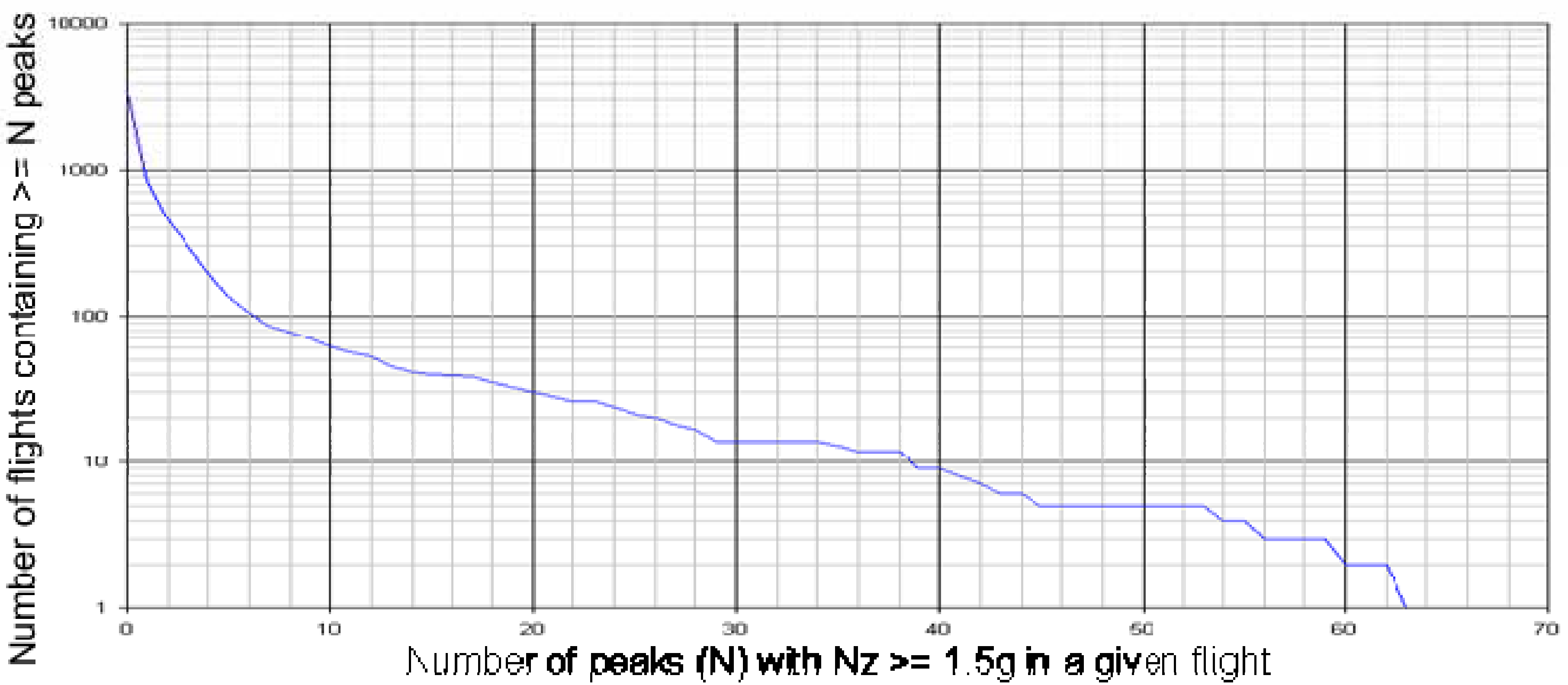
  "The application of a given number of loading cycles between each ground-to-air cycle is unrealistic. Some flights are calm, some are extremely turbulent, and the majority of flights range somewhere between the two extremes."

- The objective is to quantify this statement
- First to be determined was the distribution of the number of peaks at-or-above a given g-level across flights
  - i.e., how uniform was the distribution of gust cycles flight-to-flight

 ** Bullen, N.I.; "The Chance of a Rough Flight;" February 1965*

Gust Cycle Clustering Effects

- Results show a broad distribution of the number of gust cycles across flights (1.5g example)



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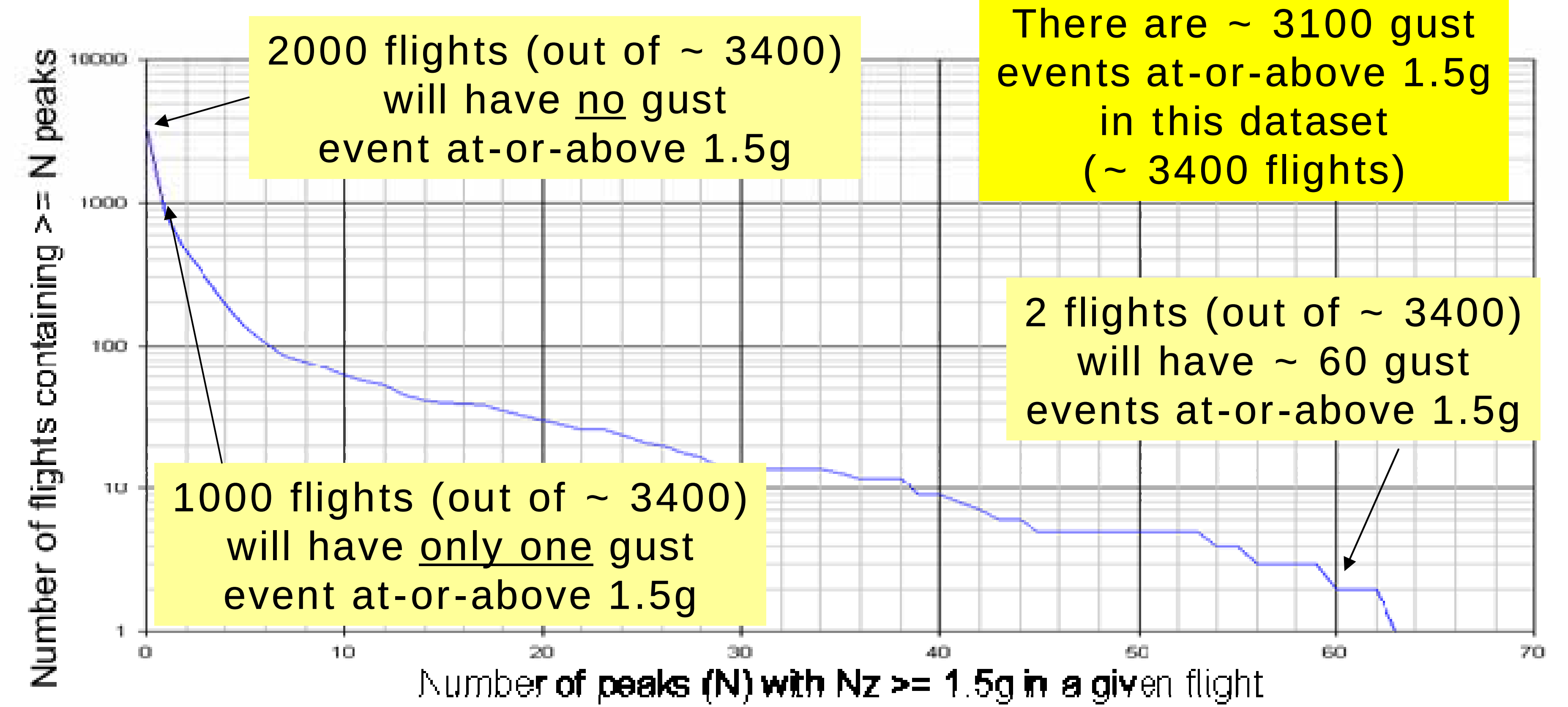

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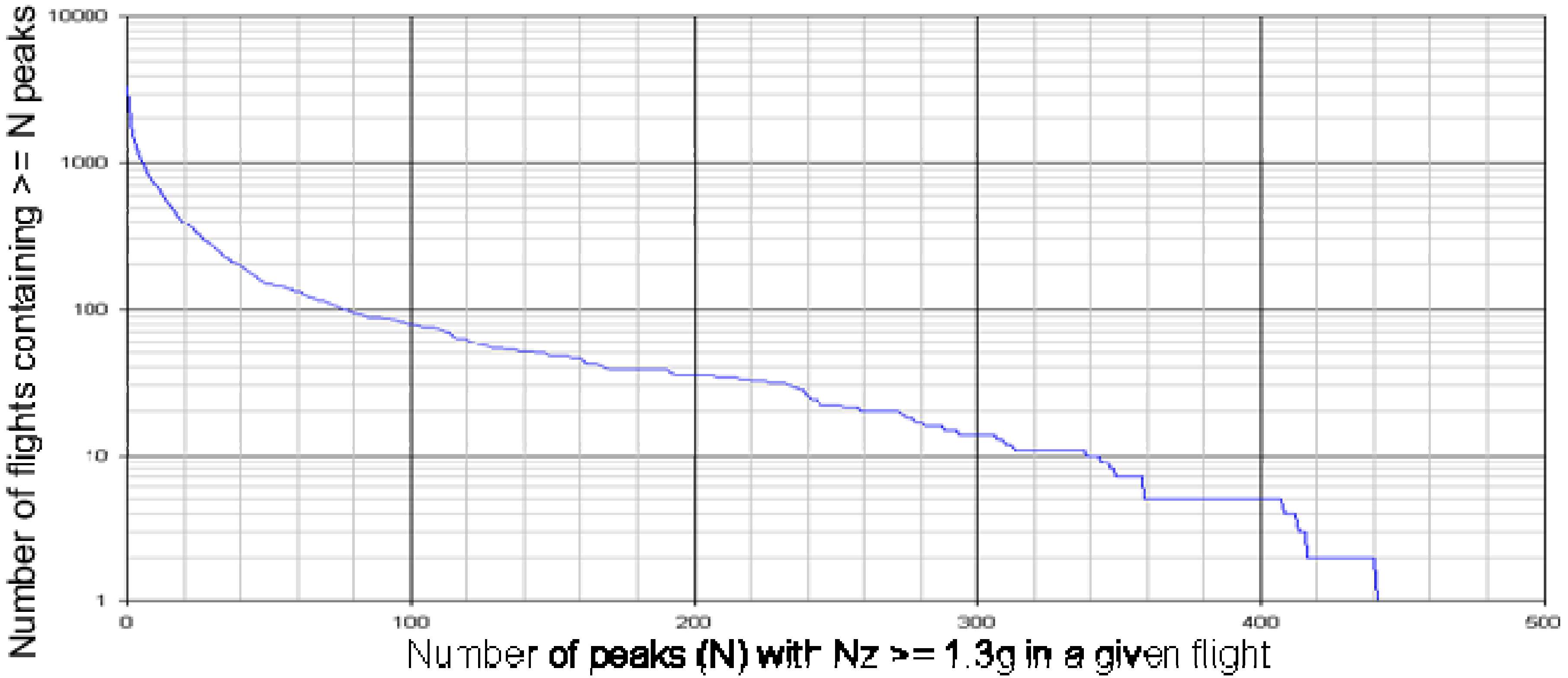
Gust Cycle Clustering Effects

- Results show a broad distribution of the number of gust cycles across flights (1.3g example)



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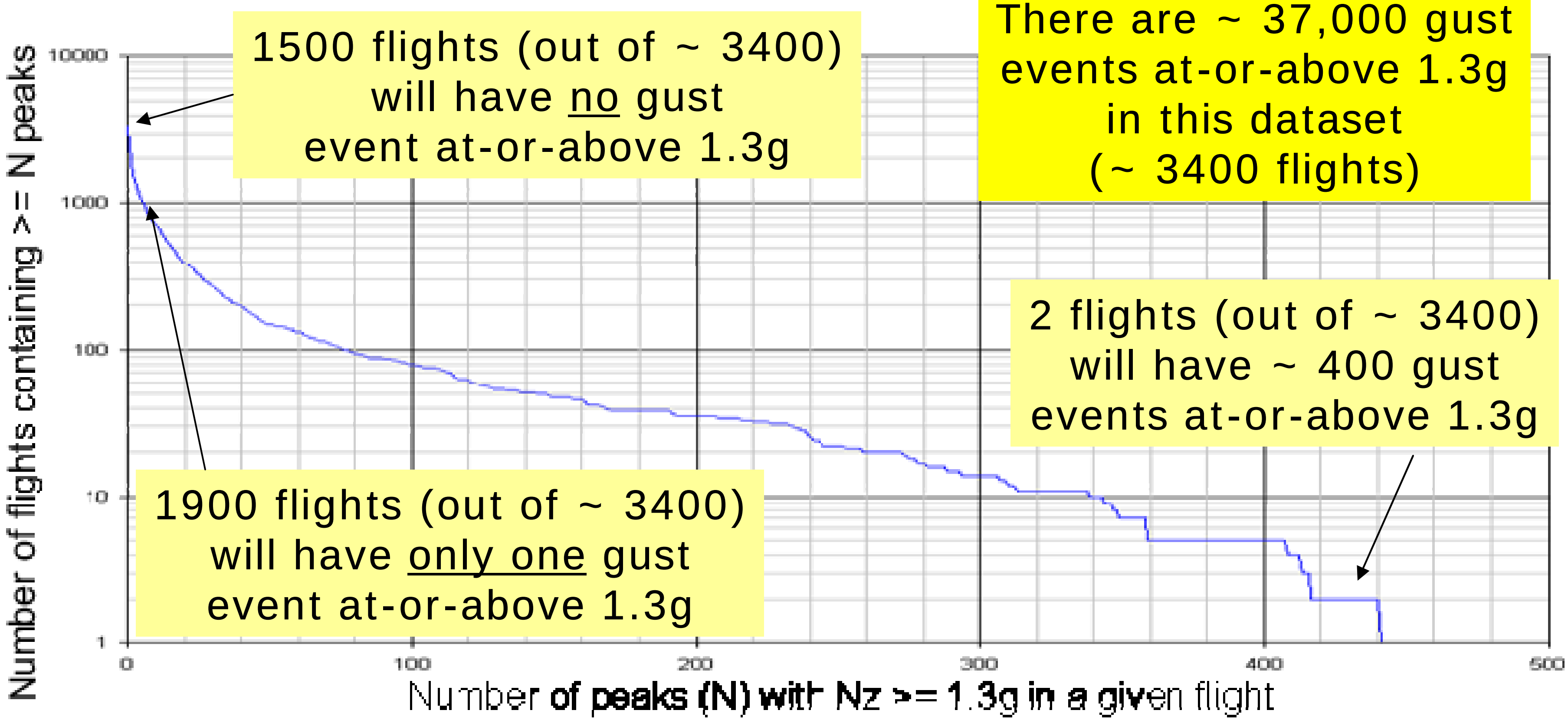

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Gust Cycle Clustering Effects

- For higher g-levels (with more isolated events), the distribution tends to converge
  - 1.7g:
    - Occurs in ~7% of flights
    - Multiple cycles per flight occur across 30% these flights

- This is based in-part on limited dataset, yet likely still a real phenomenon
- However, fatigue and crack growth can be extremely sensitive to these abundantly occurring “mid” g-level gust events, so it is critical to spread them appropriately

Gust Cycle Clustering Effects

- Next to be determined were gust cycle clustering effects, wherein high amplitude gust cycles potentially congregate together in a subset of flights across the spectrum
- Gust occurrences due to discrete g-levels (1.2, 1.3, ..., 1.9g) were determined
  - *Gust cycles ≥ 2.0g were examined as well, but determined to be too small a dataset*
- Correlation (measure of linearity between two quantities) and significance were calculated across g-levels within flights
- Also determined was the presence of lower-g events clustered together within each flight
- The general trend (as seen in following two charts) is that the flights with the higher g-counts tend to have more overall gust cycles within that flight; i.e., gust cycles tend to “cluster” together

Correlation coefficient (ρ_{ij}) matrix

	nz_1.1	nz_1.2	nz_1.3	nz_1.4	nz_1.5	nz_1.6	nz_1.7	nz_1.8	nz_1.9	nz_2	nz_2.1	nz_2.2	nz_2.3	nz_2.4
nz_1.1		0.6749	0.575	0.506	0.4652	0.3815	0.3137	0.2067	0.1838	0.092	0.0601	0.0587	0.1033	-0.0033
nz_1.2	0.6749		0.9538	0.8834	0.8033	0.6879	0.5376	0.3965	0.2853	0.1672	0.1011	0.0884	0.072	-0.0047
nz_1.3	0.575	0.9538		0.9603	0.8917	0.7765	0.606	0.4691	0.315	0.1796	0.1057	0.0985	0.0964	-0.0047
nz_1.4	0.506	0.8834	0.9603		0.9251	0.8199	0.654	0.516	0.3126	0.2037	0.088	0.121	0.1062	-0.0025
nz_1.5	0.4652	0.8033	0.8917	0.9251		0.8182	0.6674	0.574	0.3397	0.2146	0.0953	0.1496	0.1035	-0.0042
nz_1.6	0.3815	0.6879	0.7765	0.8199	0.8182		0.5908	0.6028	0.344	0.2295	0.0681	0.1236	0.0632	-0.0036
nz_1.7	0.3137	0.5376	0.606	0.654	0.6674	0.5908		0.5246	0.2498	0.1668	0.0683	0.1241	0.0808	0.0404
nz_1.8	0.2067	0.3965	0.4691	0.516	0.574	0.6028	0.5246		0.3269	0.2074	0.0514	0.1573	0.0363	-0.002
nz_1.9	0.1838	0.2853	0.315	0.3126	0.3397	0.344	0.2498	0.3269		0.033	0.0527	0.1579	0.1579	-0.0015
nz_2	0.092	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	-0.0024	-0.0012
nz_2.1	0.0601	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	0.1754	-0.0008
nz_2.2	0.0587	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		-0.0012	-0.0006
nz_2.3	0.1033	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		-0.0006
nz_2.4	-0.0033	-0.0047	-0.0047	-0.0025	-0.0042	-0.0036	0.0404	-0.002	-0.0015	-0.0012	-0.0008	-0.0006	-0.0006	

Too small a dataset

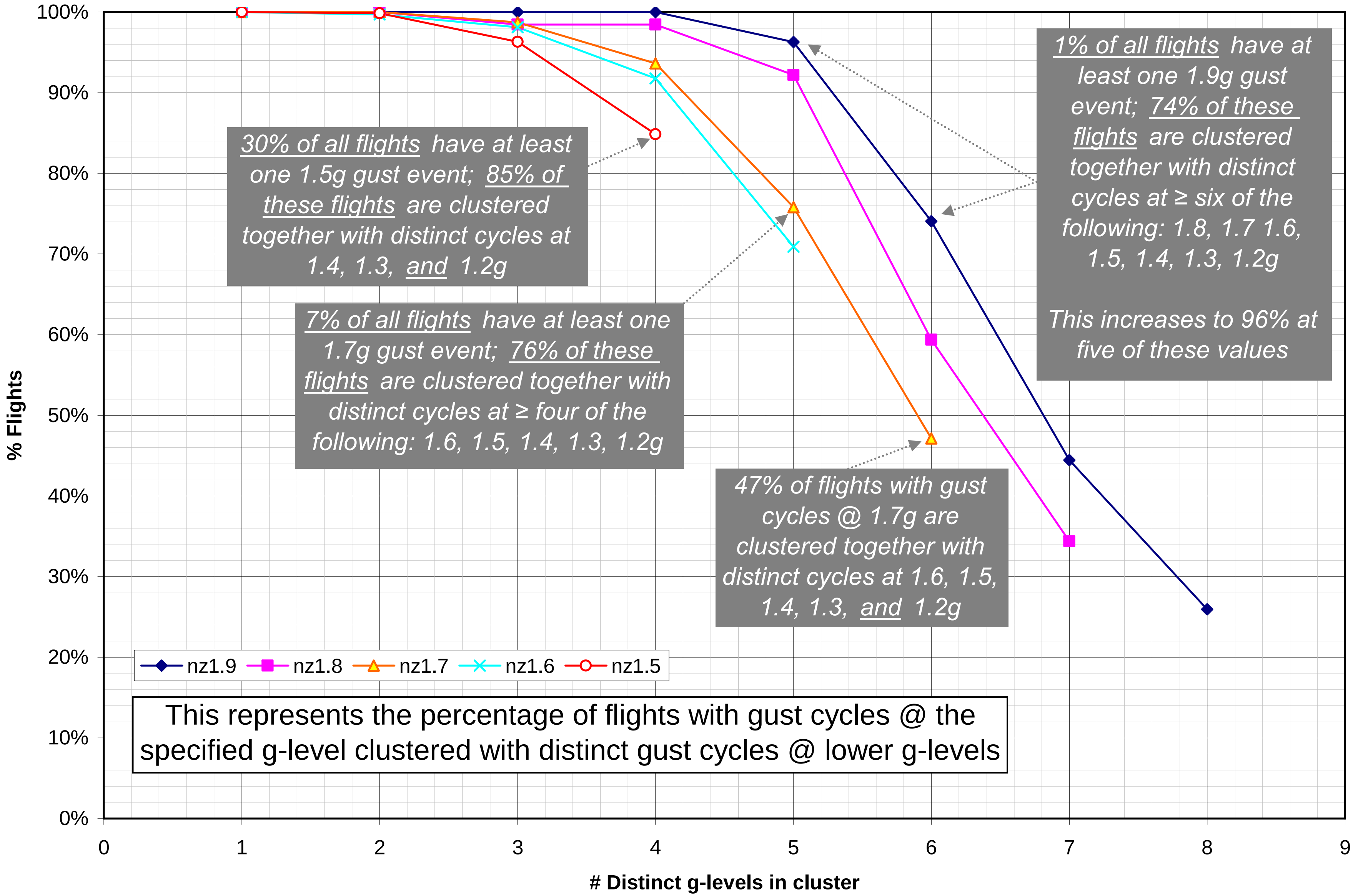
Good correlation; good significance

p-value* matrix

	nz_1.1	nz_1.2	nz_1.3	nz_1.4	nz_1.5	nz_1.6	nz_1.7	nz_1.8	nz_1.9	nz_2	nz_2.1	nz_2.2	nz_2.3	nz_2.4
nz_1.1		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	84.6%
nz_1.2	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	78.3%
nz_1.3	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	78.3%
nz_1.4	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	88.4%
nz_1.5	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	80.7%
nz_1.6	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	83.3%
nz_1.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.8%
nz_1.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.3%	0.0%	3.4%	90.8%
nz_1.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		5.4%	0.2%	0.0%	0.0%	93.2%
nz_2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.4%		84.1%	88.7%	88.7%	94.4%
nz_2.1	0.0%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	96.1%
nz_2.2	0.1%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	97.3%
nz_2.3	0.0%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		97.3%
nz_2.4	84.6%	78.3%	78.3%	88.4%	80.7%	83.3%	1.8%	90.8%	93.2%	94.4%	96.1%	97.3%	97.3%	

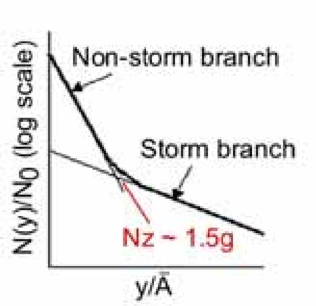
Too small a dataset

* The **p-value** (p) is the probability of getting a correlation as large as the observed value by random chance, when the true correlation is zero; for small p (less than a 5% significance level is standard) the correlation ρ_{ij} is significant


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Flights
0
1
2
3
4
5
6
7
8
9
Distinct g-levels in cluster
nz1.9
nz1.8
nz1.7
nz1.6
nz1.5
30% of all flights have at least one 1.5g gust event; 85% of these flights are clustered together with distinct cycles at 1.4, 1.3, and 1.2g
7% of all flights have at least one 1.7g gust event; 76% of these flights are clustered together with distinct cycles at ≥ four of the following: 1.6, 1.5, 1.4, 1.3, 1.2g
1% of all flights have at least one 1.9g gust event; 74% of these flights are clustered together with distinct cycles at ≥ six of the following: 1.8, 1.7 1.6, 1.5, 1.4, 1.3, 1.2g
This increases to 96% at five of these values
47% of flights with gust cycles @ 1.7g are clustered together with distinct cycles at 1.6, 1.5, 1.4, 1.3, and 1.2g
This represents the percentage of flights with gust cycles @ the specified g-level clustered with distinct gust cycles @ lower g-levels

C-130 Environmental Criteria

- Maneuver and gust criteria for the KC-130 F/R/T and C-130T is based on measured SDRS data
  - 132,000+ hours data
  - Event-based recording
  - Captures maneuver, storm gust



- Maneuver, gust, and ground criteria for the KC-130J is based on measured GMS data
  - 18,000+ hours data
  - High sample rate
  - Continuous recording
  - Captures all load sources

- Landing impact criteria is based on legacy analysis compared with recent measured test data

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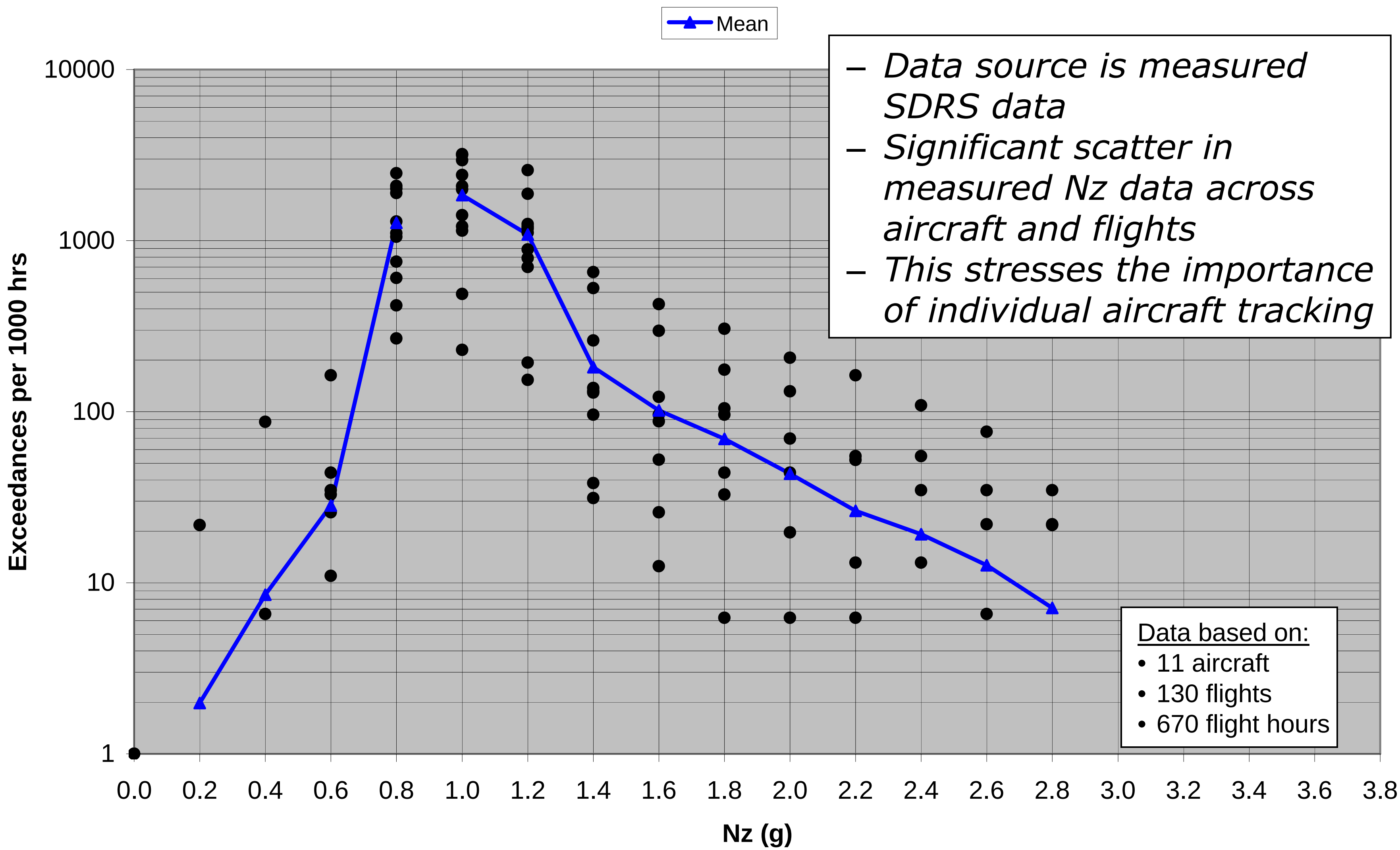
KC-130R Transport Mission Maneuver Nz Exceedances

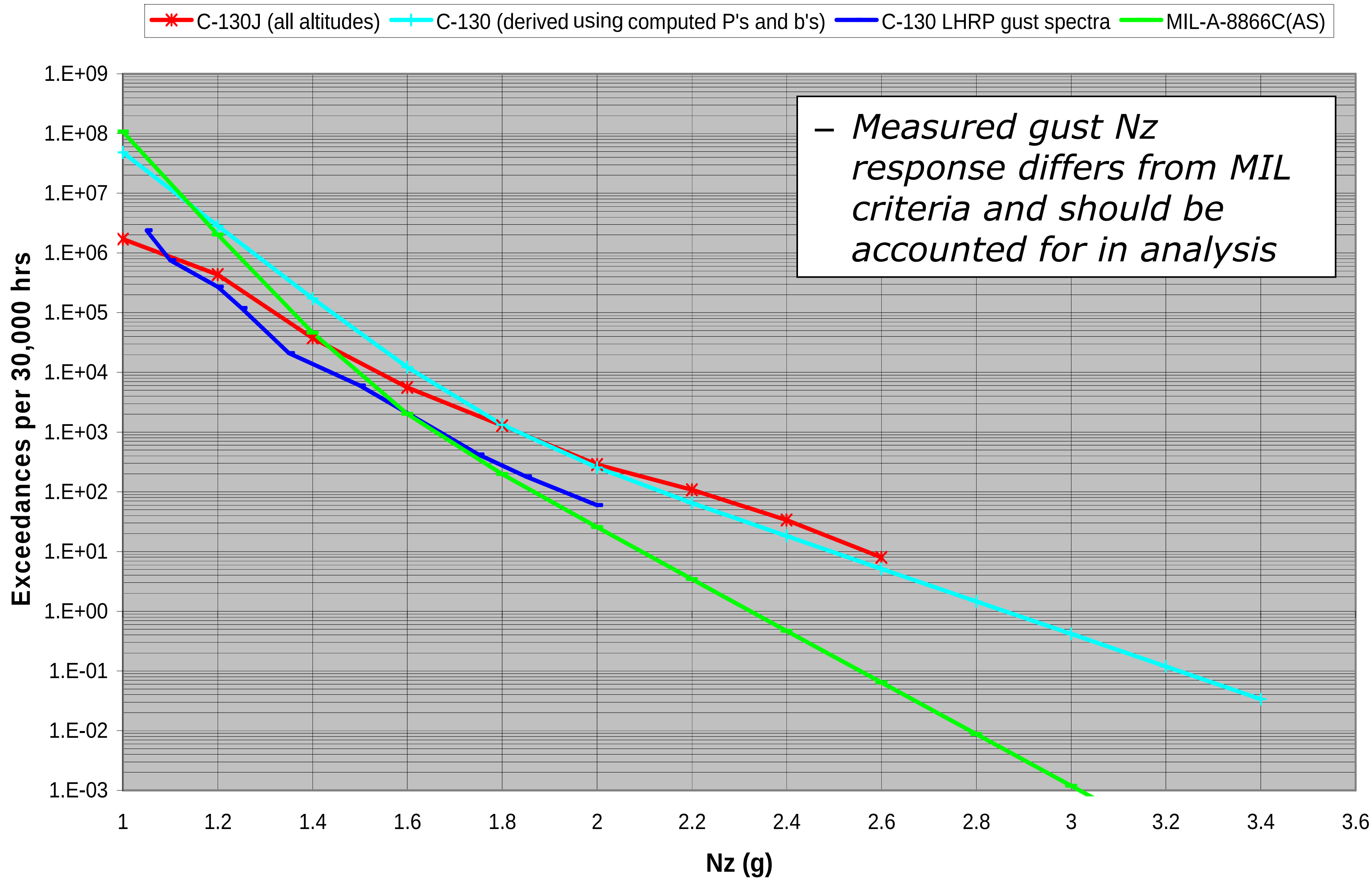


- *Data source is measured SDRS data*
- *Significant scatter in measured Nz data across aircraft and flights*
- *This stresses the importance of individual aircraft tracking*

Data based on:

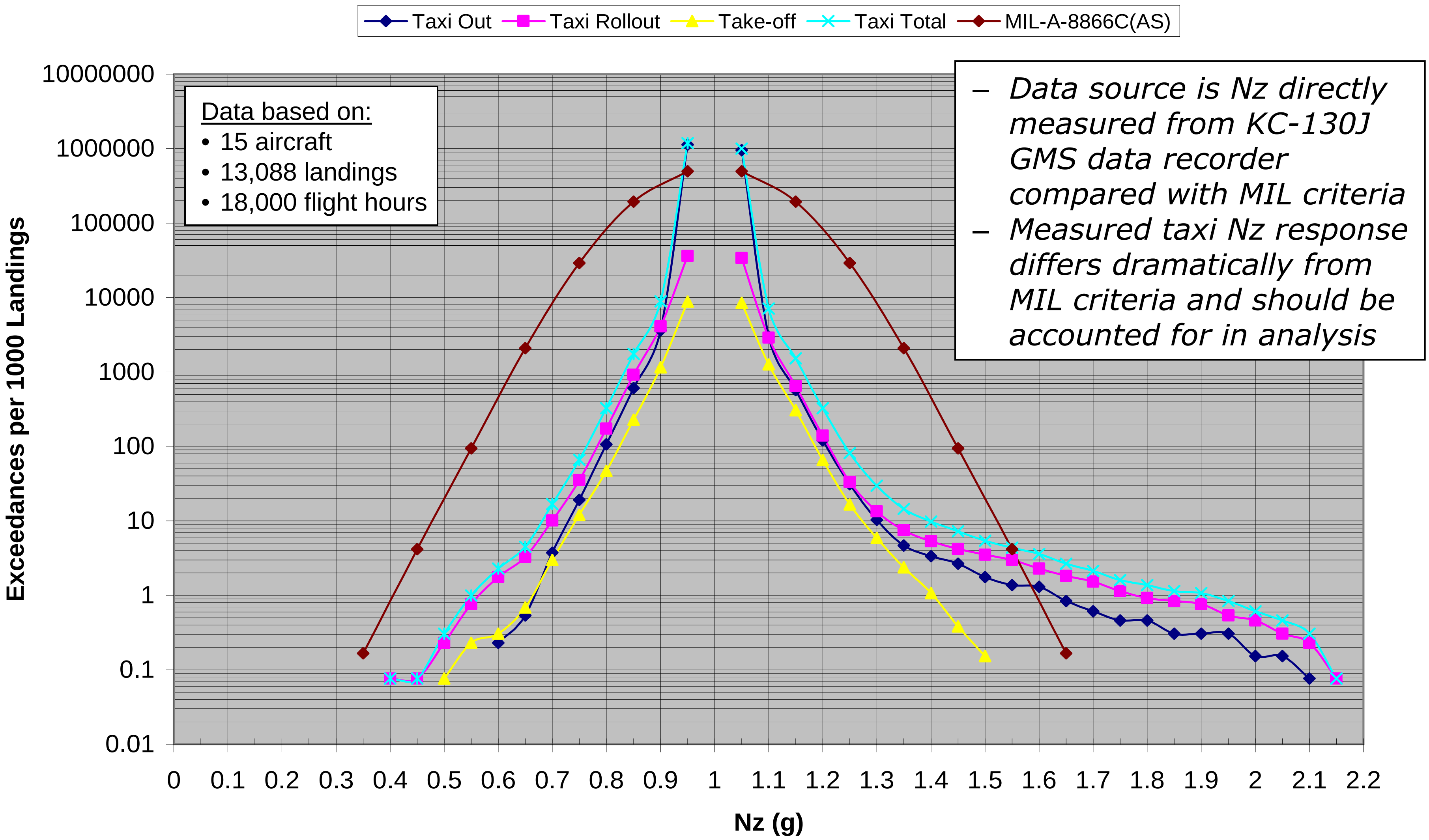
- 11 aircraft
- 130 flights
- 670 flight hours

C-130 Gust Nz Exceedances Comparison



- *Measured gust Nz response differs from MIL criteria and should be accounted for in analysis*

KC-130J Taxi Nz Exceedances

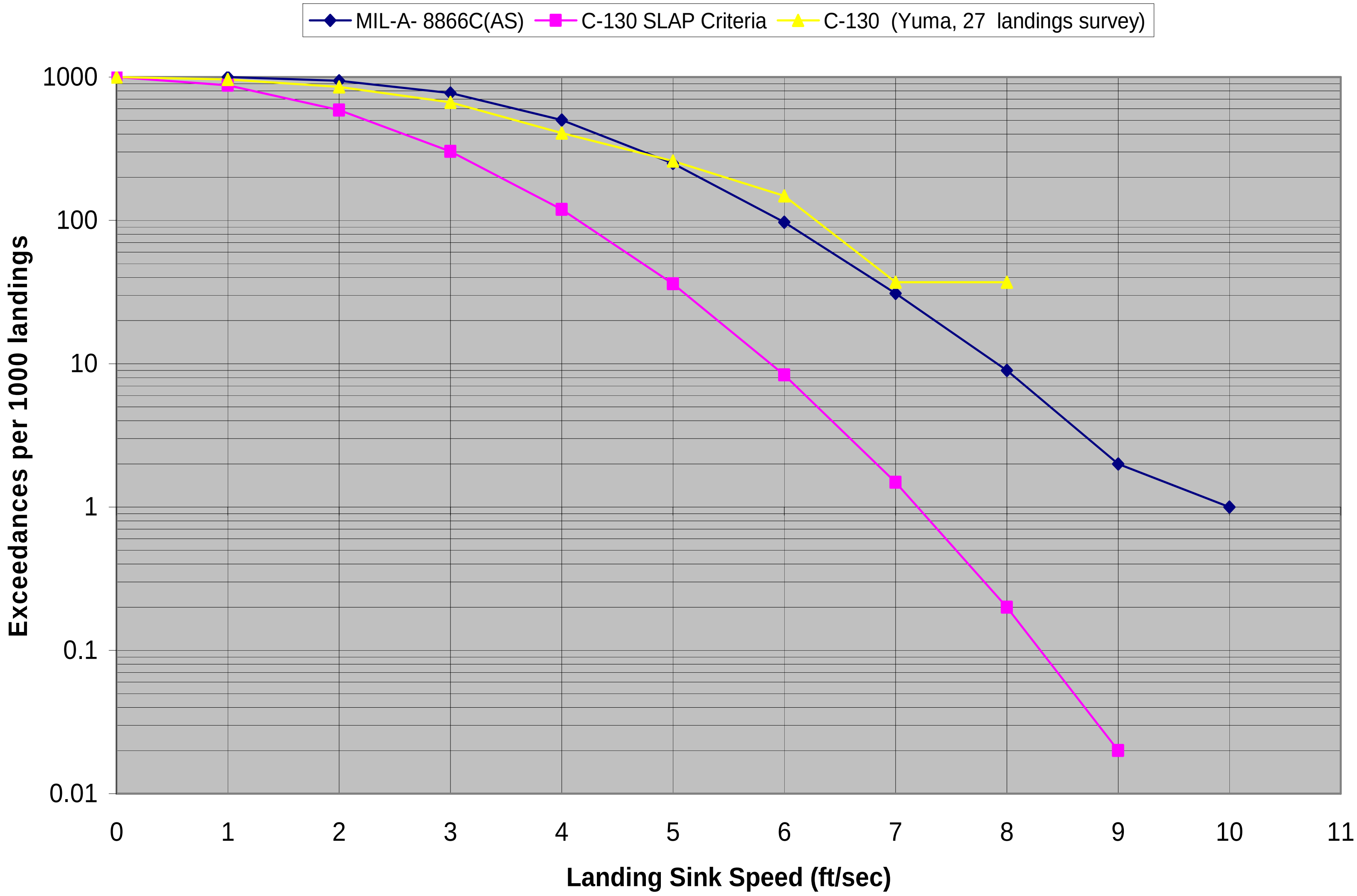


- *Data source is Nz directly measured from KC-130J GMS data recorder compared with MIL criteria*
- *Measured taxi Nz response differs dramatically from MIL criteria and should be accounted for in analysis*

Landing Impact Criteria

- NAVAIR has performed video landing surveys at Cherry Point, NC; Yuma, AZ; and Gila Bend, AZ
- The purpose is as follows:
  - Provide a non-interference method to:
    - Collect operational data for the calculation of landing loads
    - Identify trends in aircraft landing performance
  - Vertical velocity (sink speed), horizontal velocity, and attitude are determined at touchdown

C-130 Landing Sink Survey (Yuma, 27 landings)



Conclusions

- Gust cycle clustering is a real phenomena and should be considered when assembling a stress spectrum
  - The criticality of crack growth due to gust loads dictates the development of realistic gust cycle placement methods
- Measured KC-130F/R/T and C-130T flight data have been analyzed to develop maneuver, gust, VH, VGH, weight distributions, missions profiles, and mission maneuver sequence criteria
- Measured KC-130J data have been analyzed to develop criteria for taxi, sink speed, lateral maneuvers, and ground handling
- The severity of maneuver loading and landing sink has been increased relative to baseline criteria
- High-fidelity flight data recorders and individual aircraft tracking are critical for realistic aircraft life management

Questions?