Design Margin Analysis & Prediction

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R6σ Raytheon Six Sigma

Definition of "Margin"

- An amount allowed beyond what is needed (e.g. a small margin of safety)*

* The American Heritage Dictionary, Fourth Edit

So.....How can we quantify design margin such that the effects of expected unit-to-unit variation are comprehended?

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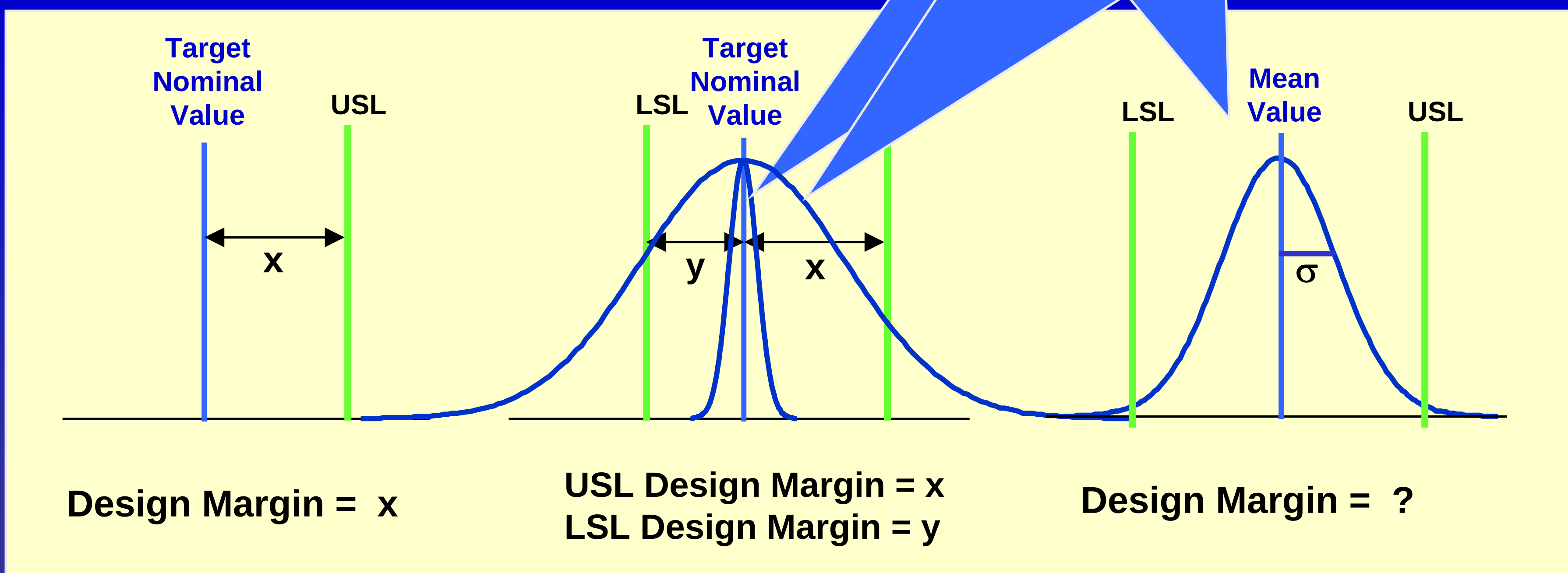
How do we apply "Mar

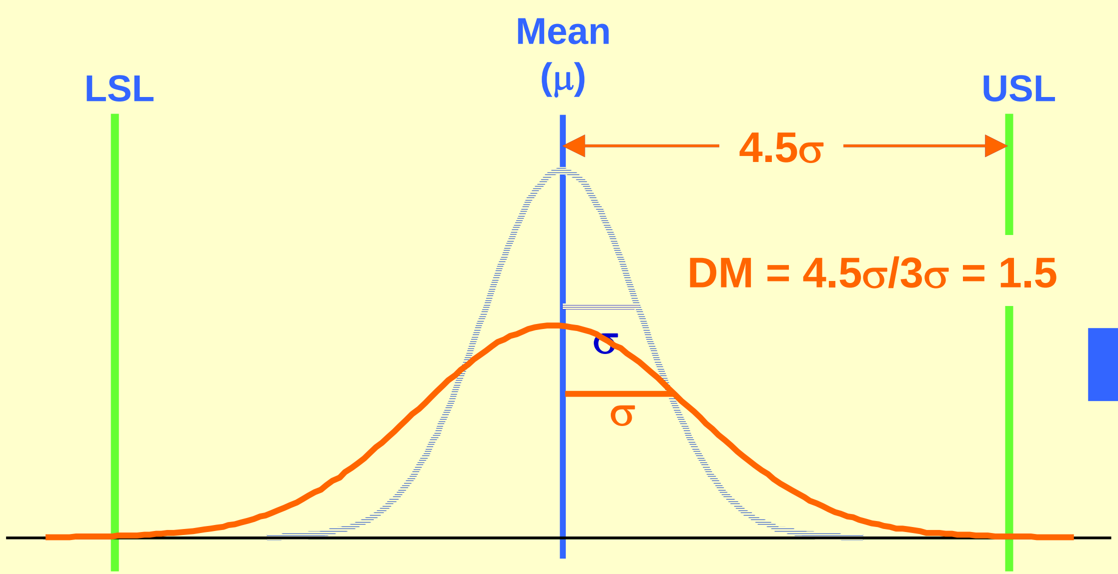


What is Design Margin in the DFSS Paradigm?

Design Margin can be quantified using the Mid-Term Capability Index (Cpk)

$$\text{Design Margin (DM)} = \frac{\text{MIN}(\text{USL} - \mu,\ \mu - \text{LSL})}{3\sigma} = \text{Cpk}$$

- Assumes that μ is between USL and LSL



Desired DM:

DM = 2.0

Min Acceptable DM:

DM = 1.5

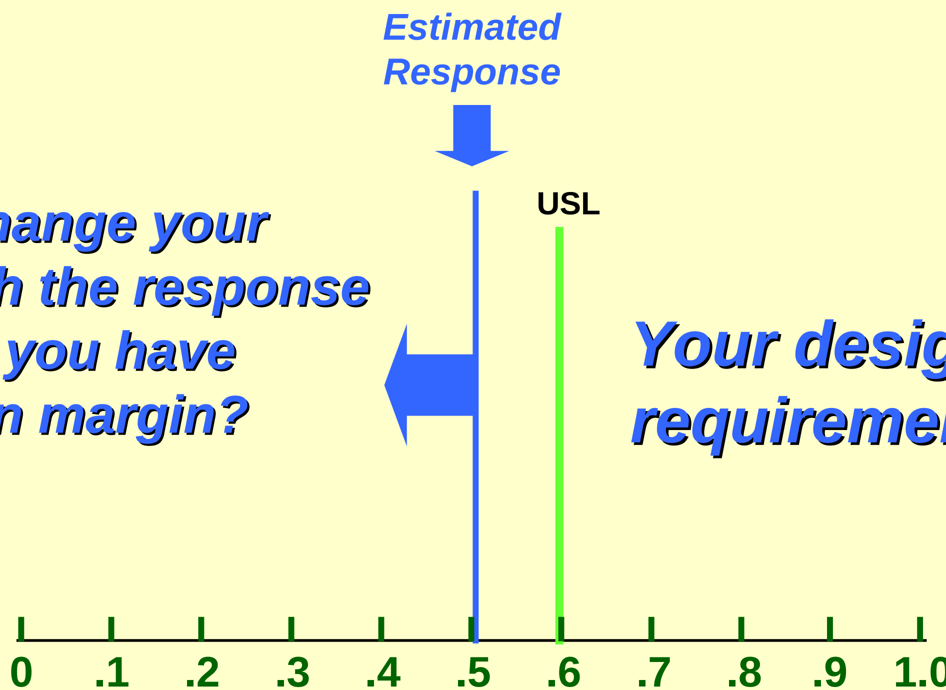
A Common Dilemma

You work hard to get your estimated response below the USL.......

- **Pushing the response estimate lower will**
  - **Take more design time (more design iterations)**
  - **Require higher-cost components & materials**
  - **Drive tighter manufacturing tolerances**

Negative impact on Program Schedule

Negative impact on Product Cost

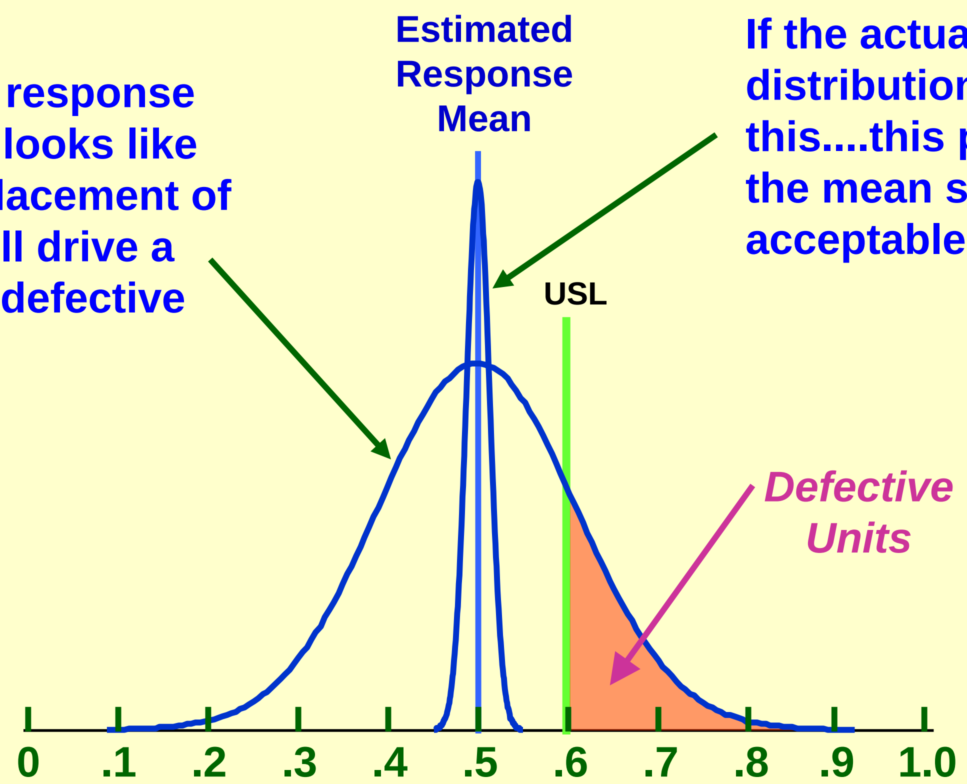


Should you change your design to push the response lower? ..... Do you have enough design margin?

Your design meets the requirement..... Right?

A Common Dilemma

If the actual response distribution looks like this....this placement of the mean will drive a high rate of defective units at test



If the actual response distribution looks like this....this placement of the mean should result in acceptable yields at test

Placement of the estimated response mean with respect to the specified limit is a "guessing game" if the expected response variation is not known

Design Margin Analysis Example

Military Radio Production

- Experiencing poor first pass yields at several ambient gain tests
- Design margin analysis recommended
  - Mean value of many test measurements are close to limit
- Poor design margin suspected to be the problem

Program Example – Military Radio Production

Design Margin Analysis

Approach

- Select tests to be analyzed
- Download historical test data to statistical data analysis tool
    - Agilent ADS (Advanced Design System)
- Analyze the Data
- Calculate Design Margin
- Verify correlation of DM analysis with probabilistic predictions

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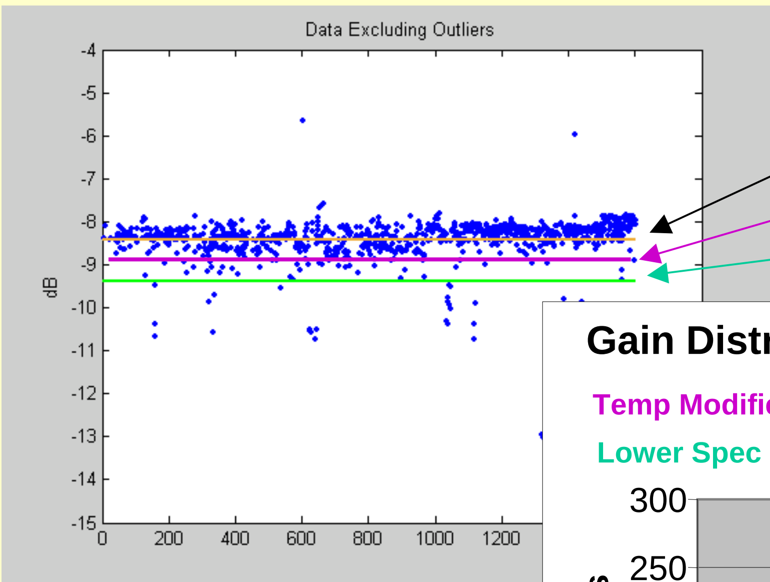
Program Example – Military Radio Production

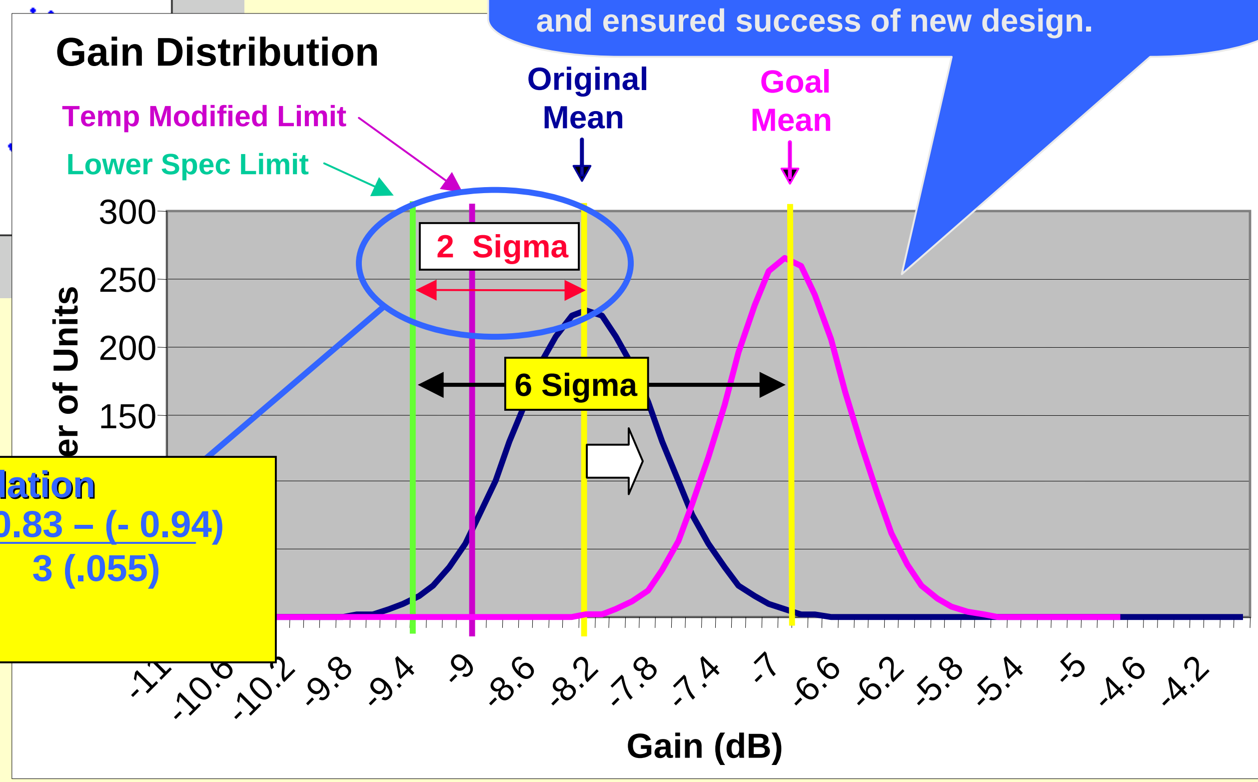
Design Margin Analysis



Ant SW: Gain Margin

03-07320 Test #60 : Gain J10 to P5

Probabilistic modeling of performance output verified that inadequate design margin could have been predicted, identified input variables driving most of response variation, and ensured success of new design.



Design Margin Calculation

$$DM = \frac{\mu - LSL}{3\sigma} = \frac{-0.83 - (-0.94)}{3\,(.055)}$$

$$DM = 0.67$$

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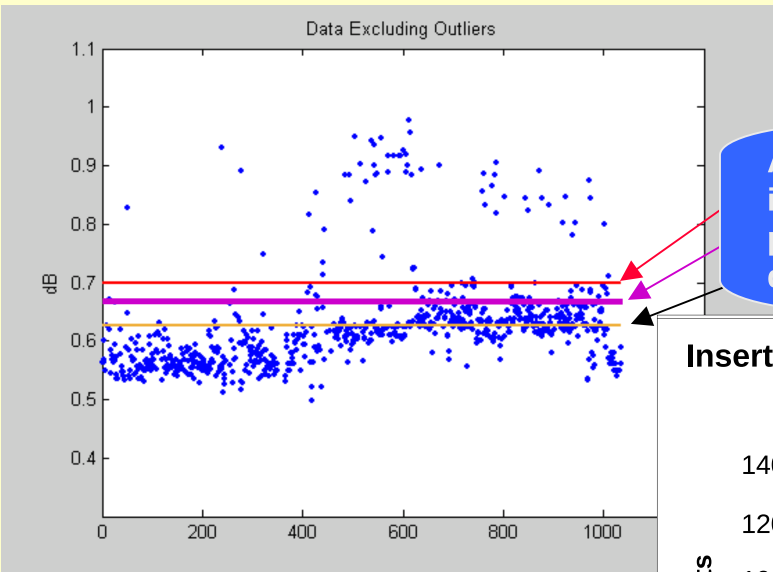
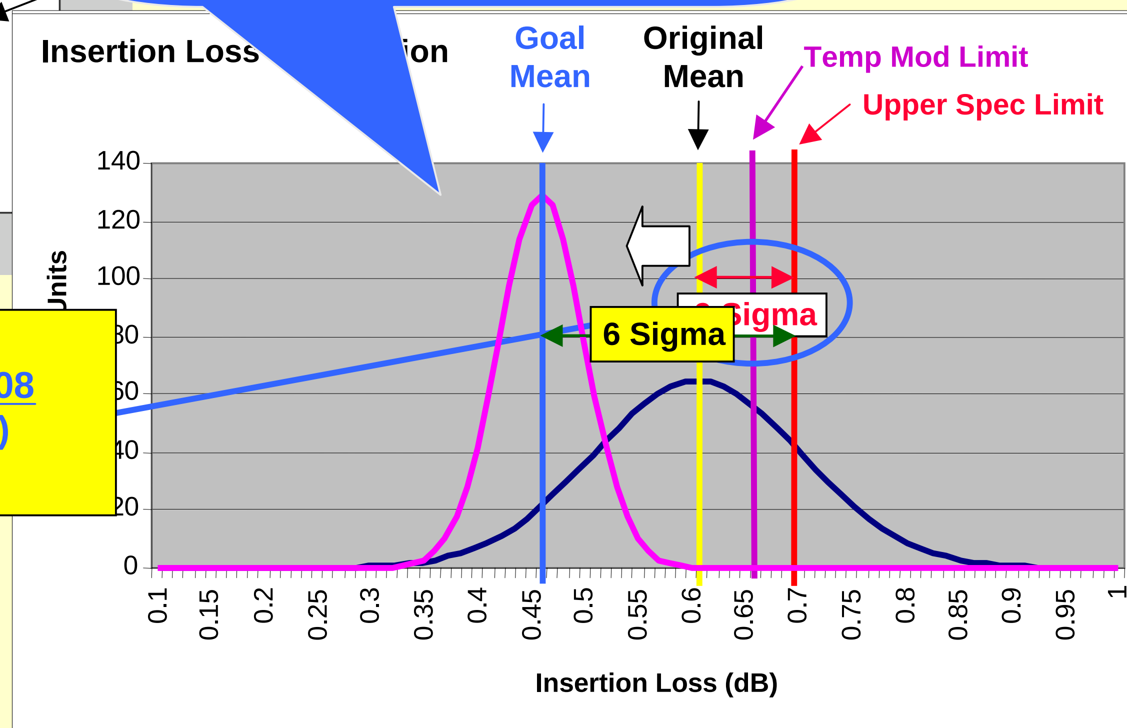
Program Example – Military Radio Production

Design Margin Analysis

Coupler T/R: Insertion Loss Margin 61-41680 Test #18 : RX Insertion



Again, probabilistic modeling showed that inadequate design margin could have been predicted and identified the components driving most of the response variation.



Design Margin Calculation

$$DM = \frac{USL - \mu}{3\sigma} = \frac{0.70 - .608}{3(.1022)}$$

$$DM = .30$$

Program Example – Military Radio Production

Design Margin Analysis

Results

- 19 of 37 analog circuits were identified with low design margin (Cpk<.72)
- Probabilistic modeling using design specifications verified that the low design margins could have been predicted
- Design margin analysis on production test data coupled with probabilistic modeling & simulation of the circuit designs provided clear visibility to which design variables could be adjusted to achieve desired margins

Design Margin Prediction Example

Lightweight Video Sight (LVS)

- LVS mounted on grenade machine gun
- Developed for military combat applications
- Implemented design improvements to include optical path

Design Margin Prediction Example

Objectives

- **Determine the Line of Sight (LOS) variation for the LVS sensors**
  - Image-Intensified Night Vision Camera (I^2TV)
  - Day Television Camera (DTV)
  - Laser Rangefinder (LRF)

Design Margin Prediction Example

Approach

- Identify error sources
- Create model (transfer function)
    - Establish relationships
    - Develop equations
- Run simulation
    - Monte Carlo
- Analyze results

Design Margin Prediction Example

Identify Error Sources

- Error sources identified which affect line of sight
  - Optics and housings
  - Detectors
- Fabrication and Assembly
- Tilts and De-centering
- Az and EL separated

Examples of LVS Boresight Error Sources						
Error #	**Assy**	**Part**	**Feature #1**	**Feature #2**	**Type**	**Direction**
1	I/F	SEL/Sight Mount	SEL mtg holes		assy	az
2	Sight mount	Plate	SEL mtg hole	Plate edges	fab	az
3	Sight mount	Plate	SEL mtg surf	Housing mtg surf. - flat	fab	el
4	Sight mount	Plate	SEL mtg surf	Housing mtg surf. - ang.	fab	az
5	Sight mount	Plate	Housing mtg surf. - ang.	Plate edge	fab	az
6	I/F	Sight mount/Sight	Sight mount (?)	Sight (?)	assy	
7	Housing	Housing	Sight mount- angular	Plate mtg flange	fab	az
8	Housing	Housing	Sight mount- flat	Plate mtg flange	fab	el
9	Housing	Housing	Sight mount- flat	Plate mtg pins	fab	
10	Housing	Housing	Sight mount- angular	Plate mtg pins	fab	

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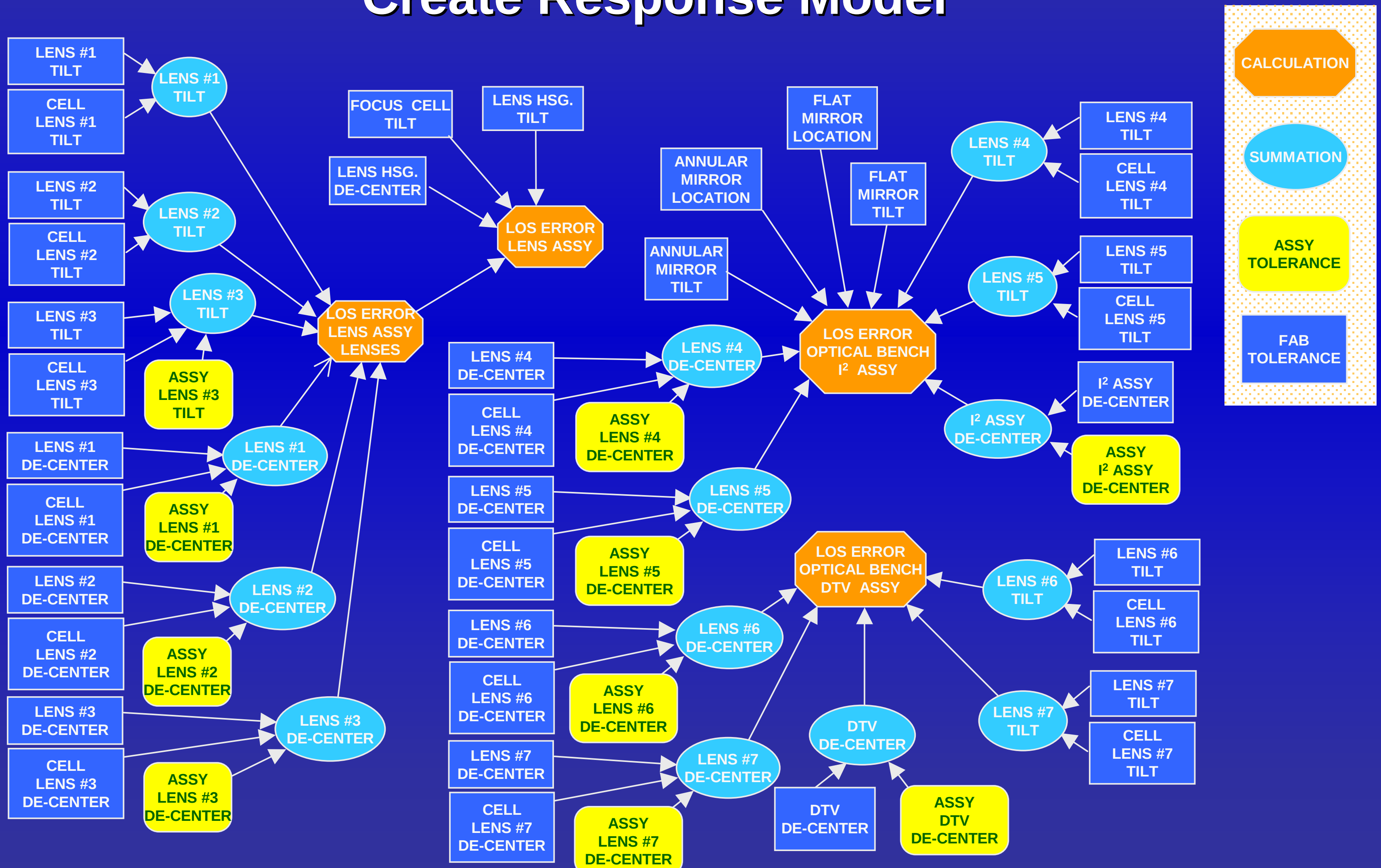
Design Margin Prediction Example

Create Response Model



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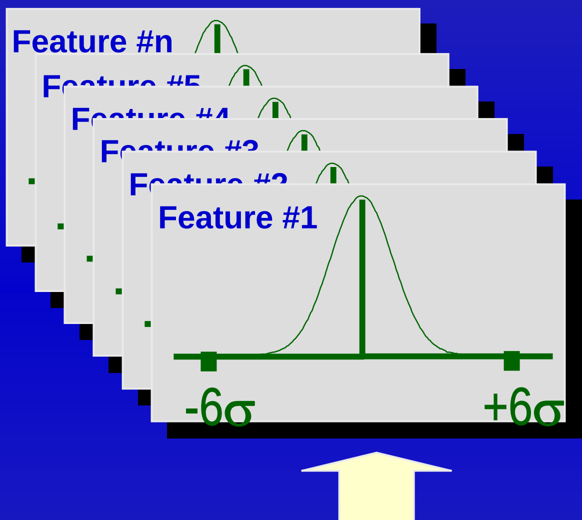
Design Margin Prediction Example

Create Response Model

Input Variables



Six Sigma Tolerances for Some of the Machined Features Involved

- FAB TOLERANCES, LENS ASSY
  - TILT, LENS SEATS - ⊕ .00076 (N/C Lathe)
  - DE-CENTER, LENS BORES - ⊕ .00076 (N/C Lathe)
- FAB TOLERANCES, OPTICAL BENCH ASSY
  - TILT, LENS SEATS - // .003, ⊥ .0036 (N/C Mill)
  - DE-CENTER, LENS BORES - ⊕ .00174 (N/C Mill)
  - TILT, MIRRORS - ⌓ .006 (N/C Mill)
  - LOCATION, MIRRORS - ⌓ .006 (N/C Mill)

- Six Sigma tolerances used for all fabrication errors
- Obtained tolerances from Raytheon Internal Process Capability Database
  - 6σ tolerances derived from actual measured part data
  - Methods and Tooling group consulted for distribution fit

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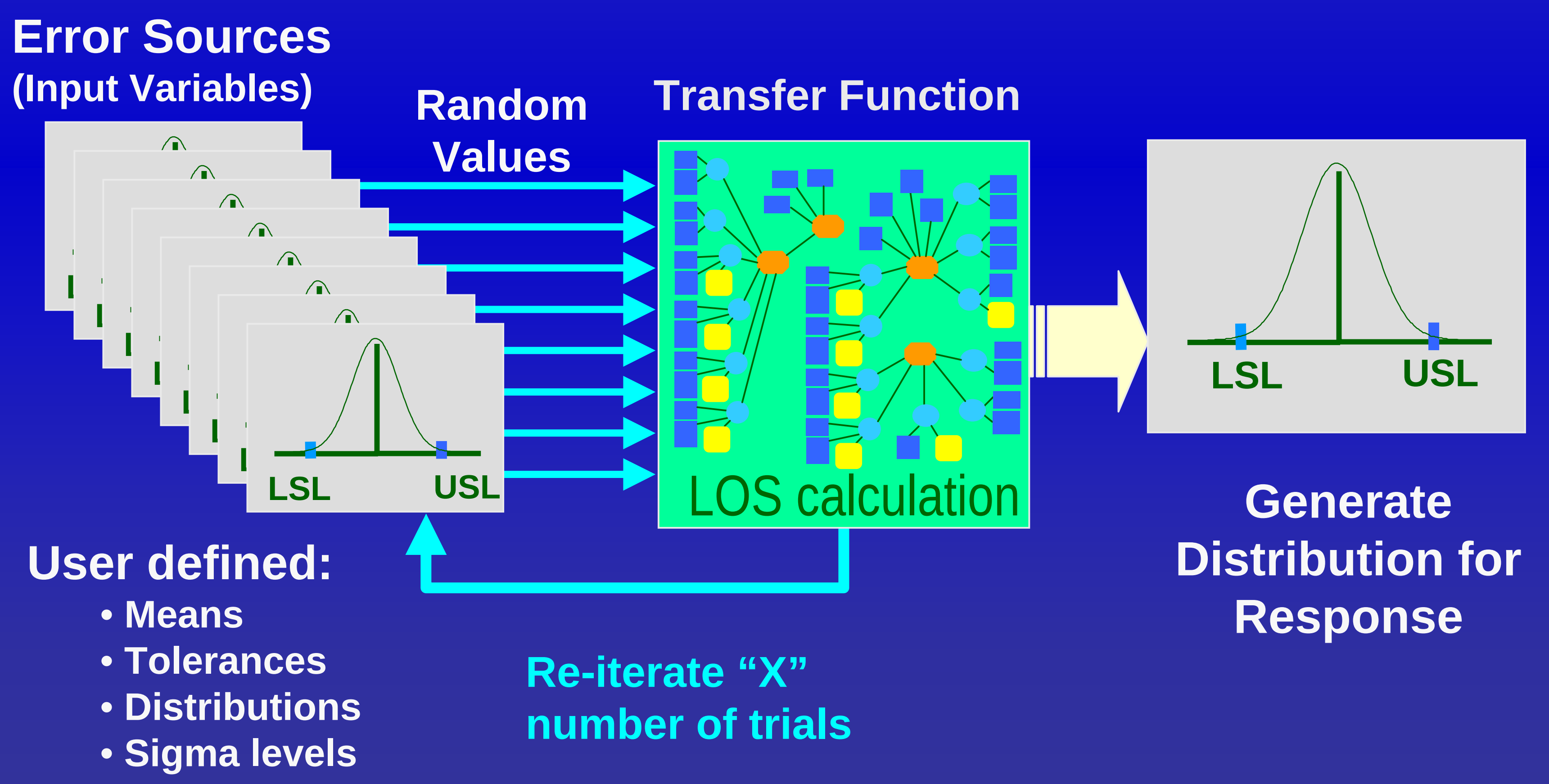
Design Margin Prediction Example

Create the Response Model

Using Decisioneering's Crystal Ball ® – Monte Carlo Simulation



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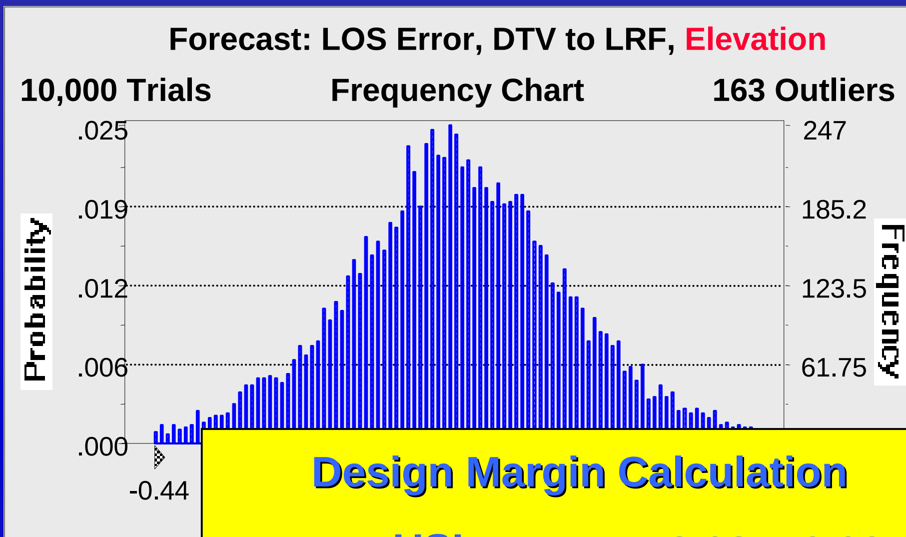
Design Margin Prediction Example

Run the Simulation and Analyze the Results



Forecast: LOS Error, DTV to LRF, Elevation

Statistic	Value	
Trials	10,000	
Mean	0.00	
Median	-0.00	
Mode	---	
Standard Deviation	0.17	(6σ = 1.02 mrad)
Variance	0.03	
Skewness	-0.03	
urtosis	3.61	
ean Std. Error		

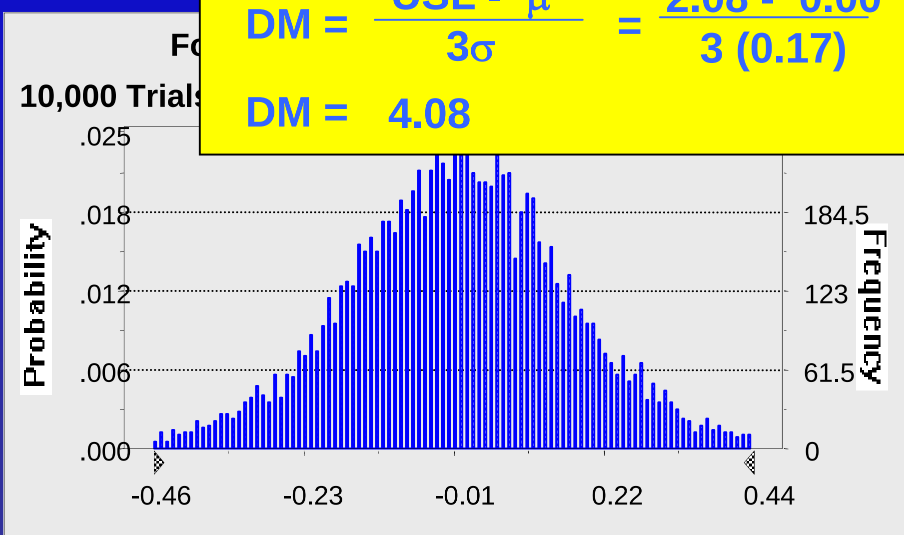
Using 6 Sigma Manufacturing Tolerances!

Design Margin Calculation

$$DM = \frac{USL - \mu}{3\sigma} = \frac{2.08 - 0.00}{3\ (0.17)}$$

$$DM = 4.08$$

Spec = 2.08 mrad Max



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Mean	0.00	
Median	0.00	
Mode	---	
Standard Deviation	0.17	(6σ = 1.02 mrad)
Variance	0.03	
Skewness	-0.02	
Kurtosis	3.51	
Mean Std. Error		0.00

Design Margin Prediction Example

Results

- System level mechanical boresight alignment not required (~$300K Avoidance).
- Optical alignment of the I^2 and DTV camera components will be required.
- Software alignment of the aiming reticle to the LRF transmitter beam at the system level will be required.

Analysis Tools

Data Analysis

- Statistical Analysis and Acceptance Test Software (STAATS)
- Advanced Design System – Agilent Technologies
- Minitab
- Microsoft Excel

Probabilistic Performance Modeling

- Raytheon Analysis of Variability Engine (RAVE)
- Crystal Ball - Decisioneering
- Advanced Design System (ADS) – Agilent Technologies
- Statistical Design Institute Tools

Conclusions

- Design Margin is a familiar concept in engineering and manufacturing environments, but has been under-utilized because classical methods of quantifying design margin in product performance do not comprehend unit-to-unit variability
  - Classical design methods recognized the existence of unit-to-unit variability, but in the absence of available/efficient methods and tools to model variability, adopted the use of safety factors and worst-case design (infinite margin)
    - More design iterations
    - Higher-cost materials/components
    - Tighter tolerances
- Using Cpk as a design margin model provides way to:
  - Communicate how much variability is occurring or tolerable
  - Communicate how much risk is present or tolerable