

# Interactive Tolerance Allocation Using HFSS and Optimetrics with Excel

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# Why Analyze Tolerances?

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- **Select the best design from alternatives**
- **Improve yield**
- **Reduce cost with alternate fabrication techniques**
- **Improve quality**
- **Reduce risk**
- **Distinguish your products from your competition**
- **Why not?**
  - ▶ **Tolerance analysis can be tedious and time-consuming**
  
- **Examples of tolerance analysis:**
  - ▶ **Reduce cost of machined radiators in a phased array**
    - Which tolerances can be relaxed to obtain 2x cost reduction?
  - ▶ **Select radome attach methods for radiators in a phased array**
    - Rigid bond, elastomeric bond, screws, combinations
    - Surface mount, spacers
  - ▶ **Improve performance of a laboratory coax-waveguide transition**
    - Selected a simpler design having reduced dependence on tolerances

# Design of Experiments (DOE) Is One Approach To Tolerance Analysis

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- **Why consider DOE?**
  - ▶ Monte Carlo and other methods can be too slow for large 3D EM problems
  - ▶ DOE has been extensively used in industrial processes, from which data may be even more difficult or expensive to obtain than HFSS
  - ▶ DOE is quite powerful and efficient
  - ▶ Also applicable to optimization
- **DOE systematically identifies the significance of process variables, how they interact, and what changes would improve the process**
- **After a Raytheon (Hughes) team spent nearly two years improving a set of processes with DOE and related tools, it became clear that 90% of DOE's utility was contained in about 10% of its complexity**
  - ▶ Engineering judgment can substitute for some of the formal process
  - ▶ I'll address this 10% and hopefully save you some time

- DOE is a method of collecting and analyzing data on processes that:
  - ▶ Identifies the significant independent variables  $x_i$  and dependent variables  $z_k$
  - ▶ Determines coefficients in a functional form for  $z_k(x_i)$ 
    - JMP [3] (typical): 
$$z_k = \sum_{i \neq j} a_i x_i + b_i x_i^2 + c_{ij} x_i x_j$$
    - Other software may allow more complicated interactions and functional forms
  - ▶ Typically the  $x_i$  are real (e.g. deviations in dimensions, dielectric constants)
  - ▶ Typically the  $z_k$  are complex, e.g. reflection coefficient in real and imaginary form
- DOE obtains maximum information from minimum data
  - ▶ There is an extensive theory on different “Experimental Designs” [1], [2]
  - ▶ Commercial software can be a big help in constructing them [3]
  - ▶ User-written DOE software can be useful for special functional forms
- **Key result** from experience: A screening-level DOE is usually necessary and may be sufficient
  - ▶ One can perform this easily with HFSS / Optimetrics and Excel or other commonly-available software

# Background: DOE Minimizes Computation

	x1	x2	x3	x4
Case	a	b	c	d
1	-1	-1	-1	-1
2	+1	-1	-1	-1
3	-1	+1	-1	-1
4	+1	+1	-1	-1
5	-1	-1	+1	-1
6	+1	-1	+1	-1
7	-1	+1	+1	-1
8	+1	+1	+1	-1
9	-1	-1	-1	+1
10	+1	-1	-1	+1
11	-1	+1	-1	+1
12	+1	+1	-1	+1
13	-1	-1	+1	+1
14	+1	-1	+1	+1
15	-1	+1	+1	+1
16	+1	+1	+1	+1

Binary, non-DOE design for four  $x_i$  (+1 means  $x_i$  at max, -1 means  $x_i$  at min)

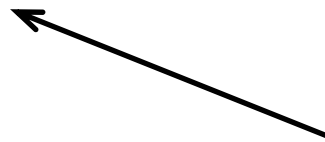
## Fractional Factorial DOE (Resolution IV)

		x1	x2	x3	x4											
Case	I	a	b	c	d	ab	ac	ad	bc	bd	cd	abc	acd	abd	bcd	abcd
1	+1	-1	-1	-1	-1	+1	+1	+1	+1	+1	+1	-1	-1	-1	-1	+1
2	+1	+1	-1	-1	+1	-1	-1	+1	+1	-1	-1	+1	-1	-1	+1	+1
3	+1	-1	+1	-1	+1	-1	+1	-1	-1	+1	-1	+1	-1	+1	-1	+1
4	+1	+1	+1	-1	-1	+1	-1	-1	-1	-1	+1	-1	-1	+1	+1	+1
5	+1	-1	-1	+1	+1	+1	-1	-1	-1	-1	+1	+1	+1	-1	-1	+1
6	+1	+1	-1	+1	-1	-1	+1	-1	-1	+1	-1	-1	+1	-1	+1	+1
7	+1	-1	+1	+1	-1	-1	-1	+1	+1	-1	-1	-1	+1	+1	-1	+1
8	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1

- For **four**  $x_i$ , a two-level binary (non-DOE) design would require  $2^N = 16$  cases
- Interactions between  $x_i$  and  $x_j$  would not be clearly identified
- In contrast, a two-level Fractional Factorial DOE for four  $x_i$  would need **8** cases
  - ▶ Interactions would be identified with some uncertainty
- For **six**  $x_i$ , **8** cases would still suffice, but with increased uncertainty (confounding)
  - ▶ Engineering judgment or additional cases might be needed to resolve the uncertainty
  - ▶ Still, eight cases is better than  $2^N = 64$  needed for binary

# A Screening-Level DOE Is the First Step

	x1	x2	x3	x4
Case	a	b	c	d
1	0	0	0	0
2	+1	0	0	0
3	0	+1	0	0
4	0	0	+1	0
5	0	0	0	+1



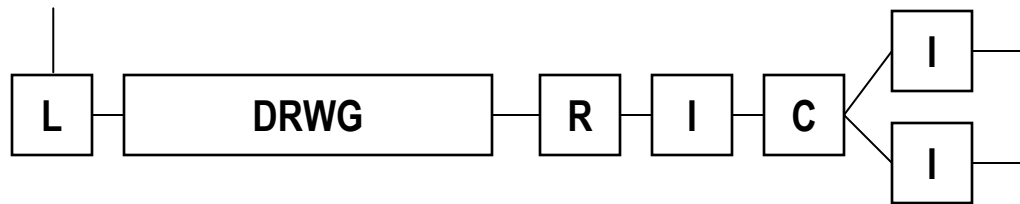
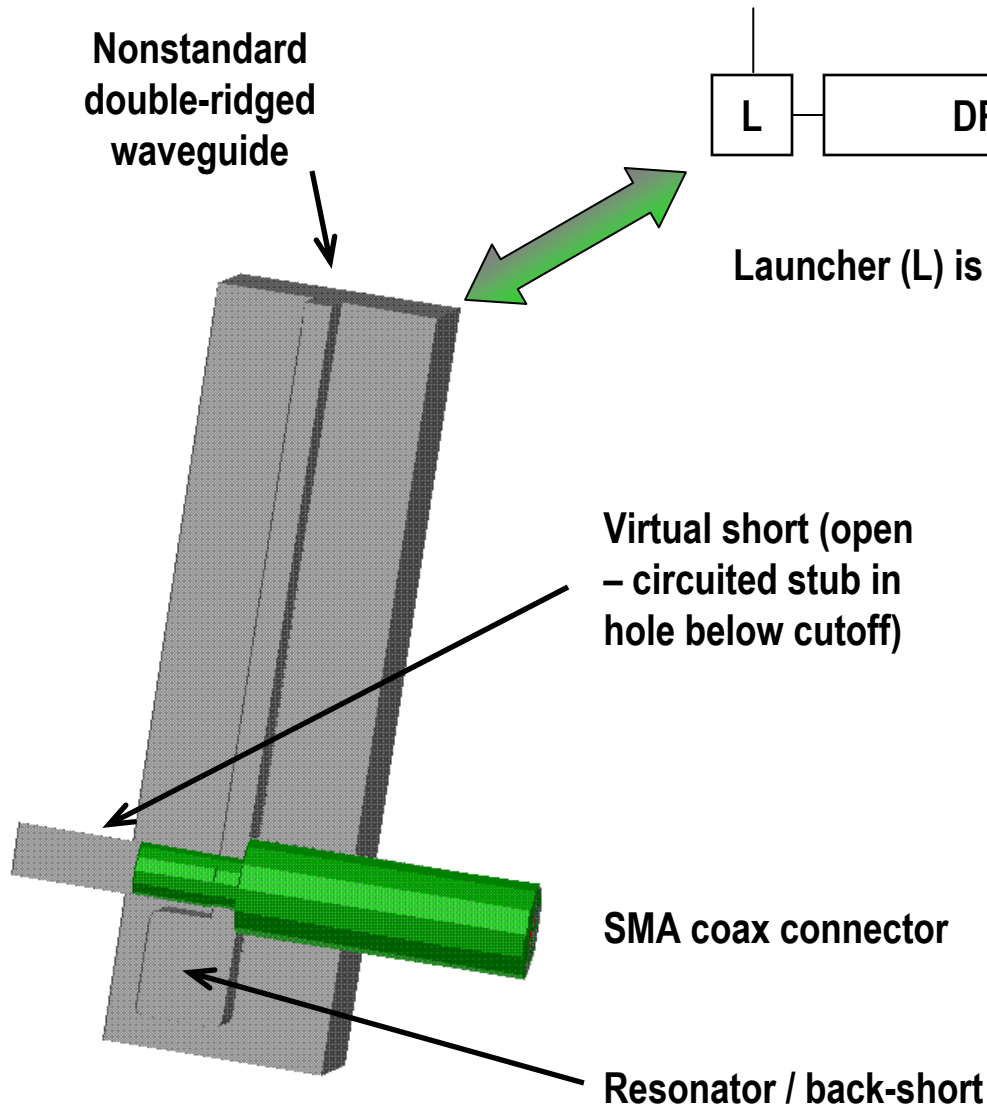
- **Problem!** – The DOE setup for more than seven  $x_i$  becomes extremely cumbersome
- First, eliminate less-critical variables by constructing and solving a “Screening-Level” DOE
- Equivalent to a total differential (difference)

$$\Delta z_k = \sum \frac{\partial z_k}{\partial x_i} \bullet \Delta x_i$$

Setup	ridgex1	coaxx	guide1s	ridgey1	guide1d	troughz1
setup1	-0.132	0	0.264	-0.023	0.046	-0.307
setup2	-0.137	0	0.264	-0.023	0.046	-0.307
setup3	-0.132	-0.01	0.264	-0.023	0.046	-0.307
setup4	-0.132	0	0.254	-0.023	0.046	-0.307
setup5	-0.132	0	0.264	-0.026	0.046	-0.307
setup6	-0.132	0	0.264	-0.023	0.05	-0.307
setup7	-0.132	0	0.264	-0.023	0.046	-0.317
setup8	-0.132	0	0.264	-0.023	0.046	-0.307
setup9	-0.132	0	0.264	-0.023	0.046	-0.307
setup10	-0.132	0	0.264	-0.023	0.046	-0.307
setup11	-0.132	0	0.264	-0.023	0.046	-0.307
setup12	-0.132	0	0.264	-0.023	0.046	-0.307
setup13	-0.132	0	0.264	-0.023	0.046	-0.307
setup14	-0.132	0	0.264	-0.023	0.046	-0.307
setup15	-0.132	0	0.264	-0.023	0.046	-0.307
setup16	-0.132	0	0.264	-0.023	0.046	-0.307
setup17	-0.132	0	0.264	-0.023	0.046	-0.307
setup18	-0.132	0	0.264	-0.023	0.046	-0.307
setup19	-0.132	0	0.264	-0.023	0.046	-0.307
setup20	-0.132	0	0.264	-0.023	0.046	-0.307

- This is straightforward with a geometry macro and Optimetrics (Optimetrics 2 / HFSS 8 shown)
- Proceed to a more-complex DOE if necessary

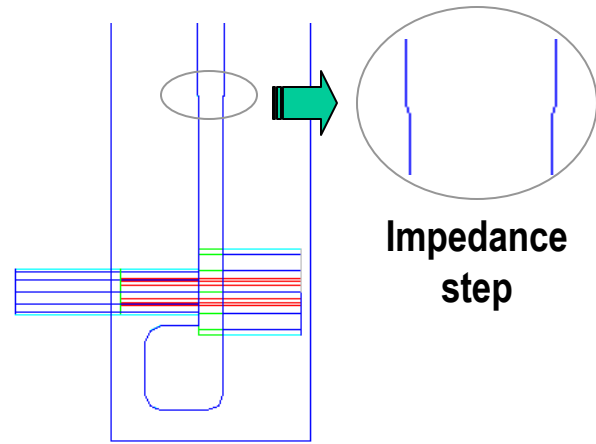
### Example: Coax to Waveguide Launcher



Launcher (L) is part of radiator-circulator bench test setup

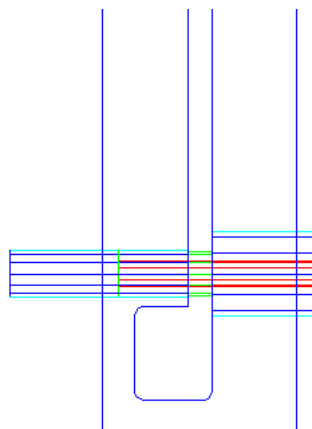
- Goal: launcher should be much better than other components
  - ▶ 25 dB or better return loss over 6-13 GHz bandwidth
- A similar launcher was designed for 35-40 dB but achieved perhaps 20 dB
- Excessive sensitivity to tolerances was suspected
  - ▶ Gap between ridges
  - ▶ Air gap around dielectric and dielectric constant

## A One-Section Transformer Improved Launcher Performance



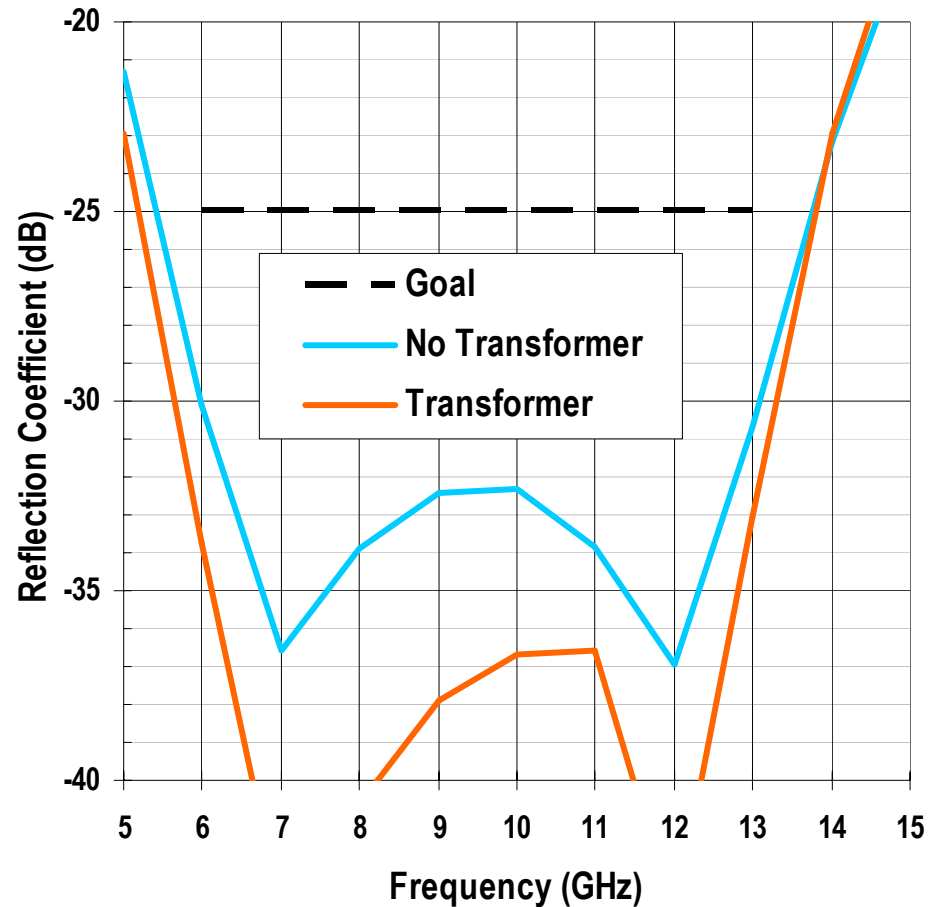
Impedance step

One-section Transformer



No Transformer

- But the 0.0015" step in ridge is difficult to fabricate
- Cutter radius makes it a ramp, not a step

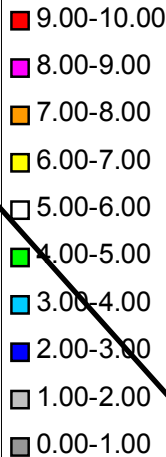


# Initial Tolerance Allocation Used "Standard" Tolerances ( $\pm 0.002$ ")

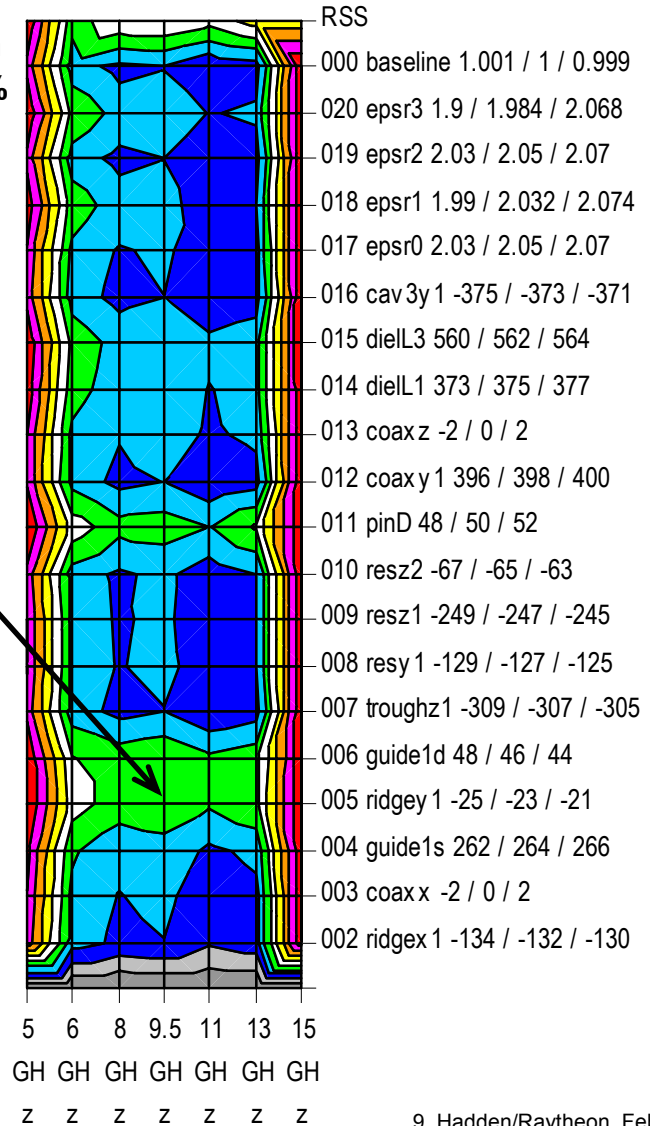
- Seven  $z_k$ , nineteen  $x_i$
- 20 (N+1) Optimetrics rows
- Ridge parameters are key

Launcher Tolerances	fab (init)	fab (init)	fab (init)	fab (final)	fab (final)	fab (final)	
parameter	Low	Nom.	High	Low	Nom.	High	units
parameters	Low	Nom.	High	Low	Nom.	High	units
ridgex1	-133	-132	-131	-134	-132	-130	mils
coaxx	-2	0	2	-2	0	2	mils
guide1s	262	264	266	262	264	266	mils
ridgey1	-24	-23	-22	-25	-23	-21	mils
guide1d	47	46	45	48	46	44	mils
troughz1	-312	-307	-302	-309	-307	-305	mils
resy1	-128	-127	-126	-129	-127	-125	mils
resz1	-248	-247	-246	-249	-247	-245	mils
resz2	-66	-65	-64	-67	-65	-63	mils
pinD	49	50	51	48	50	52	mils
coaxy1	396	398	400	396	398	400	mils

### Max. Reflection Coefficient in %



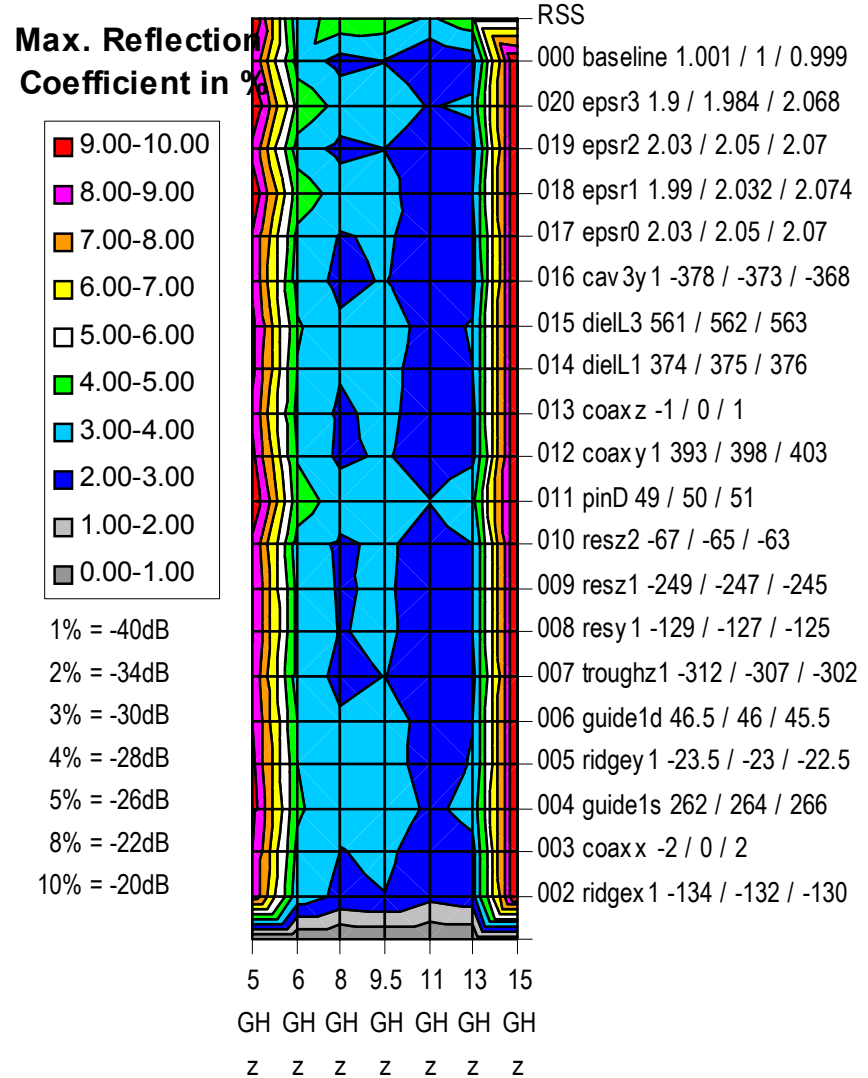
1% = -40dB  
 2% = -34dB  
 3% = -30dB  
 4% = -28dB  
 5% = -26dB  
 8% = -22dB  
 10% = -20dB



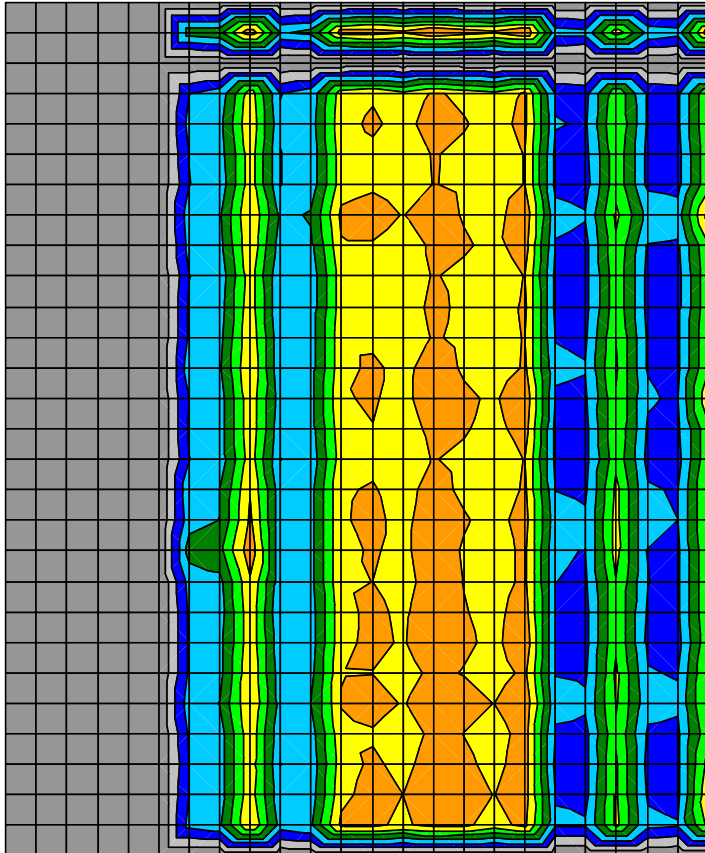
# Final Transformerless Design Emphasized Key Parameters

- Changing tolerance on ridge height to  $\pm 0.0005''$  improved RSS and allocation
- Others were relaxed for cost

Launcher Tolerances	fab (init)	fab (init)	fab (init)	fab (final)	fab (final)	fab (final)	
parameter	Low	Nom.	High	Low	Nom.	High	units
parameters	Low	Nom.	High	Low	Nom.	High	units
ridgex1	-133	-132	-131	-134	-132	-130	mils
coaxx	-2	0	2	-2	0	2	mils
guide1s	262	264	266	262	264	266	mils
ridgey1	-24	-23	-22	-23.5	-23	-22.5	mils
guide1d	47	46	45	46.5	46	45.5	mils
troughz1	-312	-307	-302	-312	-307	-302	mils
resy1	-128	-127	-126	-129	-127	-125	mils
rez1	-248	-247	-246	-249	-247	-245	mils
rez2	-66	-65	-64	-67	-65	-63	mils
pinD	49	50	51	49	50	51	mils
coaxy1	396	398	400	393	398	403	mils

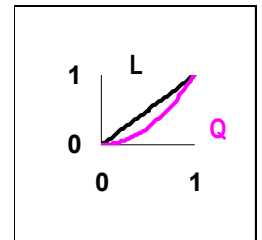


# Advantages of This Approach to Tolerance Analysis

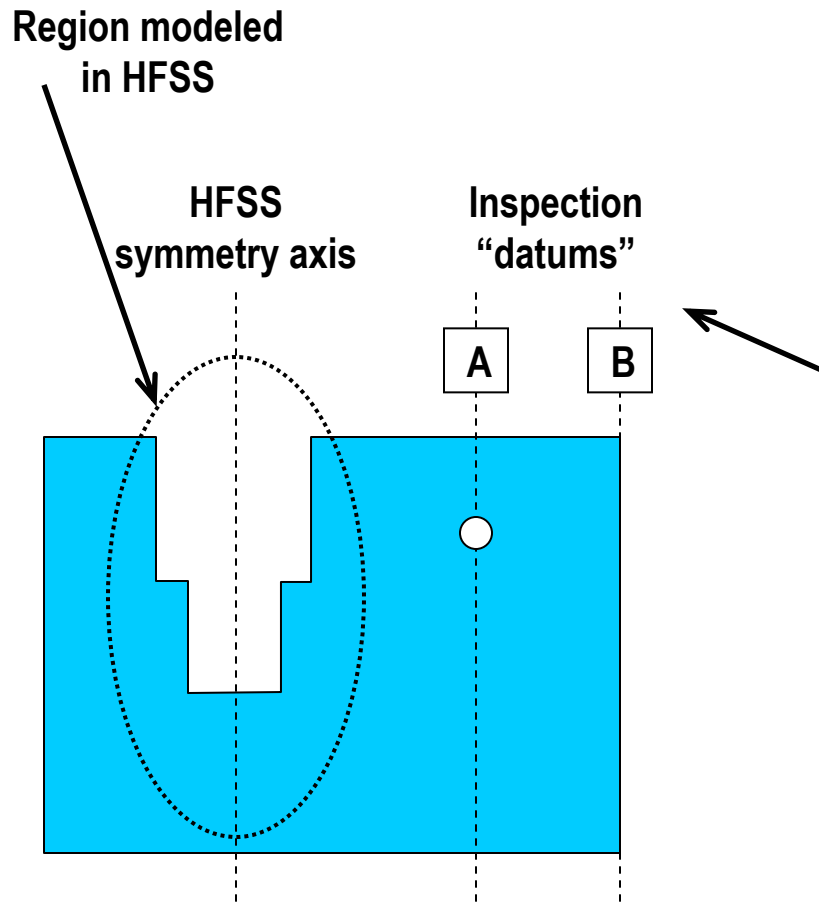


Screening-level DOE for  
scanned phased array radiator

- Presents all the data on one plot
- Can present RSS, min, max, etc.
- Immediately identifies tolerance drivers
- Real-time, interactive revision shortens design cycle – “decide now”
- Allows one to pre-compute HFSS data before tolerances are known precisely – enables ME & EE concurrency
- Can mask computational “noise”
  - ▶ If  $\Delta x_i = \pm 0.001$  expected, compute  $\pm 0.005$  and interpolate
- Linear interpolation typically bounds the variation from above vs. quadratic
- Can import legacy data and data from other software or measurements



# Setup Suggestions



- Perform a simple tolerance analysis as early as possible, usually before building and testing a prototype
- Set initial tolerances from previous experience, simple circuit models or engineering judgment
- Don't forget assembly tolerances
- It is advantageous to select the coordinate system and variable definitions to be similar to the part drawing or database
  - ▶ Avoid rotation and translation
  - ▶ Use same "datum" (edge, center of alignment hole, center of slot, etc.)
- When comparing to requirement, include computational uncertainty in addition to geometric and material variations

# Parallelization for Rapid Solution Is Simply Accomplished

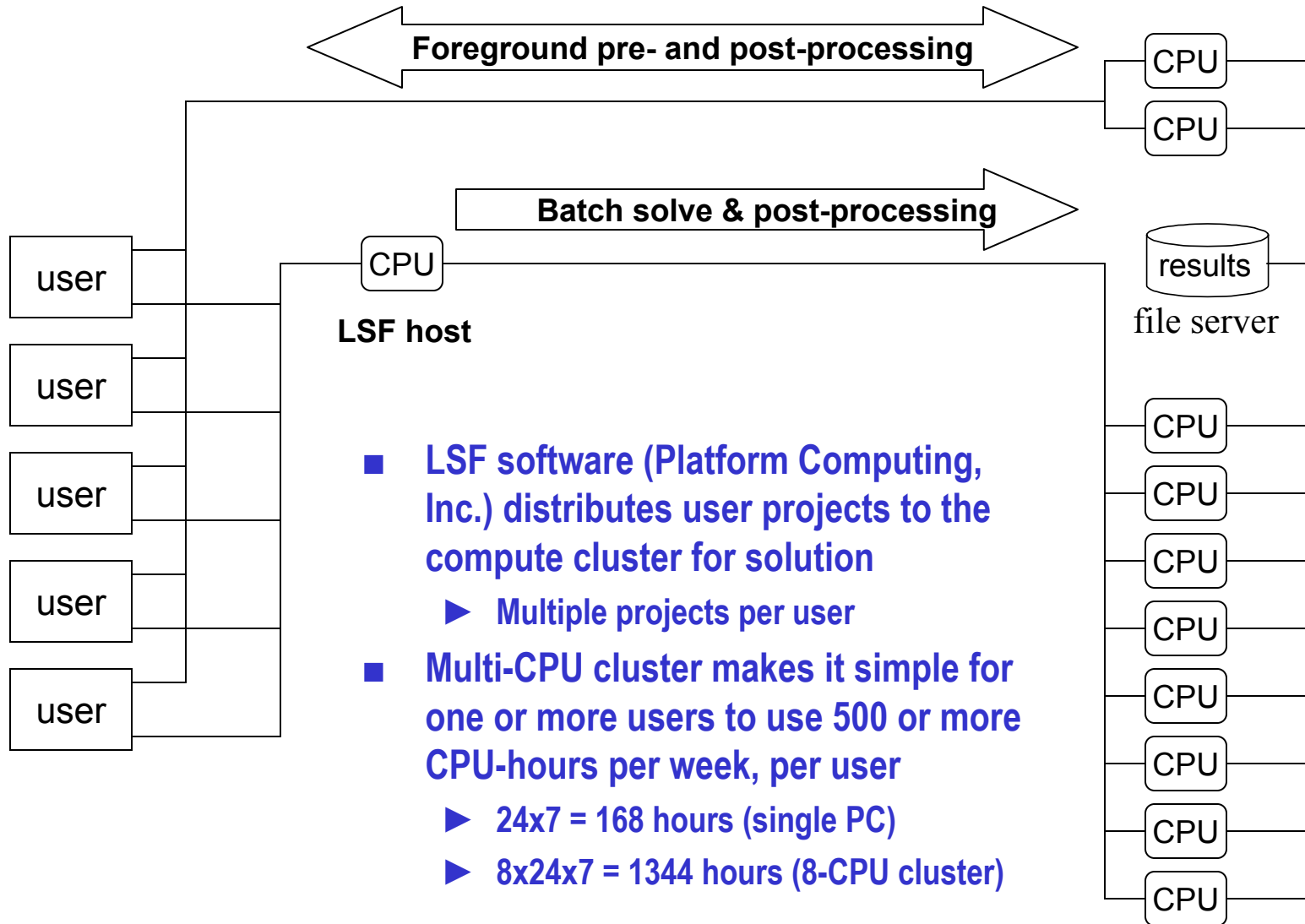
- Create master OM project launch.pjt (e.g., 40 rows with varying dimensions)
- Make 8 copies launch[1-8].pjt, deleting all but rows 1-5 in launch1.pjt, 6-10 in launch2.pjt, etc.
- Submit 8 projects for solution in parallel
- After solution, concatenate the \*.ptd files and import into Excel or DOE application
  - ▶ `"touch results ; cat /home/inbox/launch?.pjt/*.ptd >> results"`

Setup	ridgex1	coaxx	guide1s	ridgex1	guide1d	troughz1
setup1	-0.132	0	0.264	-0.023	0.046	-0.307
setup2	-0.137	0	0.264	-0.023	0.046	-0.307
setup3	-0.132	-0.01	0.264	-0.023	0.046	-0.307
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setup14	-0.132	0	0.264	-0.023	0.046	-0.307
setup15	-0.132	0	0.264	-0.023	0.046	-0.307
setup16	-0.132	0	0.264	-0.023	0.046	-0.307
setup17	-0.132	0	0.264	-0.023	0.046	-0.307
setup18	-0.132	0	0.264	-0.023	0.046	-0.307
setup19	-0.132	0	0.264	-0.023	0.046	-0.307
setup20	-0.132	0	0.264	-0.023	0.046	-0.307

launch1.pjt  
 launch2.pjt  
 launch3.pjt

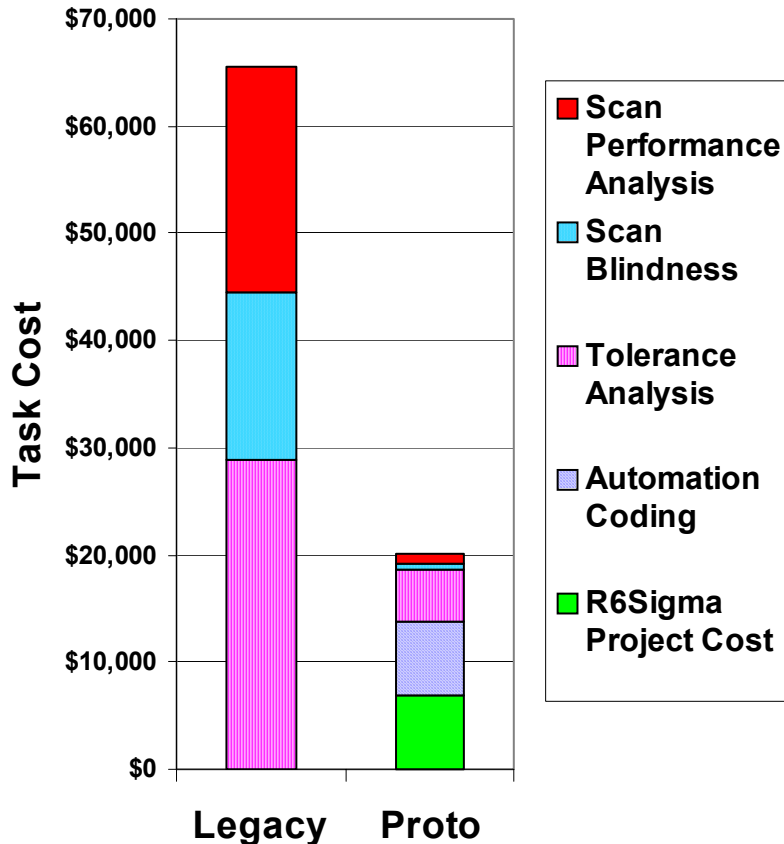
# UNIX Compute Cluster Fed By LSF

## Enables Quick Turnaround, High Throughput



- LSF software (Platform Computing, Inc.) distributes user projects to the compute cluster for solution
  - ▶ Multiple projects per user
- Multi-CPU cluster makes it simple for one or more users to use 500 or more CPU-hours per week, per user
  - ▶  $24 \times 7 = 168$  hours (single PC)
  - ▶  $8 \times 24 \times 7 = 1344$  hours (8-CPU cluster)

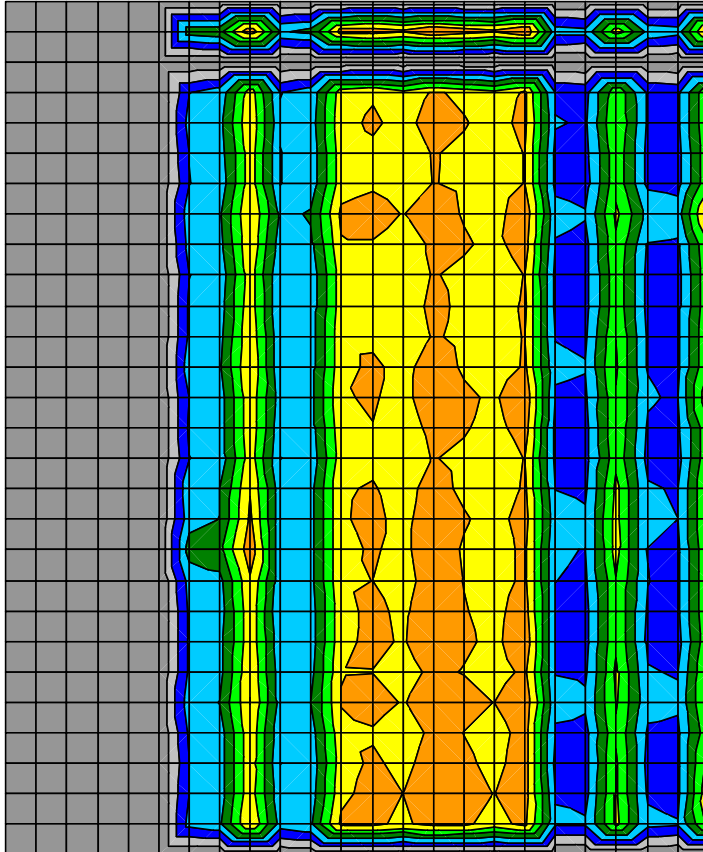
# DOE and Optimetrics Together Can Appreciably Reduce Costs



Cost comparison for design of a scanned phased array radiator

- Tolerance studies can span months, even years
- A carefully planned tolerance study can be accomplished in a few days to a few weeks
- Tolerance analysis can partially re-use the macros used for parameterization and optimization
  - ▶ Reduces development cost for each task
- Savings shown (left) for a radiator design are not estimates but rather actual costs
  - ▶ Legacy project did not use Optimetrics or this DOE approach to tolerance analysis
  - ▶ Proto project used both
  - ▶ Both legacy and proto used compute cluster

## Summary



- Tolerance analysis may not be fun, but a simplified approach can minimize the pain and time required
- I hope the approach I've presented will be useful to you
  
- Questions?  
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1. G. E. P. Box, W. G. Hunter, and J. S. Hunter, Statistics for Experimenters, John Wiley and Sons Inc., 1978
2. D. C. Montgomery, Design and Analysis of Experiments, John Wiley and Sons Inc., 1991
3. JMP, SAS Institute, Inc., Cary, NC 27513, [www.jmp.com](http://www.jmp.com)