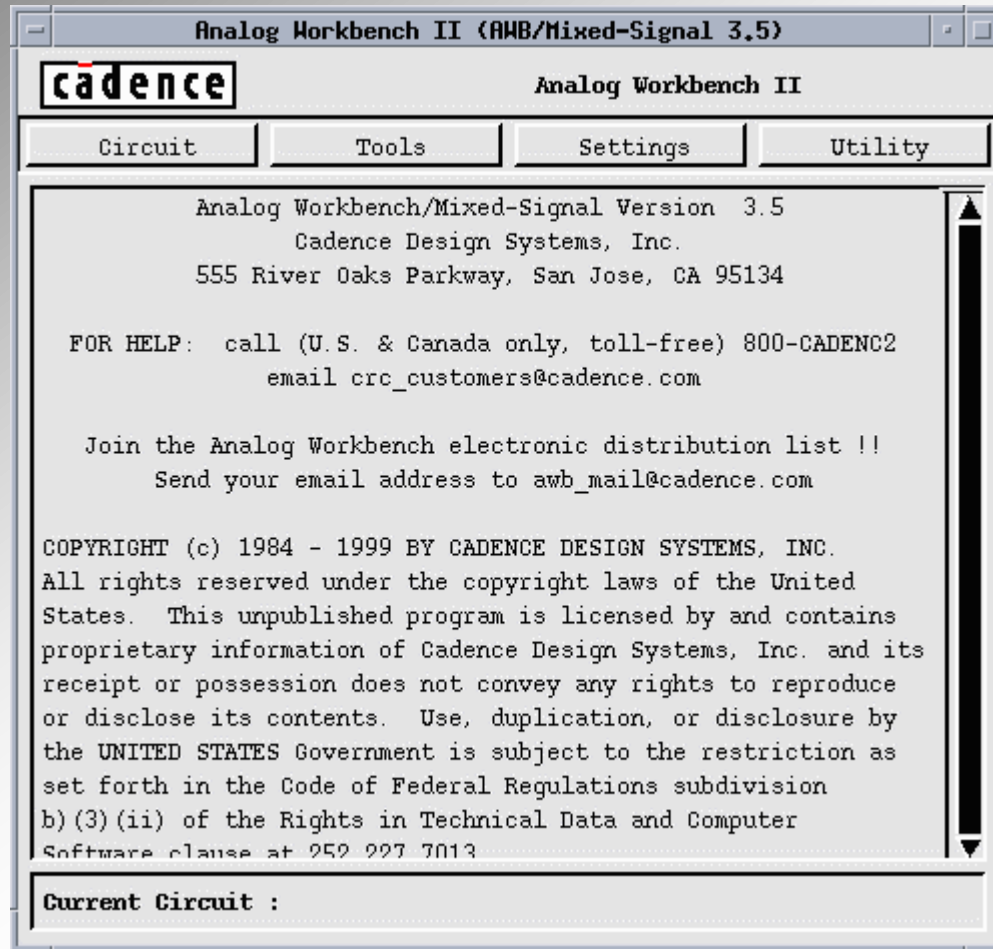


Worst Case Analysis  
Using Analog Workbench  
by Andrew G. Bell  
ITT Industries

## 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 tolerated. Second, it allows the user to establish marker functions of the user choosing.

# Worst Case Analysis Using Analog Workbench

The screenshot shows the Cadence Analog Workbench II (AWB/Mixed-Signal 3.5) interface. The main window is titled "Analog Workbench II" and contains a "Circuit" pane on the left and a tool menu on the right. The tool menu is organized into several sections:

- AWB Design Mode:** Includes checkboxes for "Mixed Signal" and "RF Design".
- Design Environment Tools:** Includes "FET Setup", "AWB Hierarchy Manager", "Parameter Entry", and "PPT Editor".
- Simulation Tools:** Includes "Simulation Controller", "DC Meter", "Function Generator", "Oscilloscope", "Frequency Sweeper", and "Network Analyzer".
- Advanced Analysis Tools:** Includes "Spectrum Analyzer", "Parametric Plotter", "Sensitivity", "Monte Carlo", "Resolve Waveforms", and "Resolve Optimizer".
- External Tools:** Includes "Smoke Alarm".
- Current Circuit:** Includes "Analog Waveform Display" and "Previous Menu".

Four callout boxes with blue borders and arrows point to specific tool categories:

- Input Tools:** Points to the "Function Generator" and "Frequency Sweeper" tools.
- Output Tools:** Points to the "DC Meter", "Oscilloscope", and "Network Analyzer" tools.
- Multi-Simulation Tools:** Points to the "Parametric Plotter", "Monte Carlo", and "Resolve Optimizer" tools.
- Sensitivity:** Points to the "Sensitivity" tool.

# Worst Case Analysis Using Analog Workbench

small signal analysis (frequency domain)

Channel	Source	Amplitude
1 Sweeper Set	ON	A 1 V
2 Sweeper Set	OFF	
3 Sweeper Set	OFF	
4 Sweeper Set	OFF	

Input Tools

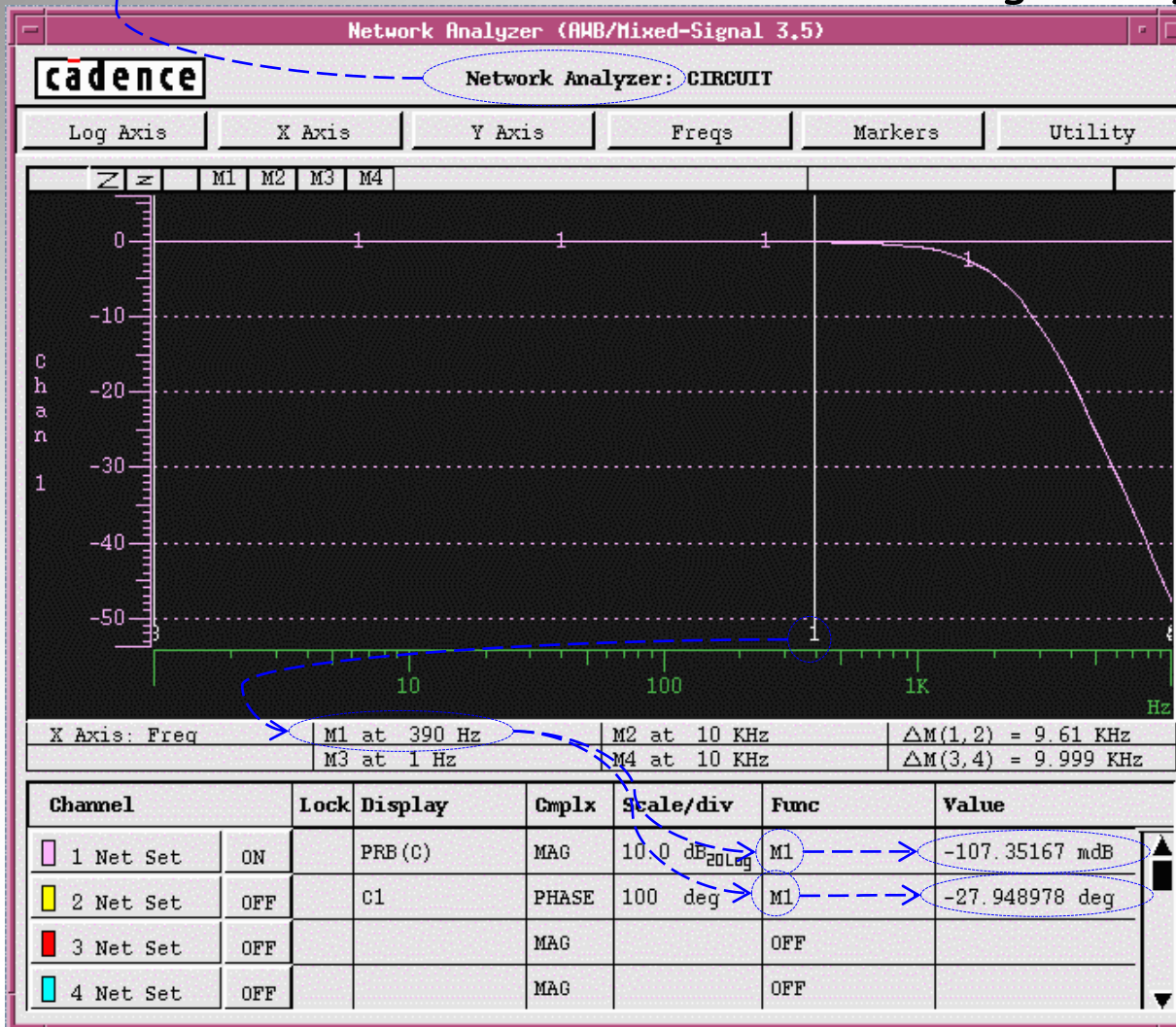
Channel	Source	Scale
1 Fgen Set	ON	A 200m
2 Fgen Set	OFF	200m
3 Fgen Set	OFF	200m
4 Fgen Set	OFF	200m

large signal analysis (time domain)

Output Tool

small signal analysis (frequency domain)

# Worst Case Analysis Using Analog Workbench

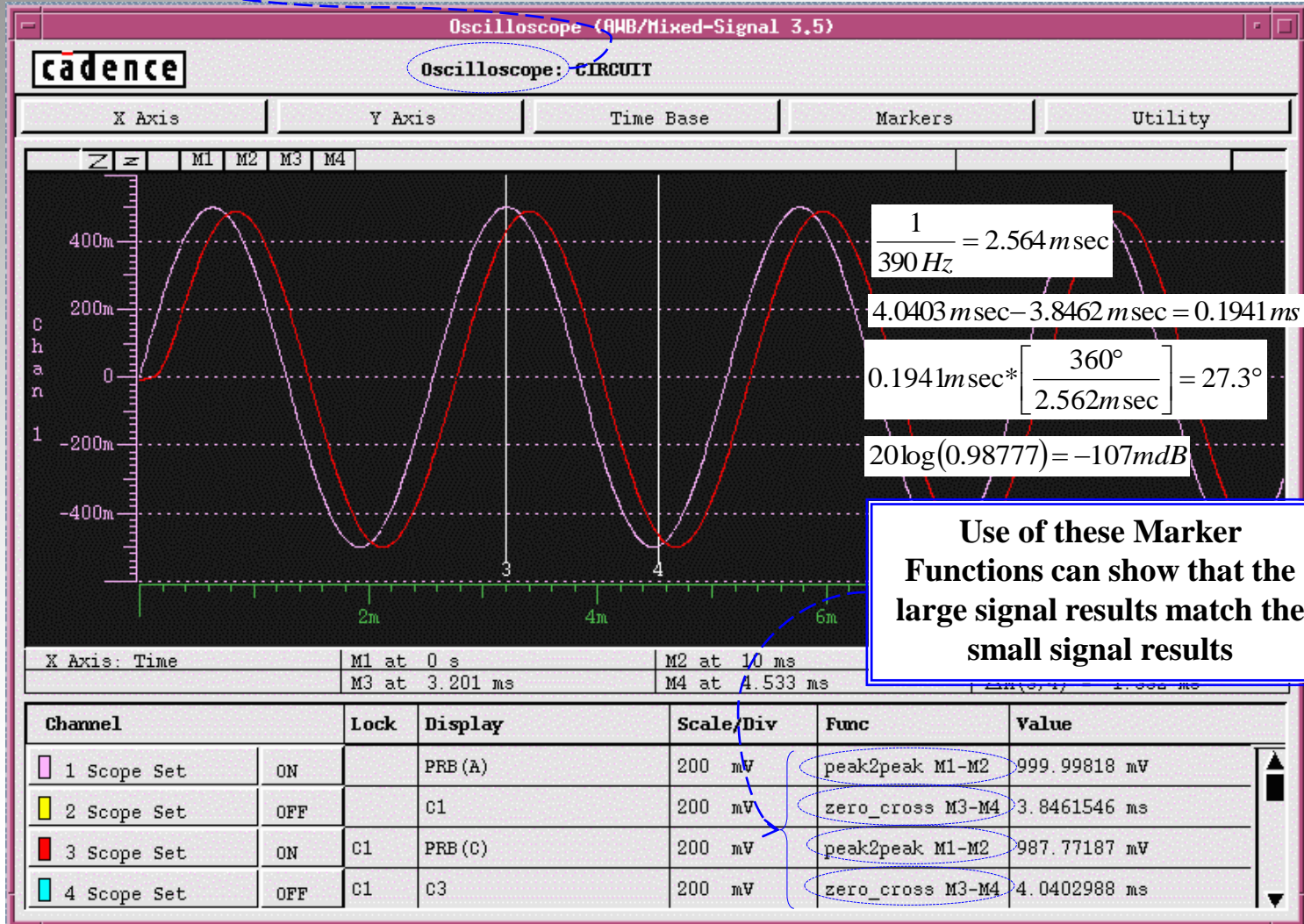


Marker Function M1 allows for the measurement of the magnitude and phase at 390Hz to be made

Output Tool

large signal analysis (time domain)

# Worst Case Analysis Using Analog Workbench



# Worst Case Analysis Using Analog Workbench

## 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**

# Worst Case Analysis Using Analog Workbench

First it is necessary to develop device models

## WCA Worksheet for RNR55 Type Resistor

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

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

Will use  $\pm 2\%$  for resistors

## WCA Worksheet for CCR05 Type Resistor

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

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

Will use  $\pm 5\%$  for capacitors



# Worst Case Analysis Using Analog Workbench

## TL061, TL061A, TL061B, TL061Y, TL062, TL062A TL062B, TL062Y, TL064, TL064A, TL064B, TL064Y LOW-POWER JFET-INPUT OPERATIONAL AMPLIFIERS

SLO6073F – NOVEMBER 1976 – REVISED JANUARY 1993

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

PARAMETER	TEST CONDITIONS†	TL061C TL062C TL064C			TL061AC TL062AC TL064AC			UNIT
		MIN	TYP	MAX	MIN	TYP	MAX	
$V_{IO}$	Input offset voltage $V_O = 0$ , $R_S = 50 \Omega$	$T_A = 25^\circ\text{C}$			$T_A = 25^\circ\text{C}$			mV
$\mu V_{IO}$	Temperature coefficient of input offset voltage $V_O = 0$ , $R_S = 50 \Omega$ $T_A = \text{Full range}$	10			10			$\mu\text{V}/^\circ\text{C}$
$I_{IO}$	Input offset current $V_O = 0$	$T_A = 25^\circ\text{C}$			$T_A = 25^\circ\text{C}$			$\mu\text{A}$
$I_{IB}$	Input bias current‡ $V_O = 0$	$T_A = 25^\circ\text{C}$			$T_A = 25^\circ\text{C}$			$\mu\text{A}$
$V_{ICR}$	Common-mode input voltage range $T_A = 25^\circ\text{C}$	$\pm 11$ to 15			$\pm 11$ to 15			V
$V_{OM}$	Maximum peak output voltage swing $R_L = 10 \text{ k}\Omega$ , $T_A = 25^\circ\text{C}$	$\pm 10$ $\pm 13.5$			$\pm 10$ $\pm 13.5$			V
	$R_L \geq 10 \text{ k}\Omega$ , $T_A = \text{Full range}$	$\pm 10$			$\pm 10$			
$A_{VD}$	Large-signal differential voltage amplification $V_O = \pm 10$ V, $R_L \geq 10 \text{ k}\Omega$	$T_A = 25^\circ\text{C}$			$T_A = 25^\circ\text{C}$			V/mV
$B_f$	Unity-gain bandwidth $R_L = 10 \text{ k}\Omega$ , $T_A = 25^\circ\text{C}$	1			1			MHz
$r_i$	Input resistance $T_A = 25^\circ\text{C}$	$10^{12}$			$10^{12}$			$\Omega$
CMRR	Common-mode rejection ratio $V_{IC} = V_{ICRmin}$ , $V_O = 0$ , $R_S = 50 \Omega$ , $T_A = 25^\circ\text{C}$	70 86			80 86			dB
KSVR	Supply-voltage rejection ratio ( $\Delta V_{CC\pm}/\Delta V_{IO}$ ) $V_{CC} = \pm 9$ V to $\pm 15$ V, $V_O = 0$ , $R_S = 50 \Omega$ , $T_A = 25^\circ\text{C}$	70 95			80 95			dB
$P_D$	Total power dissipation (each amplifier) $V_O = 0$ , No load	$T_A = 25^\circ\text{C}$			$T_A = 25^\circ\text{C}$			mW
$I_{CC}$	Supply current (each amplifier) $V_O = 0$ , No load	$T_A = 25^\circ\text{C}$			$T_A = 25^\circ\text{C}$			$\mu\text{A}$
$V_{O1}/V_{O2}$	Crosstalk attenuation $A_{VD} = 100$ , $T_A = 25^\circ\text{C}$	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  $0^\circ\text{C}$  to  $70^\circ\text{C}$  for TL06\_C, TL06\_AC, and TL06\_BC and  $-40^\circ\text{C}$  to  $85^\circ\text{C}$  for TL06\_L.

‡ 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.

# Worst Case Analysis Using Analog Workbench

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

cadence Parameter Entry: TL064\_AGB

Similar	Copy	Body	Location	Utility
---------	------	------	----------	---------

Model Parameters Level 1

Offset voltage	(VOS	)	3 m (4.5 m; 1.5 m; FLAT)	V
Input bias current	(IB	)	30 p (7 n; 15 p; FLAT)	A
Input offset current	(IBOS	)	5 p (3 n; 2.5 p; FLAT)	A
Open-loop gain	(AO	)	6000 (2000 ; 2000 ; FLAT)	V/V
Gain-BW product	(GBW	)	1 M (10 %; 10 %; FLAT)	Hz
Positive slew rate	(SRP	)	sra ( ; ; )	V/sec
Negative slew rate	(SRM	)	sra ( ; ; )	V/sec

Model Parameters Level 2

Common-mode reject.	(CMRR	)	20000 (10000 ; 10000 ; FLAT)	V/V
GBW excess phase	(PO	)	( ; ; )	deg
Quies. power dissip.	(PD	)	6 m (1.5 m; 1.5 m; FLAT)	W
I short(+ sink)	(ISCP	)	( ; ; )	A
I short(- source)	(ISCM	)	( ; ; )	A
D.C. output res	(ROUT	)	( ; ; )	ohms
A.C. output res	(ROAC	)	( ; ; )	ohms

Device Placement: /TL064\_AGB  
Device Type: FET Input Opamp  
Similar Device:  
Body: TL064\_AGB  
Similar Device Library:

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

# Worst Case Analysis Using Analog Workbench

Now the design...

The screenshot shows the CONCEPT Viewport 1 interface. On the left is a toolbar with various icons for navigation and editing. The main workspace contains a circuit diagram with an input terminal 'A' and an output terminal 'B'. Two transfer function blocks are shown in series:

$$H(s) = \frac{B_2s^2 + B_1s + B_0}{s^2 + A_1s + A_0}$$

Both blocks have the same parameters:

$$B_2=0, B_1=0, B_0=W^2, A_1=A*W, A_0=W^2$$

Below the transfer functions, the user variables are defined:

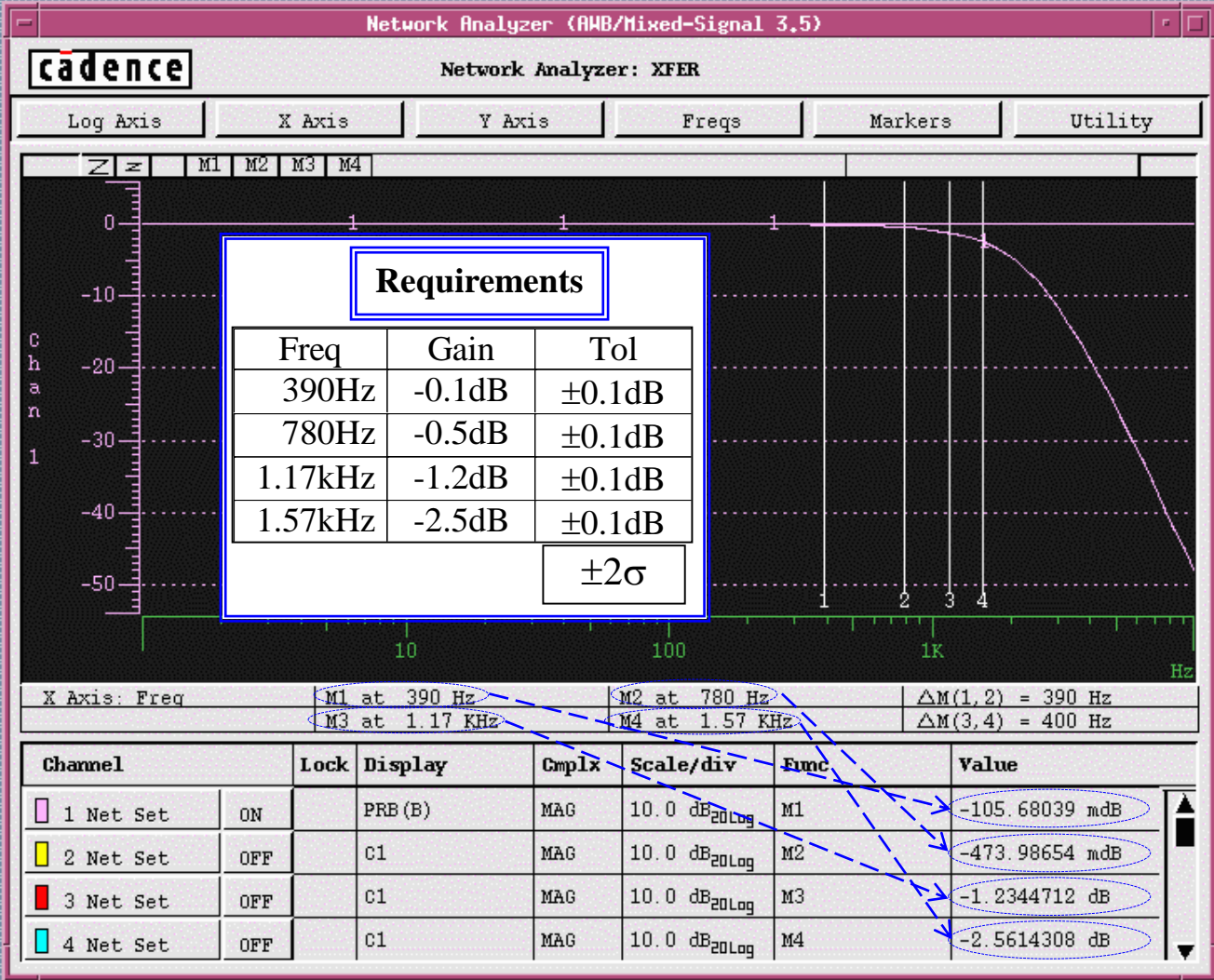
```
User Variables:
W=15750
A=1.575
```

At the bottom of the window, the status bar shows: Active View, DWG: XFER.SPICE.1.1 (In Context), GRID: 0.1000 2, DIR: bin.wrk. A console window at the bottom displays server support information for clients: CONCEPT, EDITTOOL, and FORMTOOL.

The requirement is that when implemented the above transfer function should be within  $\pm 0.1\text{dB}$  at four frequencies with a  $\pm 2\sigma$  confidence interval

# Worst Case Analysis Using Analog Workbench

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



# Worst Case Analysis Using Analog Workbench

A circuit implementation is proposed and simulated against the requirements

The screenshot shows the Analog Workbench interface with a circuit diagram. The circuit includes two op-amps, U1 and U2, both labeled TL064\_AGB. U1 is configured as a non-inverting amplifier with feedback from the output to the non-inverting input. U2 is configured as an inverting amplifier. The circuit includes resistors R1, R2, R3, and R4, and capacitors C1, C2, C3, and C4. A voltage source is connected to the input of U1.

Default Variables:

Component	Value	Tolerance	Model
R1	14.3E3	2%	FLAT
R2	5.49E3	2%	FLAT
R3	14.3E3	2%	FLAT
R4	5.49E3	2%	FLAT
C1	0.01E-6	5%	FLAT
C2	0.005E-6	5%	FLAT
C3	0.01E-6	5%	FLAT
C4	0.005E-6	5%	FLAT
U1	15	2%	1, FLAT
U2	-15	2%	1, FLAT

User Variables:

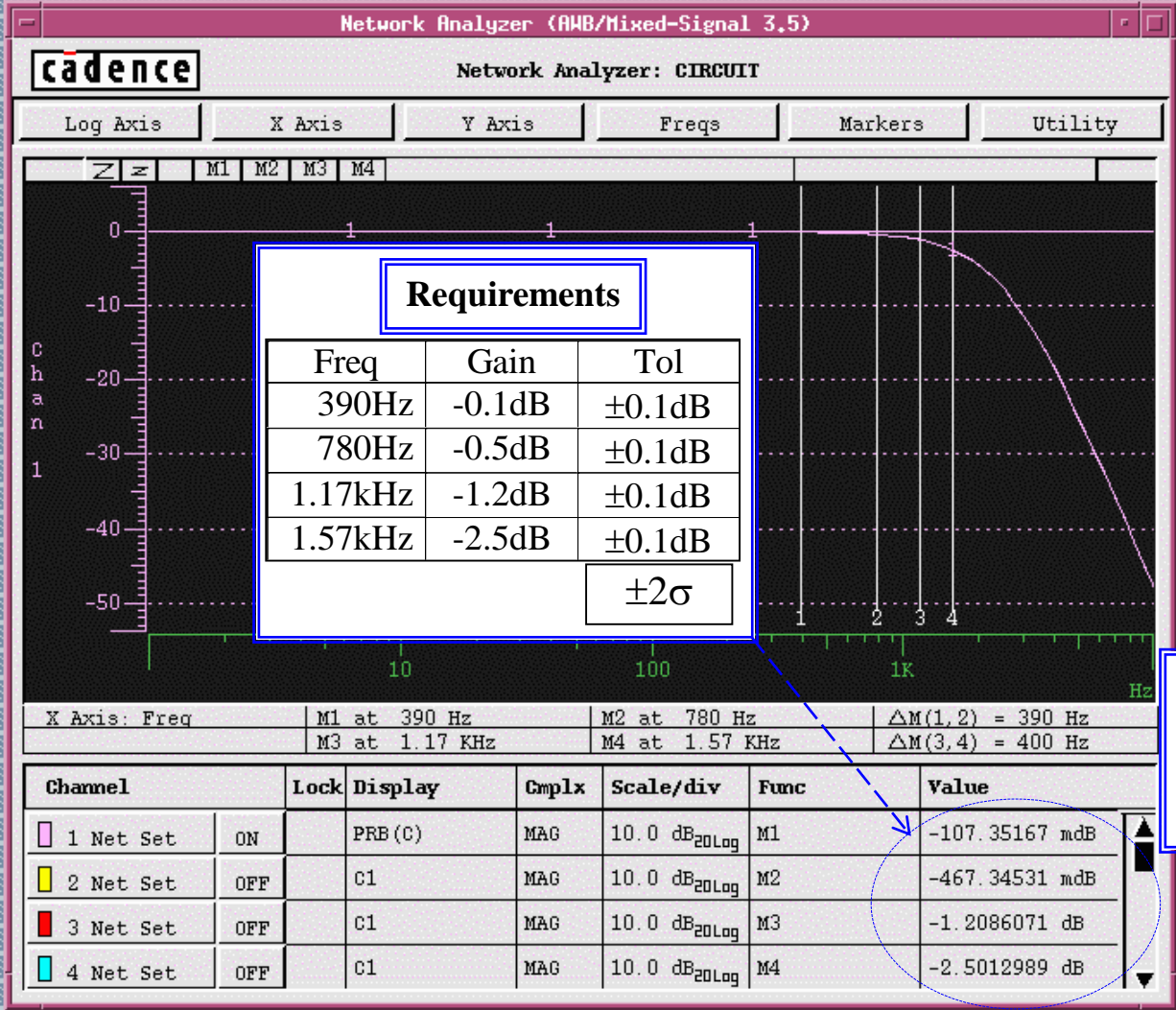
```

writing connectivity file...
writing dependency file...
...written
    
```

Parameterized model for the op amp was created

Passive part values and tolerances were also determined

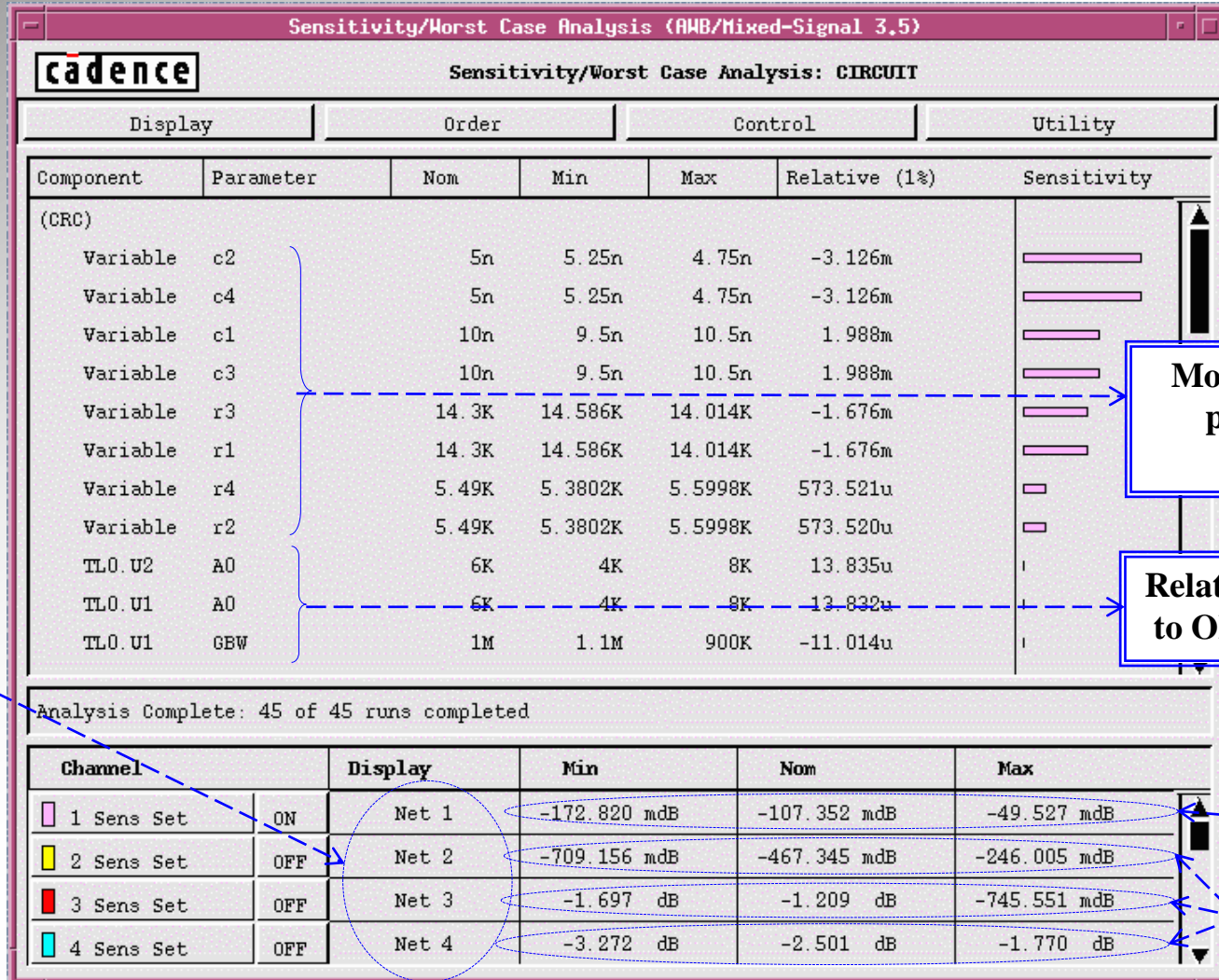
# Worst Case Analysis Using Analog Workbench



**Simulated  
circuit matches  
closely with  
requirements**

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



Most sensitive to passive part variations

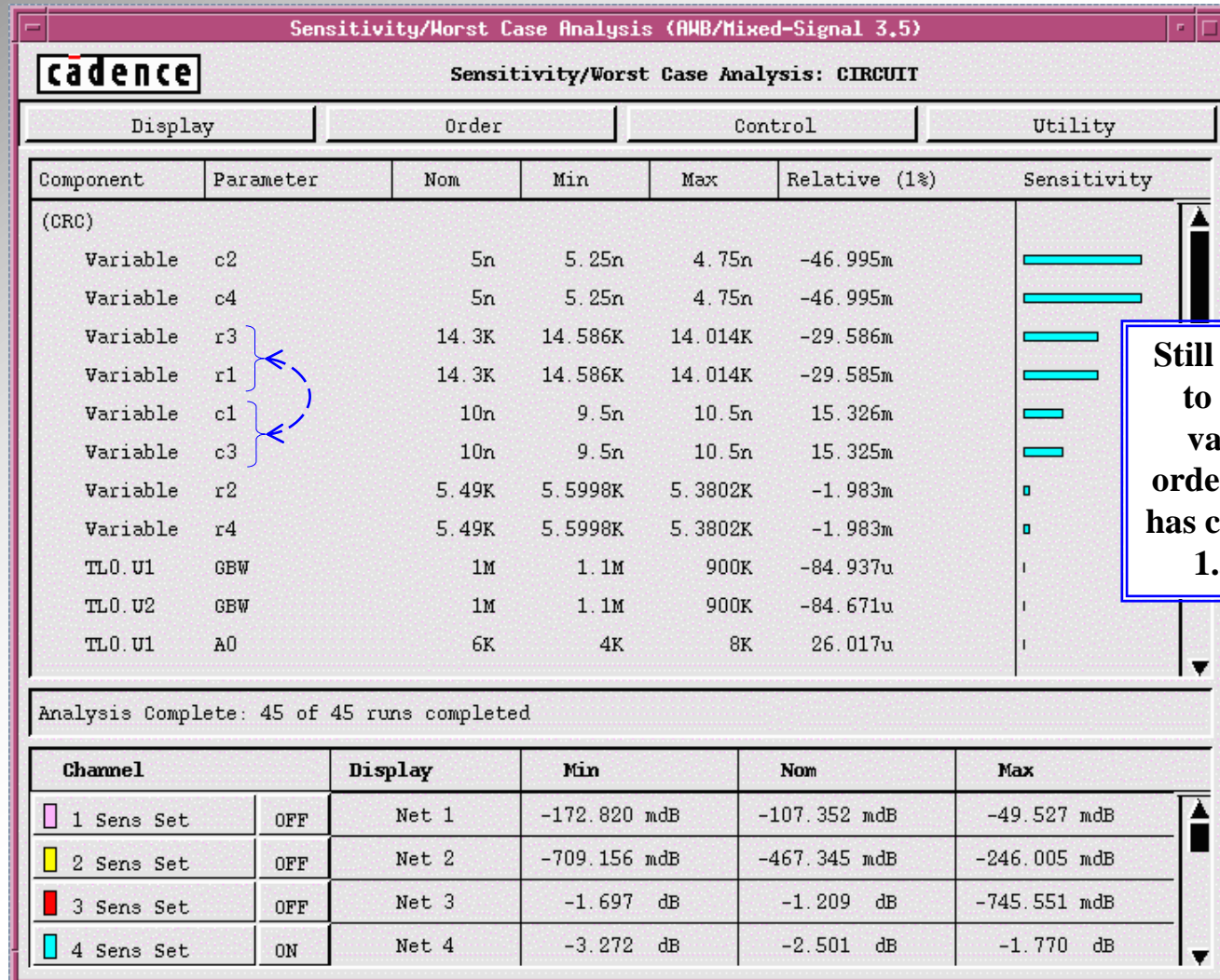
Relatively insensitive to OPAMP changes

Keyed to Network Analyzer marker functions

In spec

Out of spec

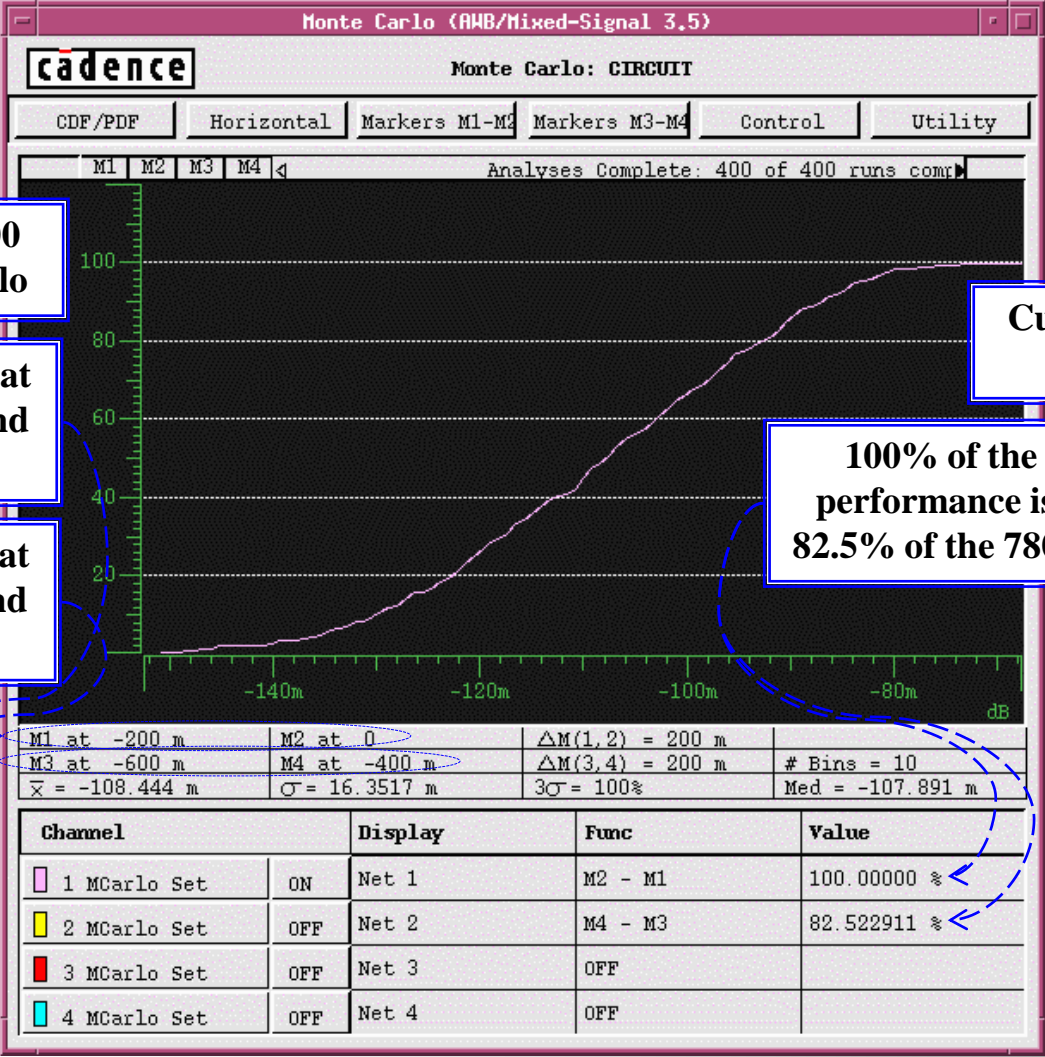
# Worst Case Analysis Using Analog Workbench



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



# Worst Case Analysis Using Analog Workbench



Next perform a 400 sample Monte Carlo

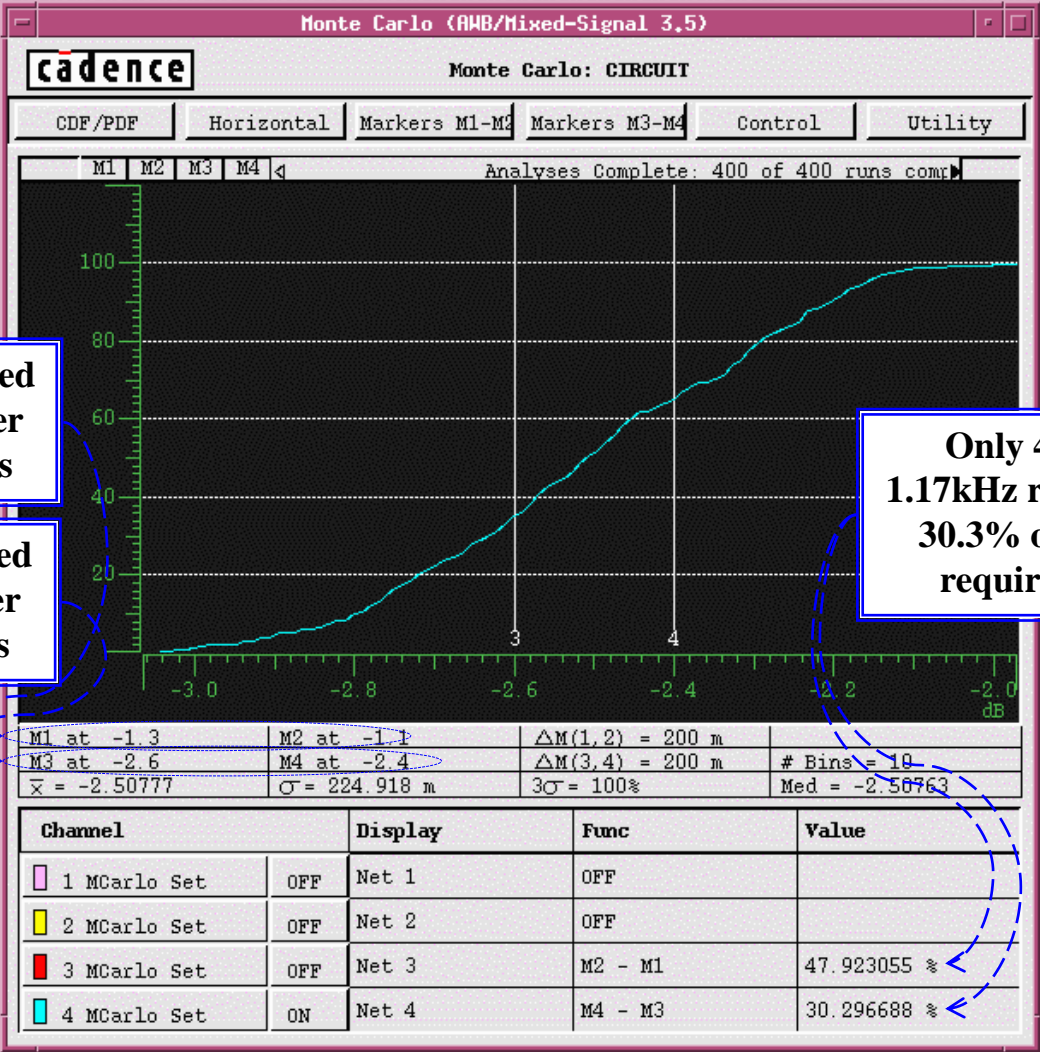
M1 and M2 set at 390Hz upper and lower limits

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

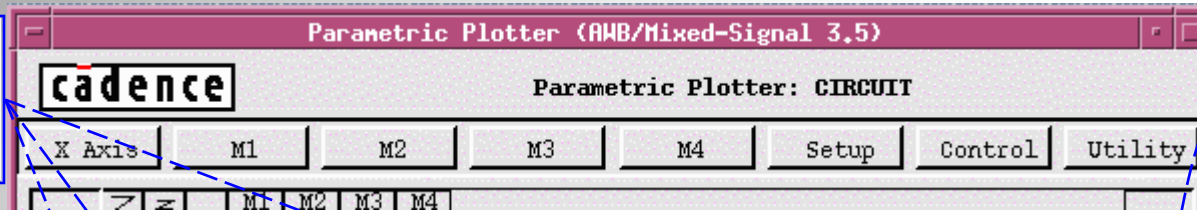
Only 47.9% of the 1.17kHz requirement and 30.3% of the 1.57kHz requirement is met

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

# Worst Case Analysis Using Analog Workbench

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	$\Delta M(1,2) = 500p$		
M3 at 4.75n	M4 at 5.25n	$\Delta M(3,4) = 500p$		
	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	$\Delta M(1,2) = 600$		
M3 at 14K	M4 at 14.6K	$\Delta M(3,4) = 600$		
	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	$\Delta M(1,2) = 1n$		
M3 at 9.5n	M4 at 10.5n	$\Delta M(3,4) = 1n$		
	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	$\Delta M(1,2) = 220$		
M3 at 5.38K	M4 at 5.6K	$\Delta M(3,4) = 220$		
	Display	Func	@Param value	Value
Plot Set		M1 - M2	0.000000	-7.7176333mdB

## Worst Case Analysis Using Analog Workbench

Purchase tolerance =  $\pm 1\%$       Original Worksheet

Aging (10 years) =  $\pm 1.5\%$

Temperature (+75°C to -55°C) =  $\pm 0.5\%$

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

Purchase tolerance = 0%      Modified Tolerance

Aging (5 years) =  $\pm 0.75\%$

Temperature (+40°C to 0°C) =  $\pm 0.25\%$

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

**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  $\pm 0.8\%$  and likewise we will reduce the capacitor tolerance by the same proportion to  $\pm 2\%$**

**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

**Default Variables:**

Tempcos (ppm):	Smoke Limits:	R1=14.3E3*LINK1
RTHPL=0	RMAX=25	R2=5.49E3*LINK1
RTHPD=0	RSMAX=0.005	R3=14.3E3*LINK1
	RTMAX=200	R4=5.49E3*LINK1
	CMAX=50	C1=0.01E-6*LINK2
	CSMAX=125	C2=0.005E-6*LINK2
	CTMAX=125	C3=0.01E-6*LINK2
	CMAX=1	C4=0.005E-6*LINK2
	LMAX=5	
	DSMAX=500	
	IMAX=1	
	VMAX=12	

**User Variables:**

VP=15,	2,	1,	FLAT
VM=-15,	2,	1,	FLAT
LINK1=1,	0.8%,	0.8%,	GAUSS0.4
LINK2=1,	2%,	2%,	GAUSS0.4

**To reduce the Severity of the WCA use:**

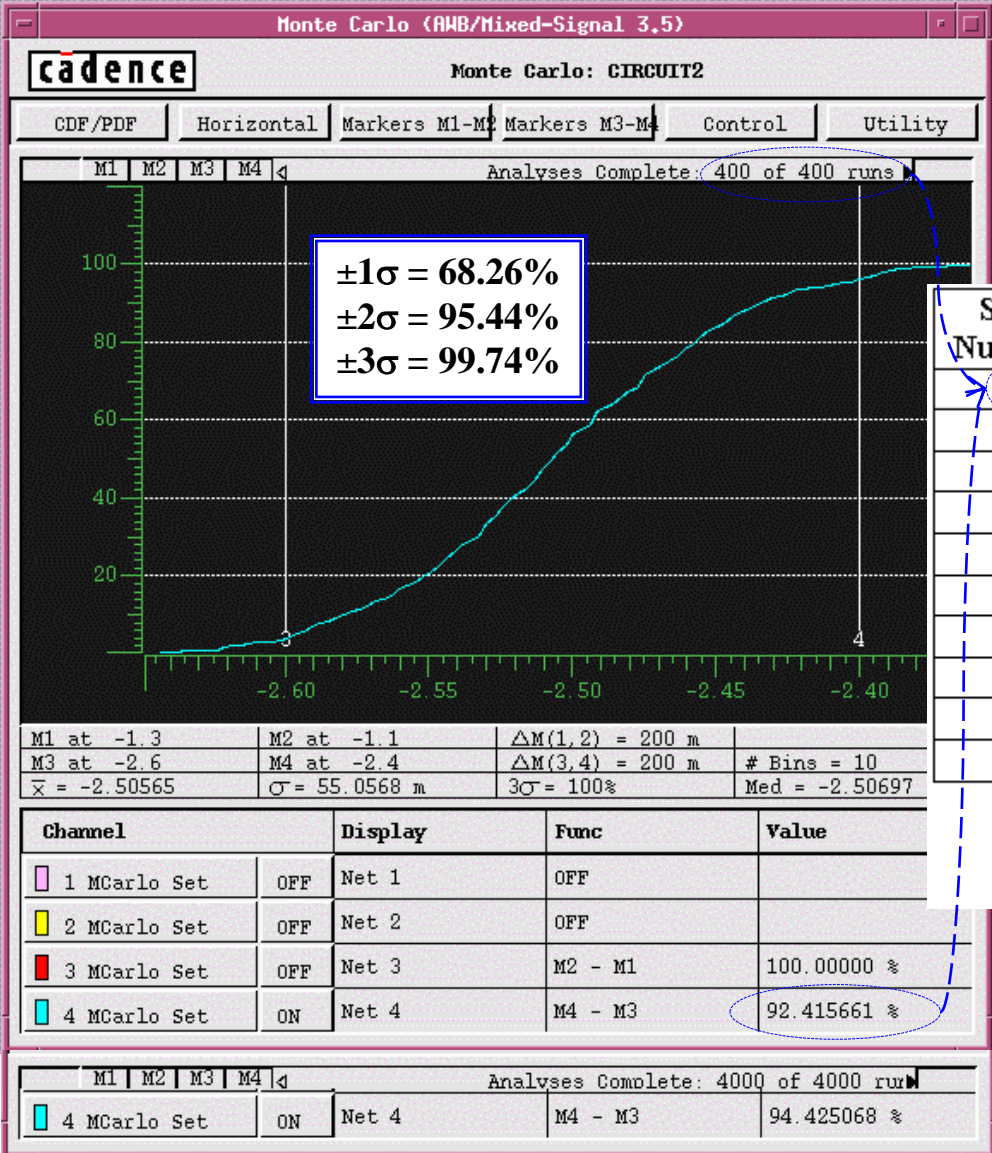
1. Linked parameters
2. Gaussian distributions
3. Reduced tolerances

Active View    DWG: CIRCUIT2.SPICE.1.1  
 GRID: 0.1000 2    DIR: bin.wrk

Reading CIRCUIT2.SPICE.3.5 into drawing #1.  
 ed .spice.1.1  
 Reading CIRCUIT2.SPICE.1.1 into drawing #1.

# 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%

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.

94.629%	= MEAN
1.3132%	= STDEV
1.7244%	= VARIANCE

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**