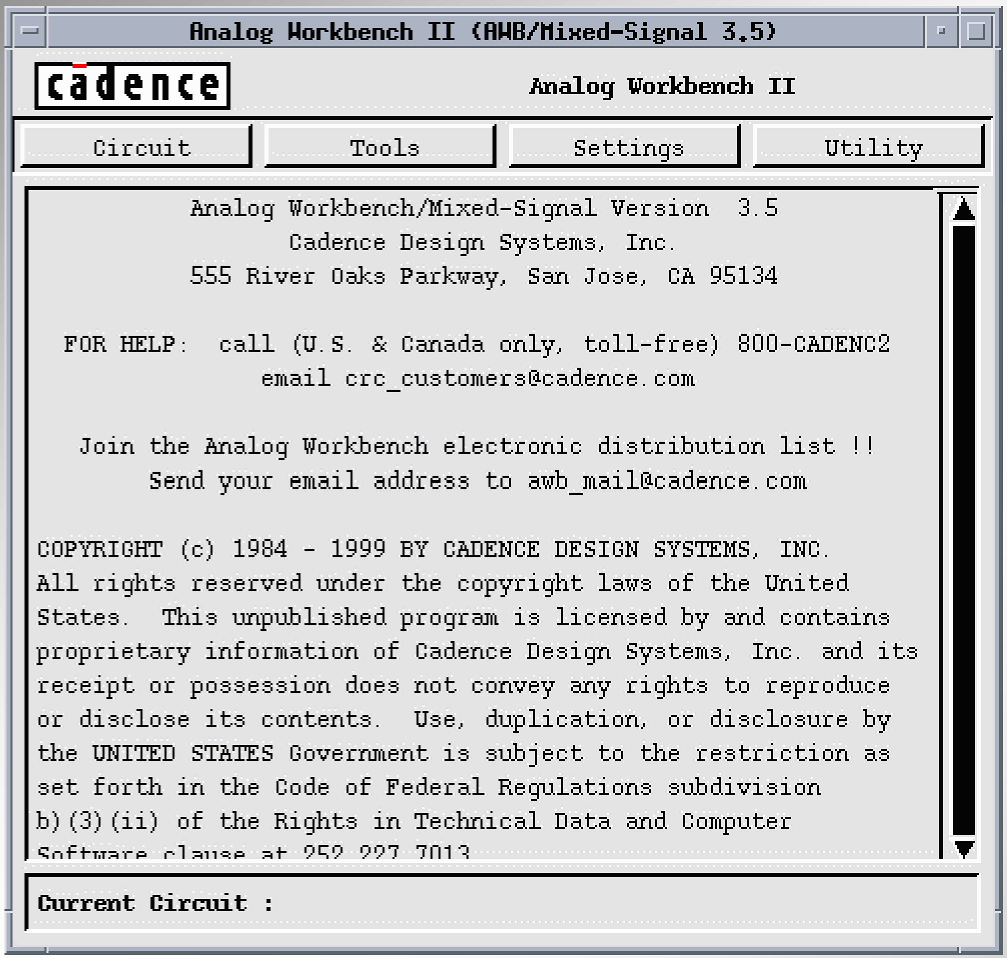
Worst Case Analysis Using Analog Workbench

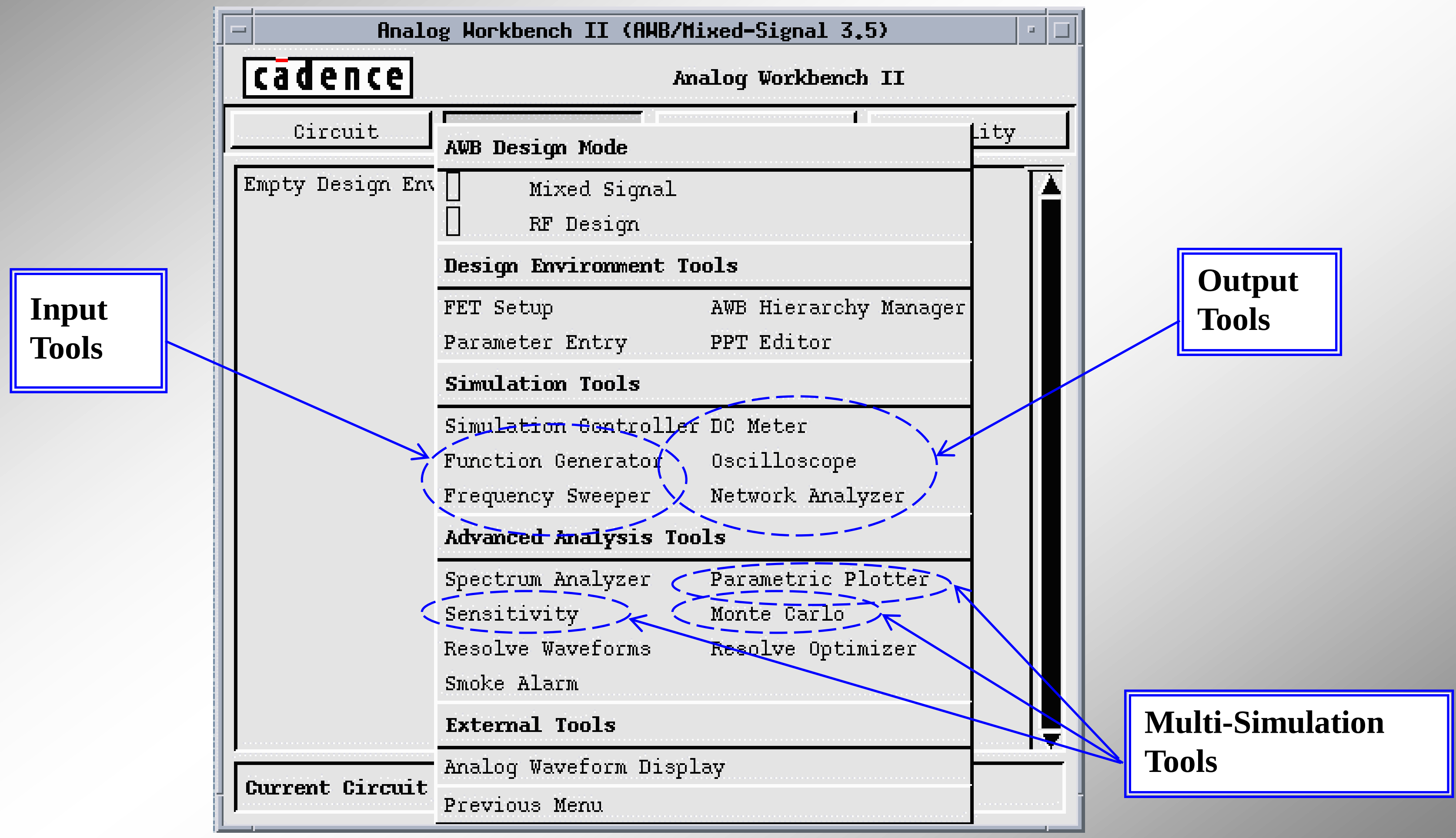
by Andrew G. Bell
ITT Industries

Worst Case Analysis
Using Analog Workbench



Analog Workbench has two powerful capabilities, which makes it very useful in WCA. First, it has parameterized models that can be toleranced. Second, it allows the user to establish marker functions of the user choosing.

Worst Case Analysis Using Analog Workbench



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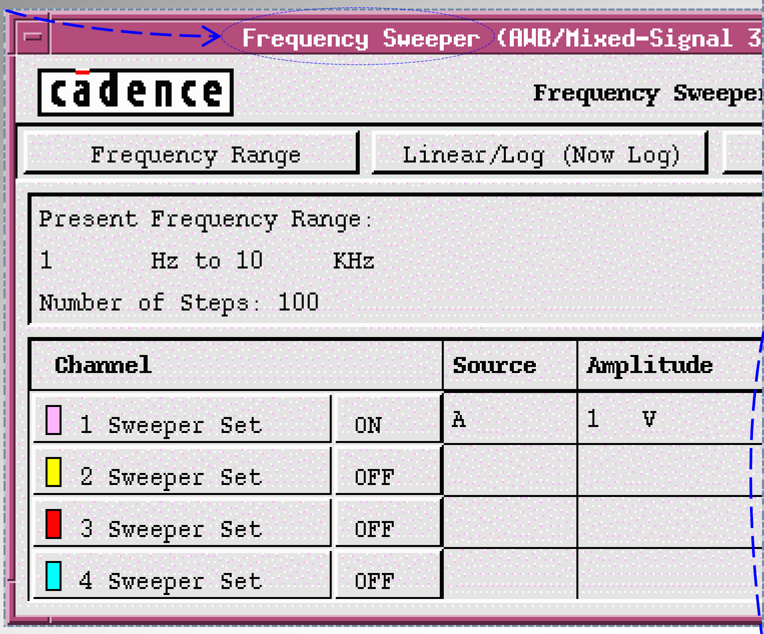
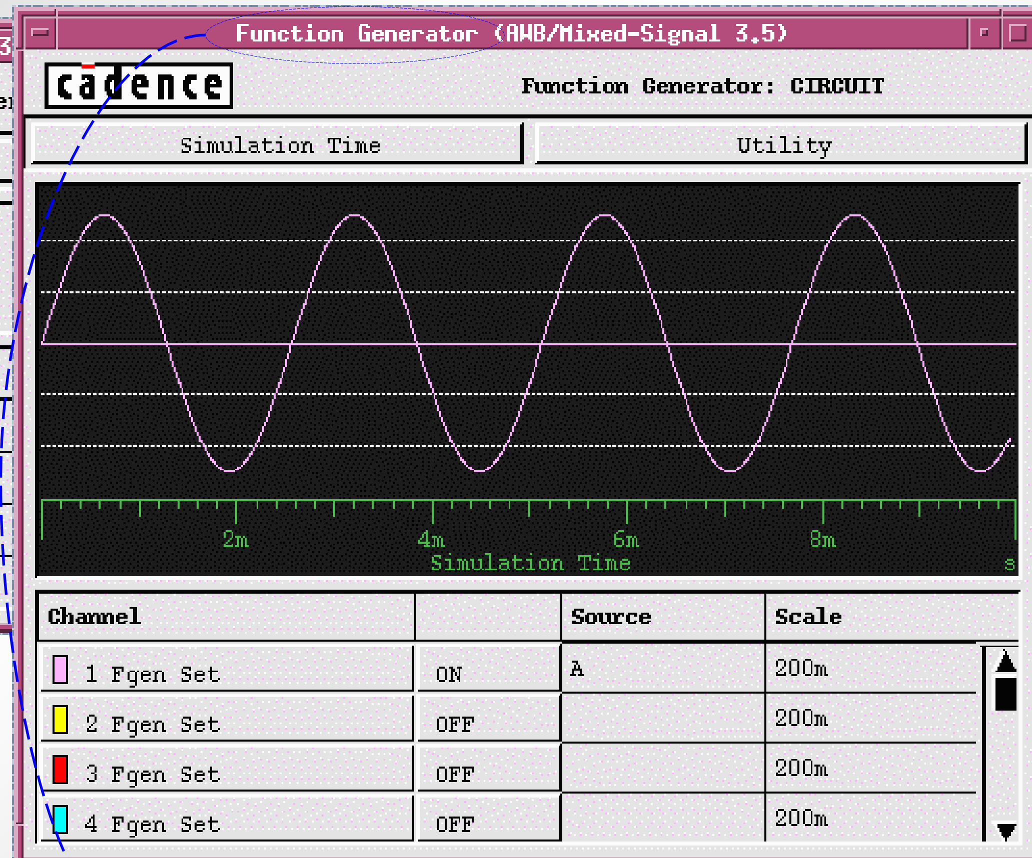
small signal analysis (frequency domain)





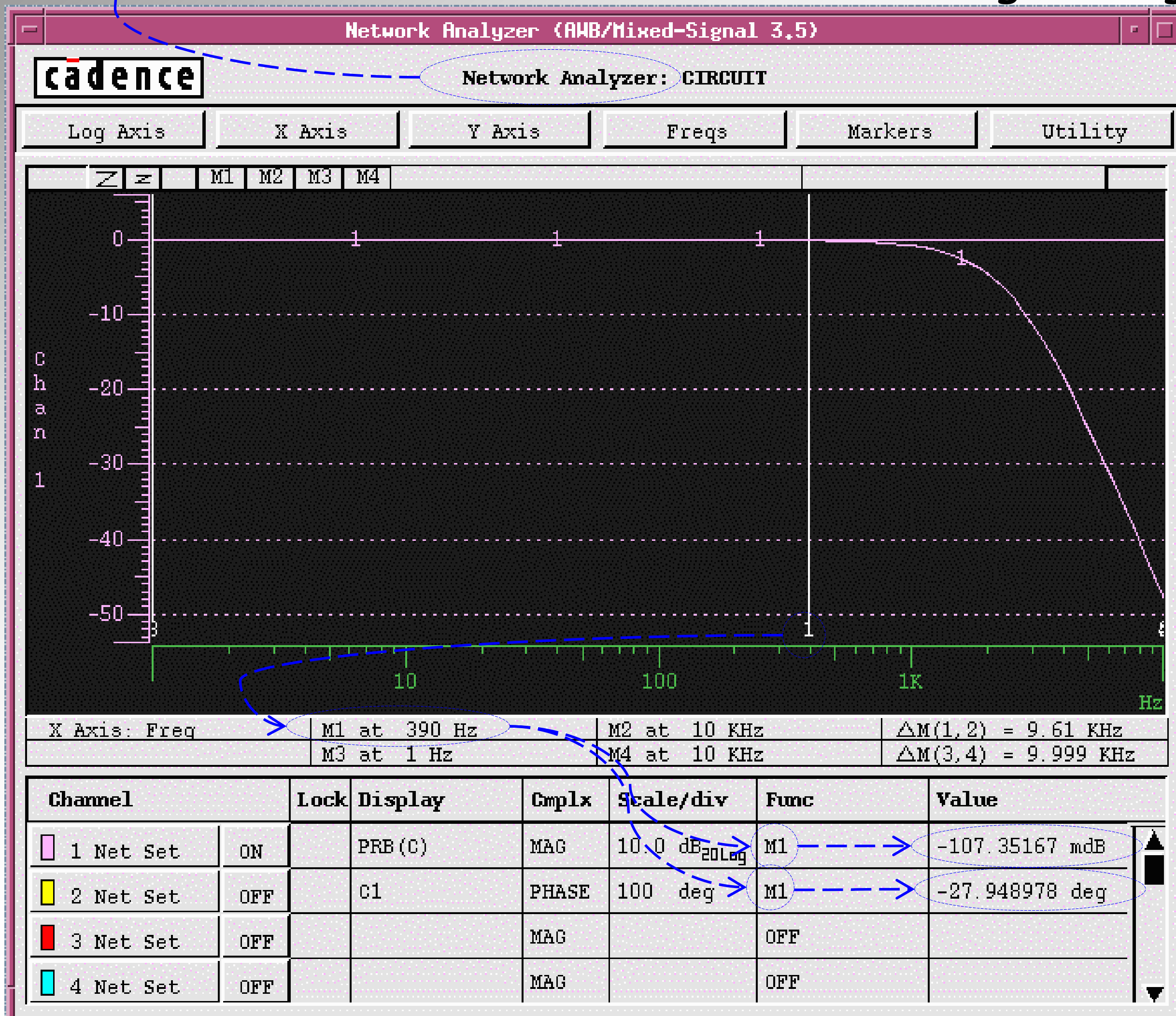
Input Tools

large signal analysis (time domain)

Worst Case Analysis Using Analog Workbench

Output Tool

small signal analysis (frequency domain)



Marker Function M1 allows for the measurement of the magnitude and phase at 390Hz to be made

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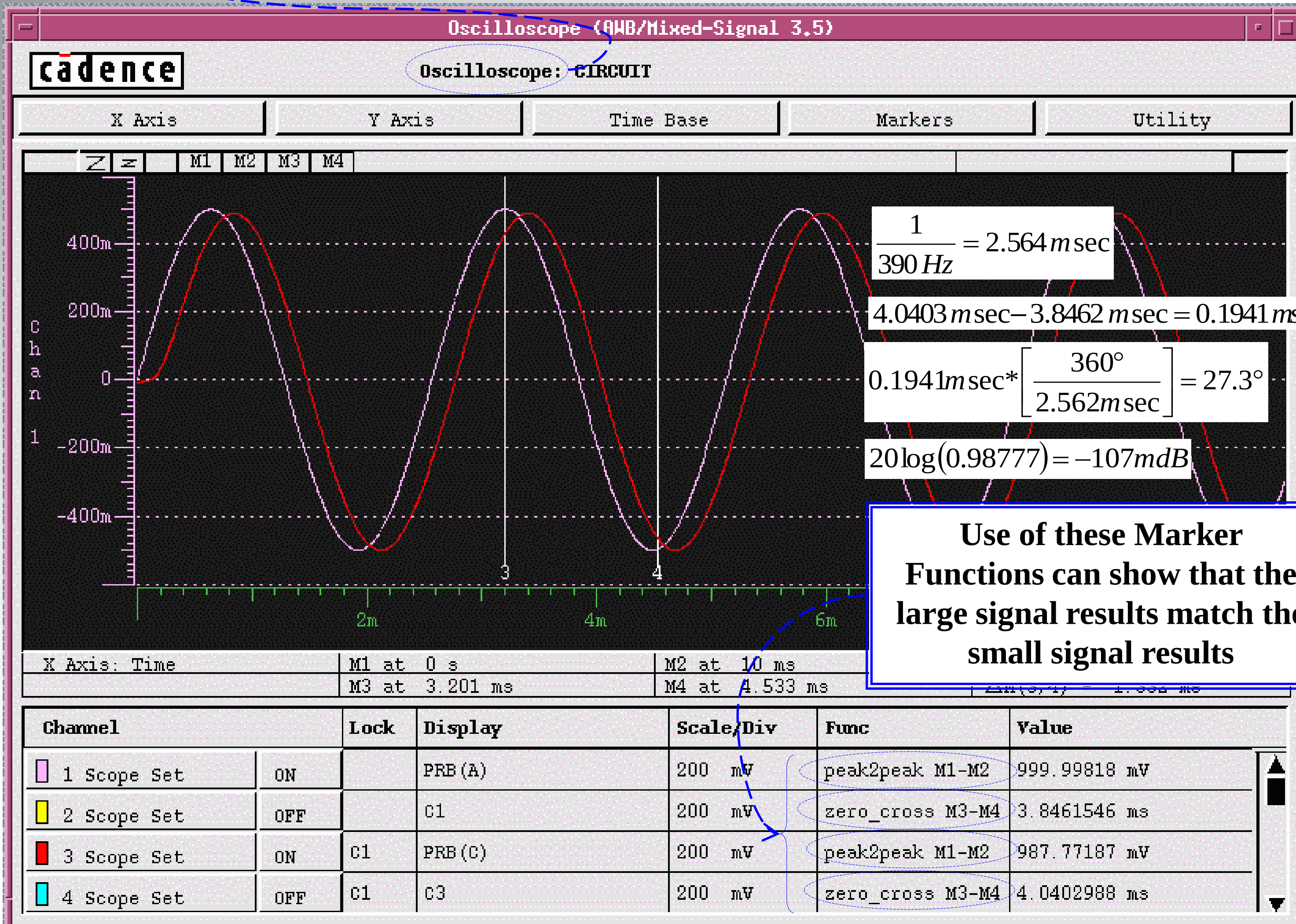
Output Tool → **large signal analysis (time domain)**



$$\frac{1}{390\,Hz} = 2.564\,m\sec$$

$$4.0403\,m\sec - 3.8462\,m\sec = 0.1941\,ms$$

$$0.1941\,m\sec * \left[\frac{360°}{2.562\,m\sec}\right] = 27.3°$$

$$20\log(0.98777) = -107\,mdB$$

Use of these Marker Functions can show that the large signal results match the small signal results

DC tool not shown

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WCA Example

Consider the following example:

A requirement is established and a circuit must be designed to meet the requirements worst case. Analog Workbench will be used to develop statistical device models and perform the worst case analysis using Monte Carlo and Sensitivity analyzes.

For the parts:

All parameters will be assigned a Flat distribution
All parameters will vary independently
Passive tolerances will be set to their extremes

For the analysis:

A Sensitivity/Worst Case analysis will be performed
A 400 sample Monte Carlo will be run
If needed additional analysis will be done to show the expected worst case performance

First it is necessary to develop device models

WCA Worksheet for
RNR55 Type Resistor

Purchase Tolerance IRC CGH-1/4-X = ±1%
Aging (10 year) MIL-STD-1547 = ±1%
Radiation = 0%
Temperature (75C) MIL-R-55182F = ±0.5%

$$tol = \sqrt{(1\%)^2 + (1.5\%)^2 + (0.5\%)^2} = \pm 1.87\%$$

Will use ±2% for resistors

WCA Worksheet for
CCR05 Type Resistor

Purchase Tolerance Kemet CCR05 = ±1%
Aging (40Khrs) Kemet Engineering Bulletin = ±5%
Radiation = 0%
Temperature (75C) MIL-C-20G = ±0.5%

$$tol = \sqrt{(1\%)^2 + (5\%)^2 + (0.5\%)^2} = \pm 5.12\%$$

Will use ±5% for capacitors

TL061, TL061A, TL061B, TL061Y, TL062, TL062A
TL062B, TL062Y, TL064, TL064A, TL064B, TL064Y
LOW-POWER JFET-INPUT OPERATIONAL AMPLIFIERS
SLOS078F – NOVEMBER 1978 – REVISED JANUARY 1999

electrical characteristics, $V_{CC\pm}$ = ±15 V (unless otherwise noted)

PARAMETER		TEST CONDITIONS†		TL061C TL062C TL064C MIN	TYP	MAX	TL061AC TL062AC TL064AC MIN	TYP	MAX	UNIT
V_{IO}	Input offset voltage	V_O = 0, R_S = 50 Ω	T_A = 25°C		3	15		3	6	mV
			T_A = Full range			20			7.5	
α_{VIO}	Temperature coefficient of input offset voltage	V_O = 0, R_S = 50 Ω, T_A = Full range			10			10		μV/°C
I_{IO}	Input offset current	V_O = 0	T_A = 25°C		5	200		5	100	pA
			T_A = Full range			5			3	nA
I_{IB}	Input bias current‡	V_O = 0	T_A = 25°C		30	400		30	200	pA
			T_A = Full range			10			7	nA
V_{ICR}	Common-mode input voltage range	T_A = 25°C		±11	−12 to 15		±11	−12 to 15		V
V_{OM}	Maximum peak output voltage swing	R_L = 10 kΩ,	T_A = 25°C	±10	±13.5		±10	±13.5		V
		R_L ≥ 10 kΩ,	T_A = Full range	±10			±10			
A_{VD}	Large-signal differential voltage amplification	V_O = ± 10 V, R_L ≥ 10 kΩ	T_A = 25°C	3	6		4	6		V/mV
			T_A = Full range	3			4			
B_1	Unity-gain bandwidth	R_L = 10 kΩ,	T_A = 25°C		1			1		MHz
r_i	Input resistance	T_A = 25°C			10^{12}			10^{12}		Ω
CMRR	Common-mode rejection ratio	V_{IC} = V_{ICR}min, V_O = 0, R_S = 50 Ω, T_A = 25°C		70	86		80	86		dB
k_{SVR}	Supply-voltage rejection ratio ($\Delta V_{CC\pm}/\Delta V_{IO}$)	V_{CC} = ± 9 V to ± 15 V, V_O = 0, R_S = 50 Ω, T_A = 25°C		70	95		80	95		dB
P_D	Total power dissipation (each amplifier)	V_O = 0, No load	T_A = 25°C,		6	7.5		6	7.5	mW
I_{CC}	Supply current (each amplifier)	V_O = 0, No load	T_A = 25°C,		200	250		200	250	μA
V_{O1}/V_{O2}	Crosstalk attenuation	A_{VD} = 100,	T_A = 25°C		120			120		dB

† All characteristics are measured under open-loop conditions with zero common-mode input voltage unless otherwise specified. Full range for T_A is 0°C to 70°C for TL06_C, TL06_AC, and TL06_BC and −40°C to 85°C for TL06_I.
‡ Input bias currents of a FET-input operational amplifier are normal junction reverse currents, which are temperature sensitive as shown in Figure 15. Pulse techniques are used to maintain the junction temperature as close to the ambient temperature as possible.

Extracting device parameters may require assumption to be made about max or min values not defined.

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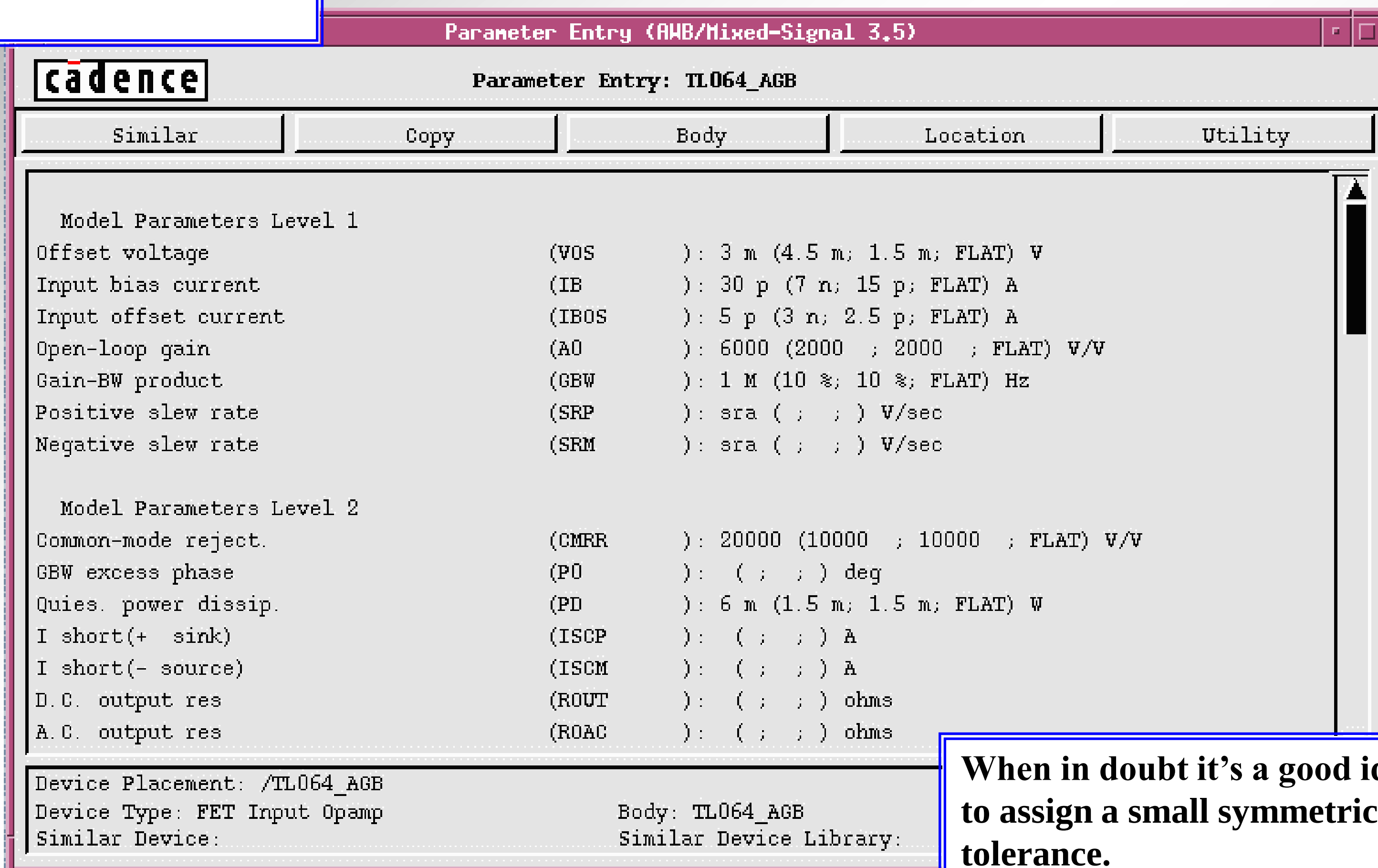
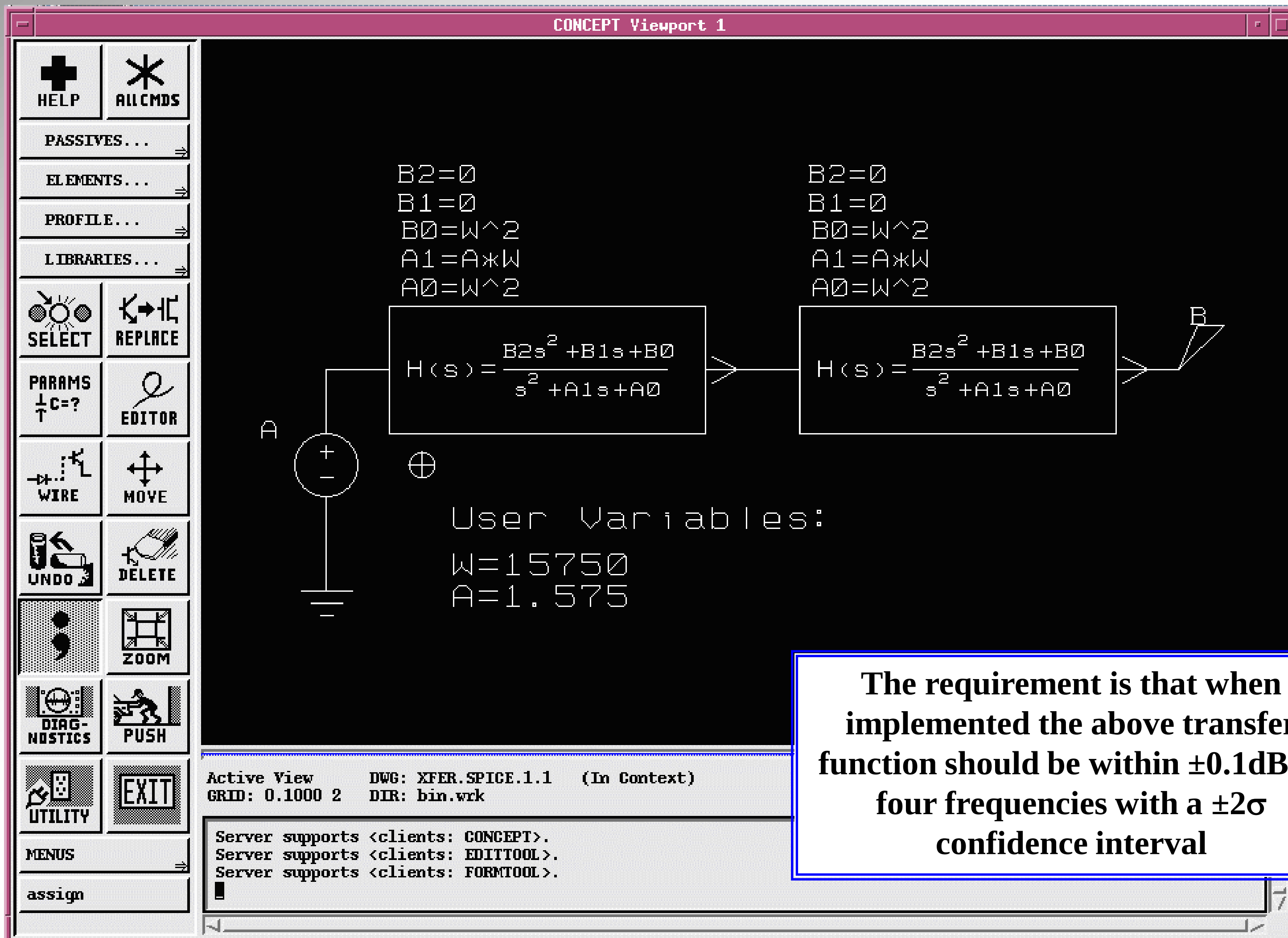
Extracted parameters used to create a device model using Analog Workbench's Parameter Entry Tool



When in doubt it's a good idea to assign a small symmetrical tolerance.

Worst Case Analysis Using Analog Workbench

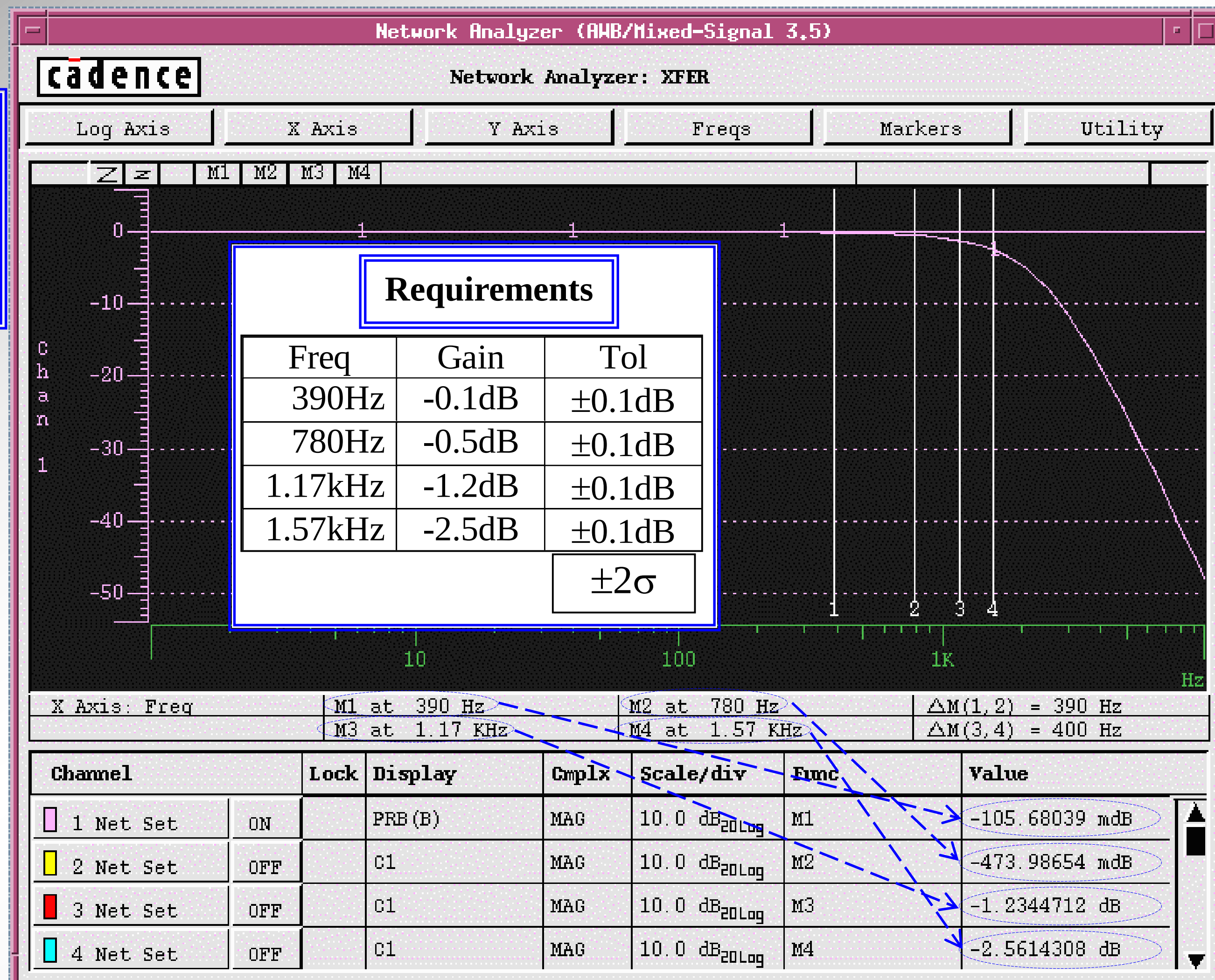
Now the design...



The requirement is that when implemented the above transfer function should be within ±0.1dB at four frequencies with a ±2σ confidence interval

Worst Case Analysis
Using Analog Workbench

Simulation of the transfer function show a close but not exact match with the requirements

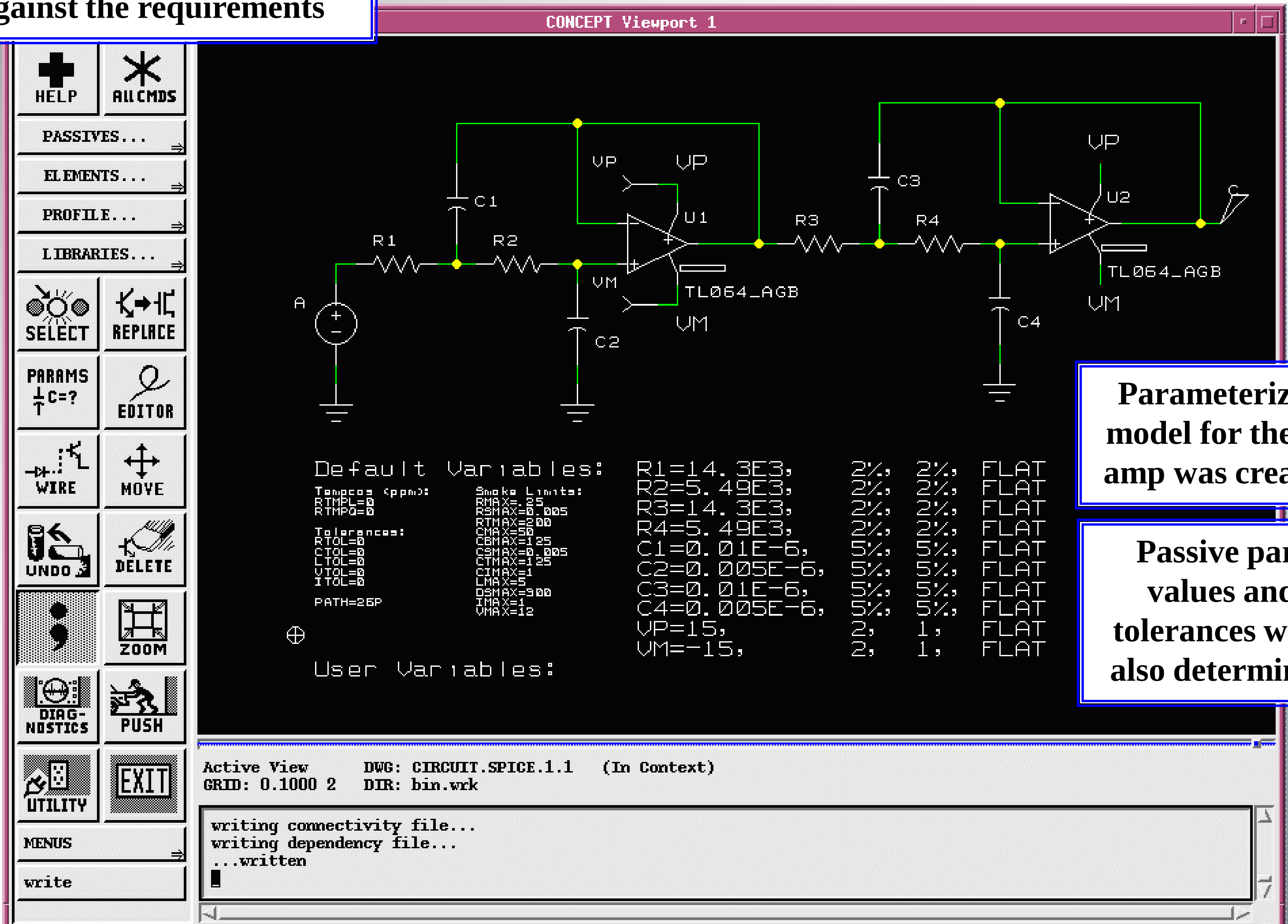


Requirements

Freq	Gain	Tol
390Hz	-0.1dB	±0.1dB
780Hz	-0.5dB	±0.1dB
1.17kHz	-1.2dB	±0.1dB
1.57kHz	-2.5dB	±0.1dB
		±2σ

Worst Case Analysis Using Analog Workbench

A circuit implementation is proposed and simulated against the requirements



Parameterized model for the op amp was created

Passive part values and tolerances were also determined

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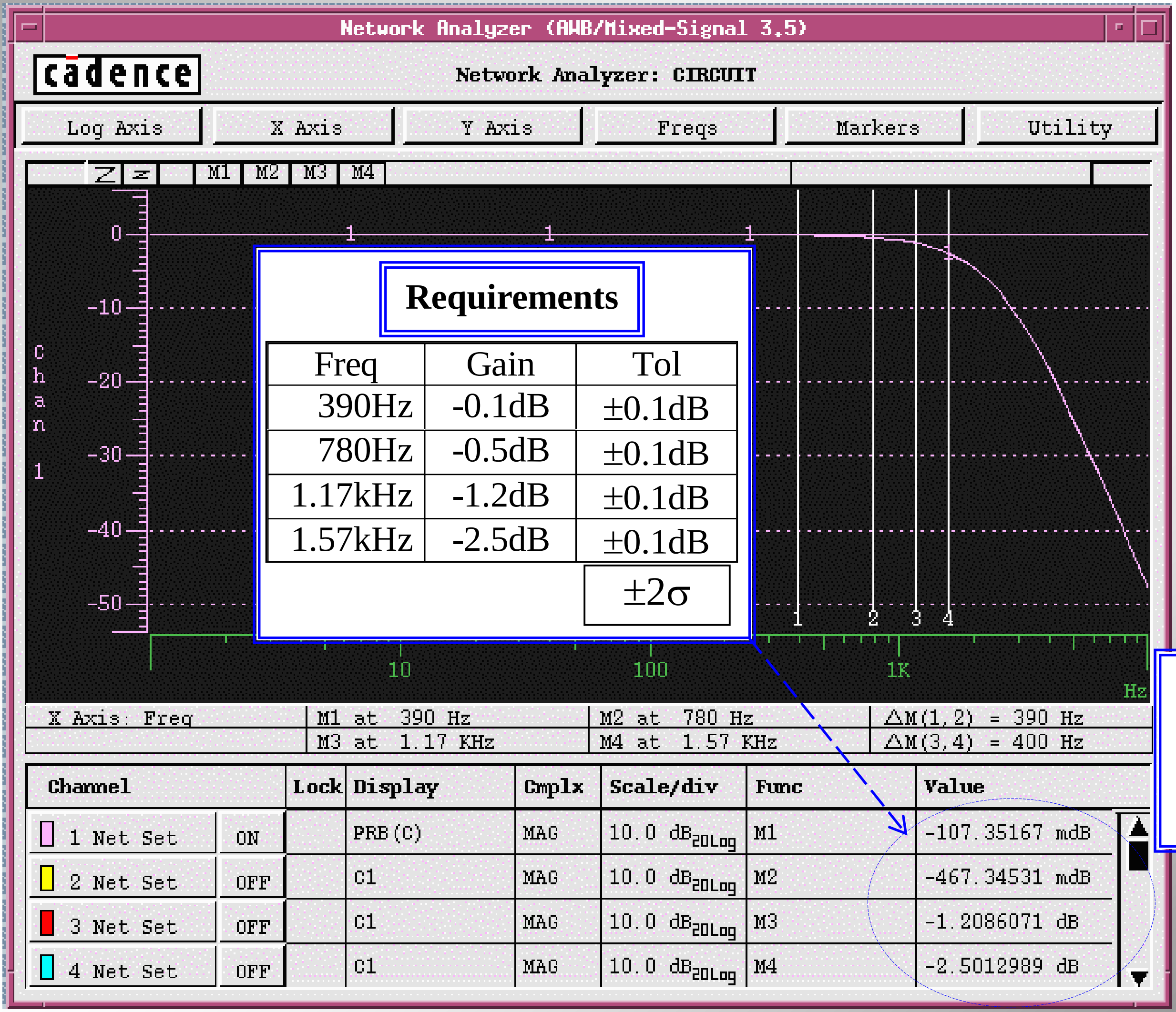
Worst Case Analysis Using Analog Workbench



Requirements

Freq	Gain	Tol
390Hz	-0.1dB	±0.1dB
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1.17kHz	-1.2dB	±0.1dB
1.57kHz	-2.5dB	±0.1dB
		±2σ

Simulated circuit matches closely with requirements

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A Sensitivity Analysis is performed next to determine how changes in each parameter will change the the frequency response at all four frequencies.

Worst Case Analysis Using Analog Workbench

Sensitivity/Worst Case Analysis (AWB/Mixed-Signal 3.5)

cadence

Sensitivity/Worst Case Analysis: CIRCUIT

Display | Order | Control | Utility

Component	Parameter	Nom	Min	Max	Relative (1%)	Sensitivity
(CRC)						
Variable	c2	5n	5.25n	4.75n	-3.126m	
Variable	c4	5n	5.25n	4.75n	-3.126m	
Variable	c1	10n	9.5n	10.5n	1.988m	
Variable	c3	10n	9.5n	10.5n	1.988m	
Variable	r3	14.3K	14.586K	14.014K	-1.676m	
Variable	r1	14.3K	14.586K	14.014K	-1.676m	
Variable	r4	5.49K	5.3802K	5.5998K	573.521u	
Variable	r2	5.49K	5.3802K	5.5998K	573.520u	
TL0.U2	A0	6K	4K	8K	13.835u	
TL0.U1	A0	6K	4K	8K	13.832u	
TL0.U1	GBW	1M	1.1M	900K	-11.014u	

Most sensitive to passive part variations

Relatively insensitive to OP AMP changes

Analysis Complete: 45 of 45 runs completed

Channel		Display	Min	Nom	Max
1 Sens Set	ON	Net 1	-172.820 mdB	-107.352 mdB	-49.527 mdB
2 Sens Set	OFF	Net 2	-709.156 mdB	-467.345 mdB	-246.005 mdB
3 Sens Set	OFF	Net 3	-1.697 dB	-1.209 dB	-745.551 mdB
4 Sens Set	OFF	Net 4	-3.272 dB	-2.501 dB	-1.770 dB

Keyed to Network Analyzer marker functions

In spec

Out of spec

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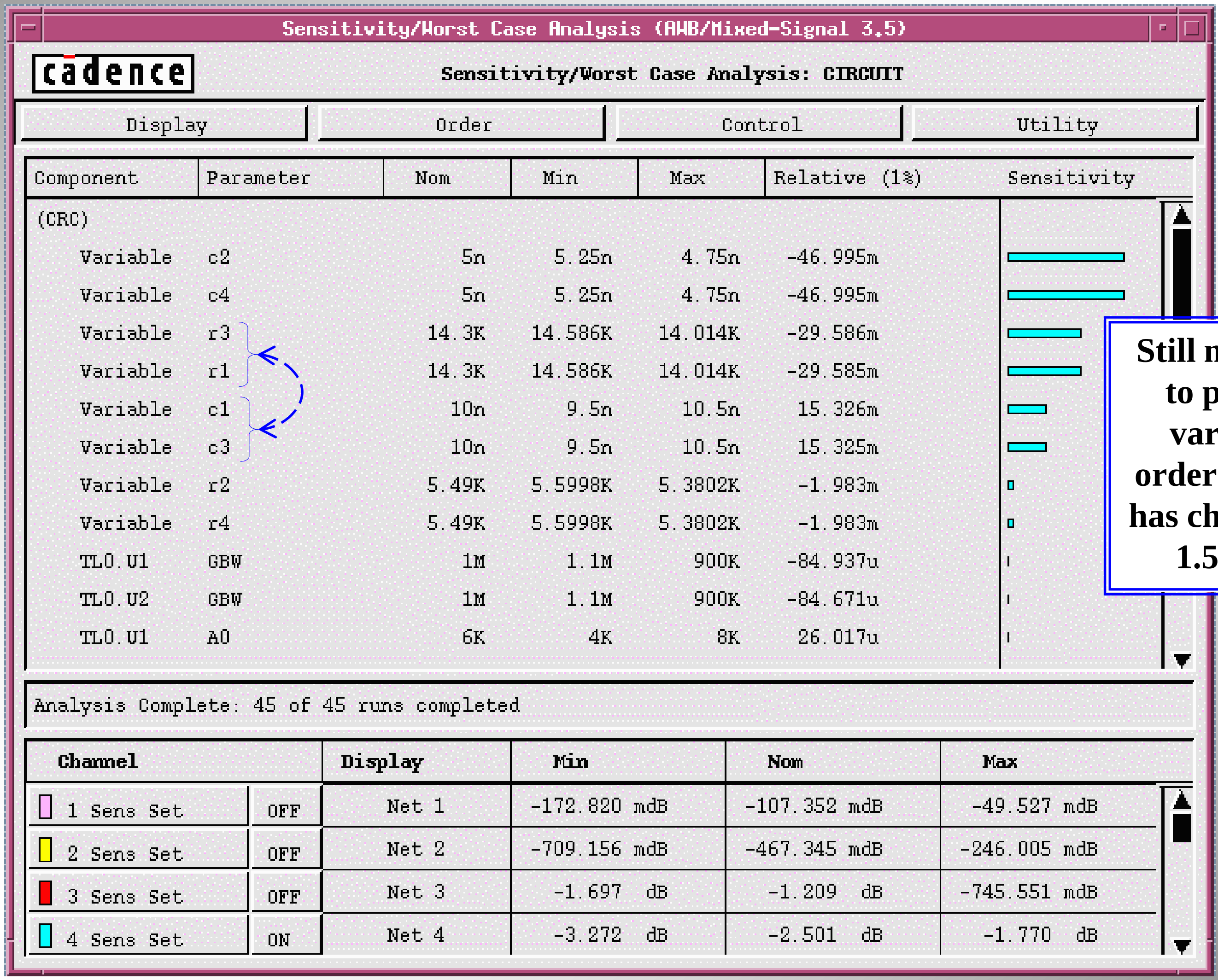
Worst Case Analysis
Using Analog Workbench



Sensitivity/Worst Case Analysis (AWB/Mixed-Signal 3.5)

cadence

Sensitivity/Worst Case Analysis: CIRCUIT

Display | Order | Control | Utility

Component	Parameter	Nom	Min	Max	Relative (1%)	Sensitivity
(CRC)						
Variable	c2	5n	5.25n	4.75n	-46.995m	
Variable	c4	5n	5.25n	4.75n	-46.995m	
Variable	r3	14.3K	14.586K	14.014K	-29.586m	
Variable	r1	14.3K	14.586K	14.014K	-29.585m	
Variable	c1	10n	9.5n	10.5n	15.326m	
Variable	c3	10n	9.5n	10.5n	15.325m	
Variable	r2	5.49K	5.5998K	5.3802K	-1.983m	
Variable	r4	5.49K	5.5998K	5.3802K	-1.983m	
TL0.U1	GBW	1M	1.1M	900K	-84.937u	
TL0.U2	GBW	1M	1.1M	900K	-84.671u	
TL0.U1	A0	6K	4K	8K	26.017u	

Analysis Complete: 45 of 45 runs completed

Channel		Display	Min	Nom	Max
1 Sens Set	OFF	Net 1	-172.820 mdB	-107.352 mdB	-49.527 mdB
2 Sens Set	OFF	Net 2	-709.156 mdB	-467.345 mdB	-246.005 mdB
3 Sens Set	OFF	Net 3	-1.697 dB	-1.209 dB	-745.551 mdB
4 Sens Set	ON	Net 4	-3.272 dB	-2.501 dB	-1.770 dB

Still most sensitive to passive part variations but order of sensitivity has changed for the 1.57kHz gain

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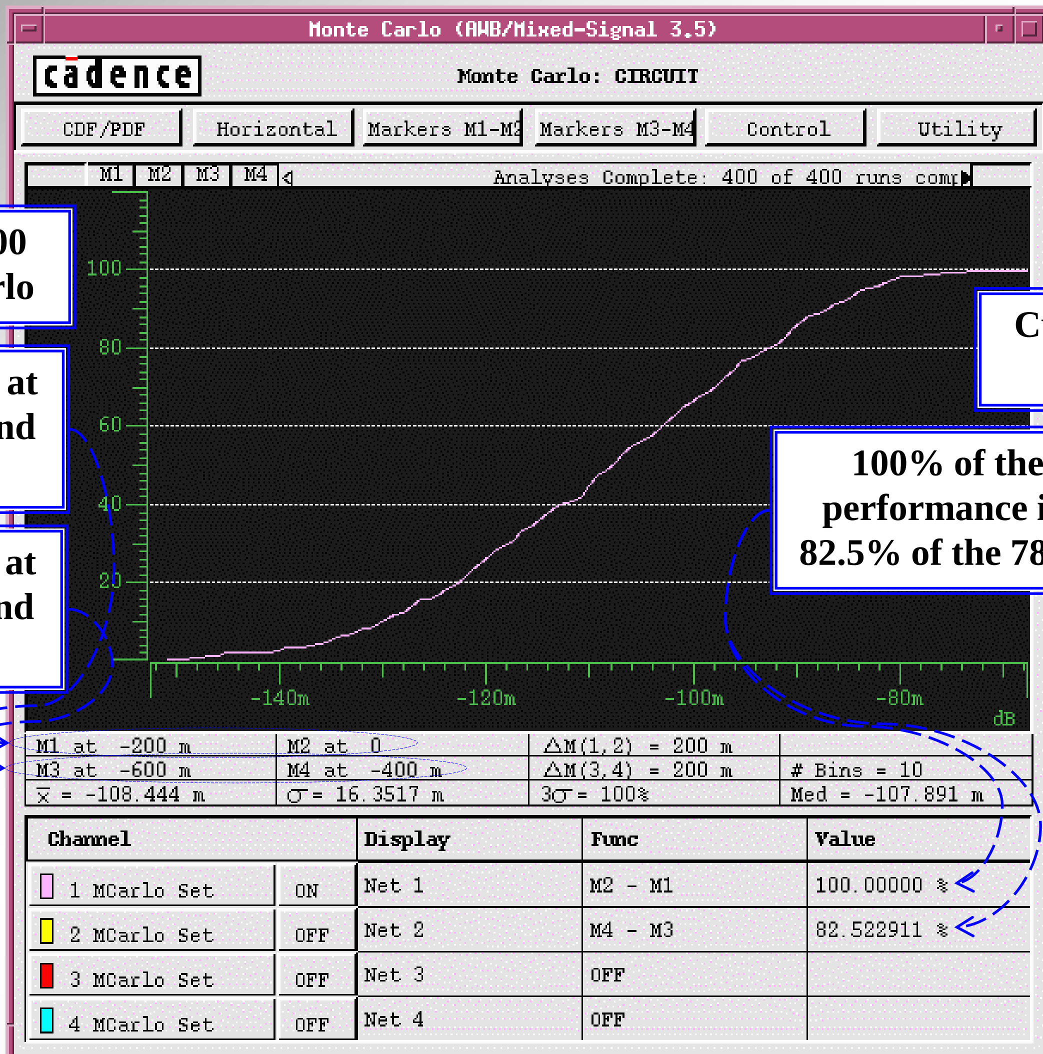
Worst Case Analysis Using Analog Workbench

Next perform a 400 sample Monte Carlo

M1 and M2 set at 390Hz upper and lower limits

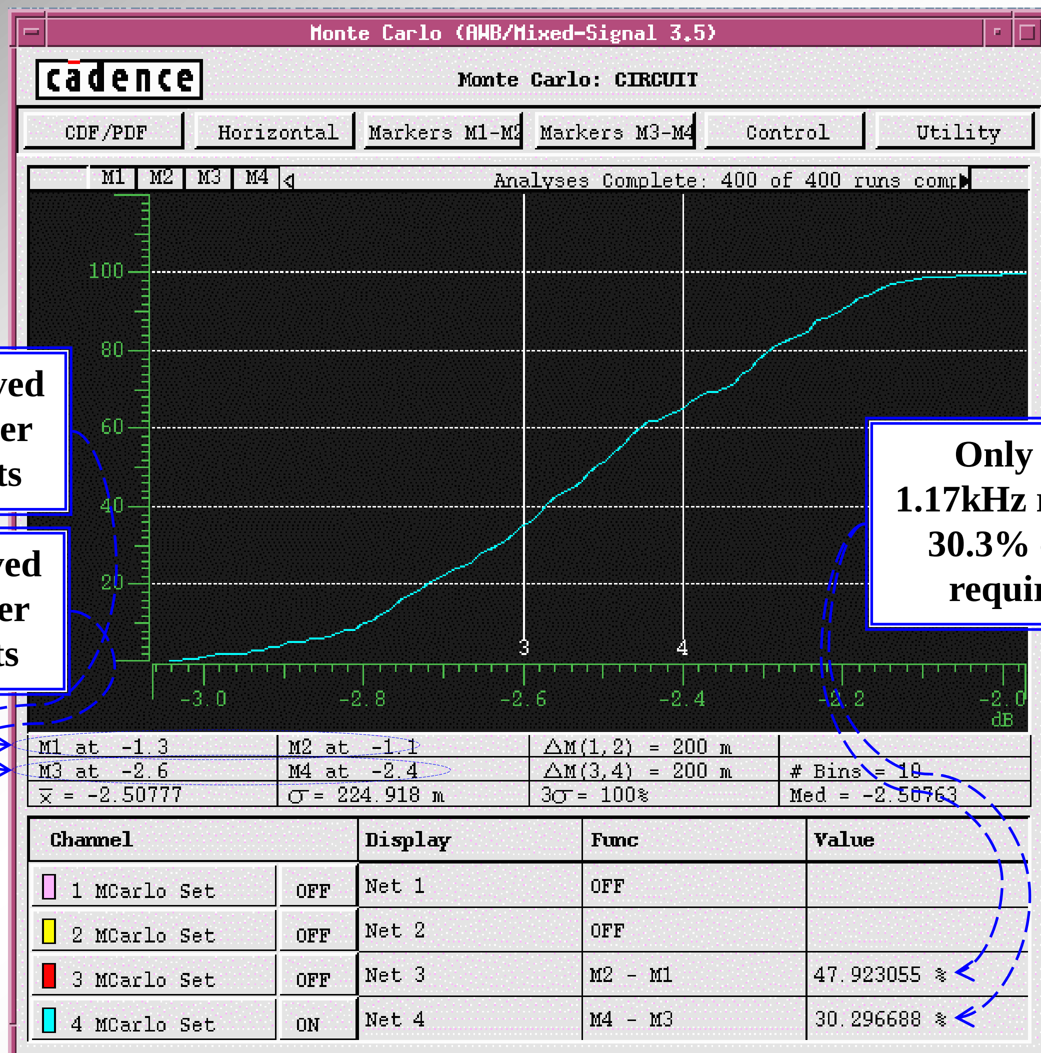
M3 and M4 set at 780Hz upper and lower limits



Curve appears gaussian

100% of the 390Hz Gain performance is met but only 82.5% of the 780Hz is achieved

Worst Case Analysis Using Analog Workbench



M1 and M2 moved to 1.17kHz upper and lower limits

M3 and M4 moved to 1.57kHz upper and lower limits

Only 47.9% of the 1.17kHz requirement and 30.3% of the 1.57kHz requirement is met

Worst Case Analysis Using Analog Workbench

Parametric Plots are performed to determine how variation in some of the more sensitive components change the performance at 1.57kHz

Need to tighten tolerances on C1-C4, R1 & R3

R2 and R4 not that important

Outer: c4 from 4.75n to 5.25n in steps of 125p units				
Inner: None				
X Axis: c4		Y Axis: Network Analyzer Value 4		
c4: N/A		: 0.0		
M1 at 4.75n	M2 at 5.25n	ΔM(1,2) = 500p		
M3 at 4.75n	M4 at 5.25n	ΔM(3,4) = 500p		
	Display	Func	@Param value	Value
Plot Set		M1 - M2	0.000000	-467.4119mdB

Outer: r1 from 14K to 14.6K in steps of 100 units				
Inner: None				
X Axis: r1		Y Axis: Network Analyzer Value 4		
r1: N/A		: 0.0		
M1 at 14K	M2 at 14.6K	ΔM(1,2) = 600		
M3 at 14K	M4 at 14.6K	ΔM(3,4) = 600		
	Display	Func	@Param value	Value
Plot Set		M1 - M2	0.000000	-123.75094mdB

Outer: c1 from 9.5n to 10.5n in steps of 250p units				
Inner: None				
X Axis: c1		Y Axis: Network Analyzer Value 4		
c1: N/A		: 0.0		
M1 at 9.5n	M2 at 10.5n	ΔM(1,2) = 1n		
M3 at 9.5n	M4 at 10.5n	ΔM(3,4) = 1n		
	Display	Func	@Param value	Value
Plot Set		M1 - M2	0.000000	153.65344mdB

Outer: r4 from 5.38K to 5.6K in steps of 22 units				
Inner: None				
X Axis: r4		Y Axis: Network Analyzer Value 4		
r4: N/A		: 0.0		
M1 at 5.38K	M2 at 5.6K	ΔM(1,2) = 220		
M3 at 5.38K	M4 at 5.6K	ΔM(3,4) = 220		
	Display	Func	@Param value	Value
Plot Set		M1 - M2	0.000000	-7.7176333mdB

Worst Case Analysis Using Analog Workbench

Original Worksheet

Purchase tolerance = ±1%

Aging (10 years) = ±1.5%

Temperature (+75°C to -55°C) = ±0.5%

$$tol = \sqrt{(1\%)^2 + (1.5\%)^2 + (0.5\%)^2} = \pm 1.87\%$$

Modified Tolerance

Purchase tolerance = 0%

Aging (5 years) = ±0.75%

Temperature (+40°C to 0°C) = ±0.25%

$$tol = \sqrt{(0.75\%)^2 + (0.25\%)^2} = \pm 0.8\%$$

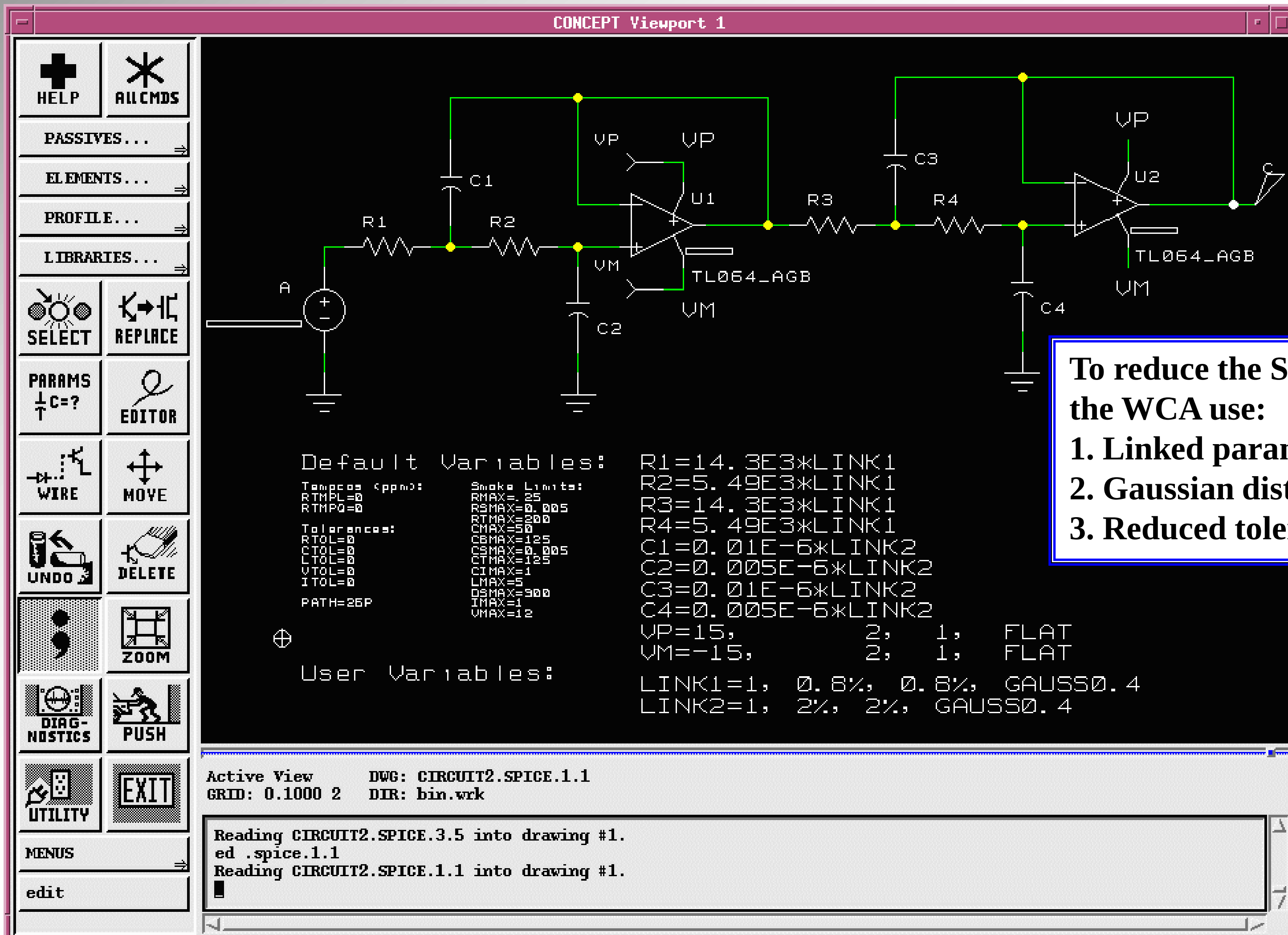
Can the passive part tolerances be relaxed or will other parts be needed?

We can reduce the resistor tolerance because we know something about how it is being used, i.e. 5 years, tailored and over smaller temperature range

This reduces the resistor variation to ±0.8% and likewise we will reduce the capacitor tolerance by the same proportion to ±2%

We will also change the distribution of each passive parameter to gaussian and link the passive part variations together

Worst Case Analysis Using Analog Workbench



To reduce the Severity of the WCA use:

1. **Linked parameters**
2. **Gaussian distributions**
3. **Reduced tolerances**

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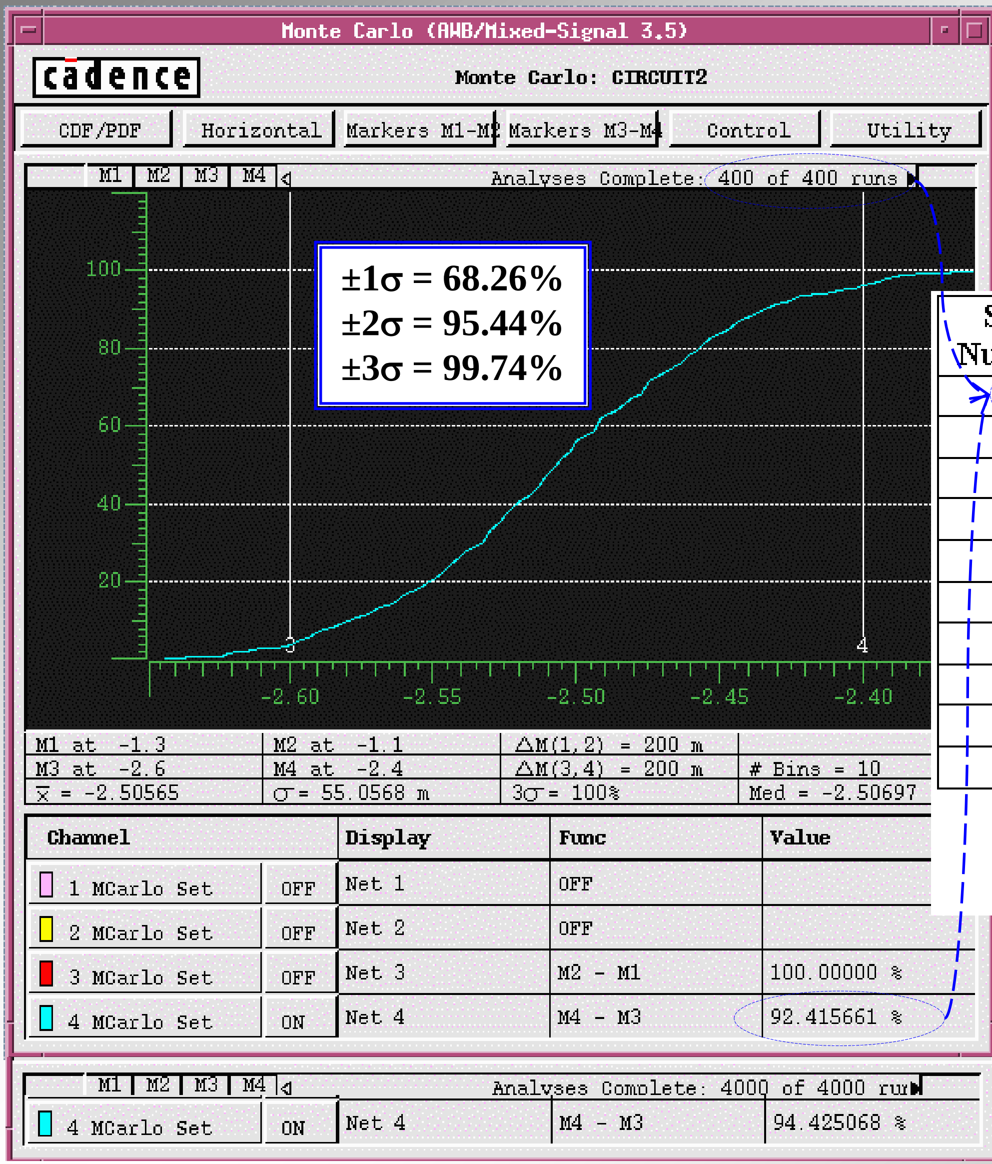
Worst Case Analysis Using Analog Workbench



The results look good but just how good?

Seed Number	2σ	
1	92.416%	
7	92.613%	
5	93.463%	
4	94.900%	
3	94.920%	
2	95.156%	
10	95.500%	
9	95.613%	
8	95.752%	
6	95.961%	
	94.629%	= MEAN
	1.3132%	= STDEV
	1.7244%	= VARIANCE

Ten 400 sample Monte Carlo were run. Note six of the seeds failed to meet the requirements but the other four did. When you are close to the requirement limit you may need to take more samples to prove that you meet the requirement.

We fail to meet the requirements for the 1.57kHz gain so either the requirements need to be changed or we will need to use some tighter tolerance parts.

If you used 4000 samples it would take longer but you have more confidence in the answer.

Conclusions:

- ✓ **AWB is a powerful tool that can be used for WCA**
- ✓ **Marker Functions provide a unique ability to check performance**
- ✓ **Both the Sensitivity and Monte Carlo tools are needed for WCA**
- ✓ **Much more work is still needed to develop statistical device models**
- ✓ **It still may be necessary to apply some realism to part variations**