

HEWLETT  PACKARD

HP-65

E.E. PAC 2

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USING EE PAC 2

EE Pac 2 is a collection of programs designed to assist the microwave circuit designer. It also includes programs of use to the system designer. Each program in the pac includes a short description of the function the program performs, the equations used, instructions for use of the program, example problems with keystroke solutions, and a program listing.

Answers to the example problems are enclosed in parentheses following the problem statement as well as at the appropriate places in the keystroke solution. Intermediate results appearing between cards of a multiprogram sequence are enclosed in parentheses.

Many of the programs use the registers in a consistent manner so that intermediate results calculated by one program may be used directly in a related program without the necessity of writing it down and re-inputting it. A chart on page 98 shows how the registers are used.

FORMAT OF USER INSTRUCTIONS

The User Instruction Form that accompanies each program is a comprehensive guide to operating the program. The form is composed of five columns. Reading from left to right, the columns are labelled as follows: STEP, INSTRUCTIONS, INPUT-DATA/UNITS, KEYS, and OUTPUT-DATA/UNITS.

Instructions are to be executed in step-number order. Some User Instruction Forms have certain numbers repeated in which case the user must read ahead to determine which path to take.

The INSTRUCTIONS column gives instructions and comments regarding the operations to be performed.

The INPUT-DATA/UNITS column gives input variable names and specifies the units to be used, where applicable.

The KEYS column specifies the key or keys to be pressed to process the input data.

The OUTPUT-DATA/UNITS column explains the contents of the display after the appropriate keys have been pressed.



The prerecorded magnetic cards supplied with EE Pac 2 contain symbols which are intended to help the user run the programs without reference to the user instructions. The following table summarizes the symbols and their meanings.

SYMBOL	MEANING
v	input v
→v	calculate v
↓ v	input v or (if input is 0) compute v
v ₁ →v ₂	input v ₁ and compute v ₂
v ₁ ↑v ₂	input v ₁ , press ENTER then input v ₂
→v ₁ , v ₂	compute v ₁ , then press R/S to compute v ₂
↓ v ₁ ↑v ₂	on input: v ₁ ↑v ₂ on output: →v ₂ , v ₁

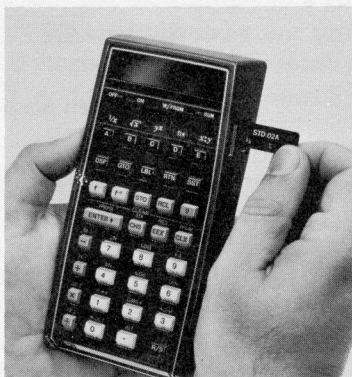
ENTERING A PROGRAM

From the card case supplied with this application pac, select a program card.

Set W/PRGM-RUN switch to RUN.

Turn the calculator ON. You should see 0.00

Gently insert the card (printed side up) in the right, lower slot as shown. When the card is part way in, the motor engages it and passes it out the left side of the calculator. Sometimes the motor engages but does not pull the card in. If this happens, push the card a little farther into the machine. Do not impede or force the card; let it move freely. (The display will flash if the card reads improperly. In this case, press **CLX** and reinsert the card.)

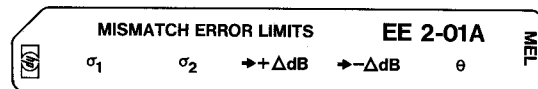


When the motor stops, remove the card from the left side of the calculator and insert it in the upper "window slot" on the right side of the calculator.

The program is now stored in the calculator. It remains stored until another program is entered or the calculator is turned off.



MISMATCH ERROR LIMITS



In a microwave circuit having source and load reflection coefficients Γ_S and Γ_L , there is an uncertainty of power transfer given by

$$+\Delta\text{dB} = +20 \log (1 + \rho_S \rho_L)$$

$$-\Delta\text{dB} = 20 \log (1 - \rho_S \rho_L)$$

where

$$\rho = |\Gamma|$$

There is a maximum phase error

$$\theta = \pm \sin^{-1} |\rho_S \rho_L|$$

associated with such a mismatch also.

This program computes the above quantities from standing wave ratios or reflection coefficients.

Note:

Mismatch error limits may be manually stored for later use in any unused register (R_3 through R_9).

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter MEL (EE2-01A)			
2	Input			
	SWR _S	σ_S	A	ρ_S
	SWR _L	σ_L	B	ρ_L
	or			
	Input			
	Source reflection coefficient	ρ_S	STO 1	ρ_S
	Load reflection coefficient	ρ_L	STO 2	ρ_L
3	Compute			
	Positive mismatch error limit		C	$+\Delta\text{dB}$
	Negative mismatch error limit		D	$-\Delta\text{dB}$
	Phase error		E	θ

Example:

Suppose we wish to determine the attenuation of an attenuator having SWR's of 1.2 and 1.25 at its input and output ends respectively. The generator's SWR is 1.06 and the detector's is 1.11. What is the uncertainty of the reference level (set before inserting the attenuator into the system)? (± 0.013 dB) Assuming that the attenuation is so large that generator-detector interaction may be neglected, what is the uncertainty of the level measured with the attenuator in the system? ($+0.086$ dB, -0.087 dB) What is the maximum phase error to be expected? (0.332°)

Keystrokes:

Enter MEL (EE2-01A)

```

1.06 [A] 1.11 [B] [C] [DSP] [•] [3] → 0.013 [STO] [3]
[D] → -0.013 [STO] [4]
1.06 [A] 1.2 [B] [C] → 0.023 [STO] [+ ] [3]
[D] → -0.023 [STO] [+ ] [4]
1.11 [A] 1.25 [B] [C] → 0.050 [STO] [+ ] [3]
[D] → -0.050 [STO] [+ ] [4]
[RCL] [3] → 0.086
[RCL] [4] → -0.087
[E] → 0.332
  
```

MULTIPLE MISMATCH ERROR LIMITS

MULTIPLE MISMATCH ERROR LIMITS **EE 2-02A**
$$\sigma_S \uparrow \sigma_L \quad \sigma_1 \uparrow \sigma_2 \quad L, \text{dB} \quad \rightarrow +\Delta, -\Delta$$

When a device is inserted between a source and load in a simple insertion-loss measurement scheme, mismatch error due to secondary reflections may be calculated from the equation

$$\text{Error (dB)} = 20 \log \left| \frac{1 - \Gamma_S \Gamma_L}{1 - \Gamma_S \Gamma_1 - \Gamma_2 \Gamma_L + \Gamma_S \Gamma_L \Gamma_1 \Gamma_2 - T^2 \Gamma_S \Gamma_L} \right|$$

where

 Γ_s = complex reflection coefficient of source Γ_L = complex reflection coefficient of load

Γ_1 = complex reflection coefficient of device input

Γ_2 = complex reflection coefficient of device output

$$T = \text{power transmission coefficient} = 10^{-\frac{\text{LOSS}}{10}}$$

This program computes the maximum and minimum error values which are given by

$$+\Delta\text{dB} = 20 \log \left(\frac{1 + \rho_S \rho_L}{1 - \rho_S \rho_1 - \rho_2 \rho_L + \rho_S \rho_L \rho_1 \rho_2 - T^2 \rho_S \rho_L} \right)$$

$$-\Delta \text{dB} = 20 \log \left(\frac{1 - \rho_S \rho_L}{1 + \rho_S \rho_1 + \rho_2 \rho_L - \rho_S \rho_L \rho_1 \rho_2 + T^2 \rho_S \rho_L} \right)$$

where

$$\rho_i = |\Gamma_i|$$

References:

Adam, Steven F., *Microwave Theory and Applications*, Prentice-Hall, Inc., 1969.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter MMEL (EE2-02A)			
2	Input source and load SWR's			
	Source SWR	σ_S		σ_S
	Load SWR	σ_L	A	ρ_S
3	Input attenuator SWR's			
	Input SWR	σ_1		σ_1
	Output SWR	σ_2	B	ρ_1
4	Input attenuation	L, dB	C	T^2
5	Compute mismatch uncertainty			
	Upper limit		D	$+\Delta dB$
	Lower limit		R/S	$-\Delta dB$

Example:

A source of SWR 1.06 is used with a detector of SWR 1.11 to measure the attenuation of a 3 dB pad having 1.2 and 1.25 input and output SWR's. What is the measurement uncertainty? (+0.090, -0.089) What is the uncertainty for a 50 dB pad? (+0.087, -0.086)

Keystrokes:

Enter MMEL (EE2-02A)

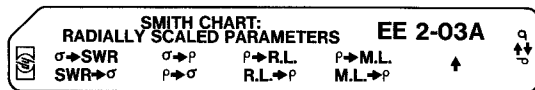
1.06 **↑** 1.11 **A** 1.2 **↑** 1.25 **B** 3 **C** **D** $\longrightarrow$ 0.090

R/S $\longrightarrow$ -0.089

50 **C** **D** $\longrightarrow$ 0.087

R/S $\longrightarrow$ -0.086

SMITH CHART: RADIALLY SCALED PARAMETERS



The distance between a point on a Smith Chart and its center may be measured by a number of parameters. Some of the most commonly used ones are standing wave ratio, reflection coefficient, return loss, and mismatch loss.

The parameters

σ = voltage standing wave ratio

SWR = standing wave ratio expressed in decibels

ρ = reflection coefficient

R.L. = return loss

M.L. = mismatch loss

are related as follows:

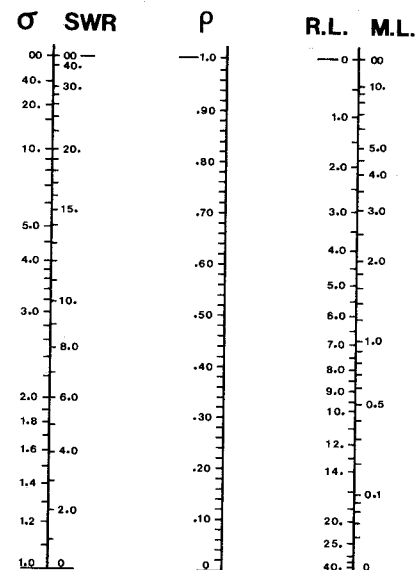
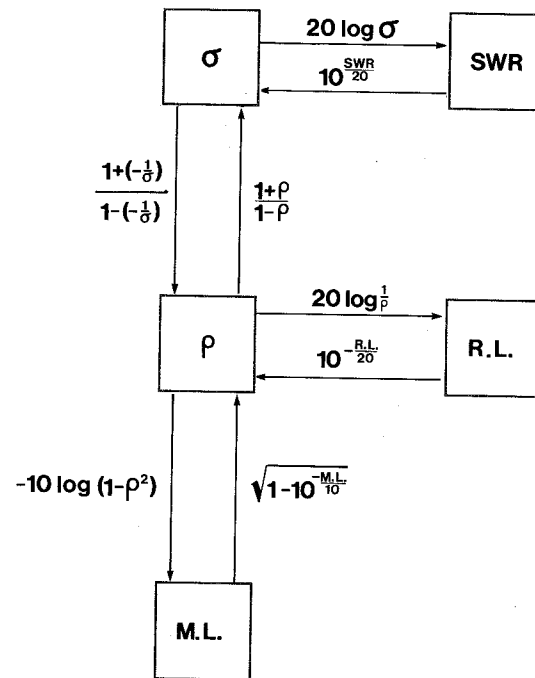
$$\text{SWR} = 20 \log \sigma$$

$$\text{R.L.} = 20 \log \frac{1}{\rho}$$

$$\sigma = \frac{1 + \rho}{1 - \rho}$$

$$\text{M.L.} = -10 \log (1 - \rho^2)$$

These relationships are perhaps more clearly seen in this sketch:



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter $\sigma \leftrightarrow \rho$ (EE2-03A)			
2	Convert as appropriate			
	Standing wave ratio to ratio			
	in dB	σ	E A	SWR, dB
	Standing wave ratio in dB			
	to ratio	SWR, dB	A	σ
	Standing wave ratio to re-			
	flection coefficient	σ	E B	ρ
	Reflection coefficient to			
	standing wave ratio	ρ	B	σ
	Reflection coefficient to			
	return loss	ρ	E C	R.L., dB
	Return loss to reflection			
	coefficient	R.L., dB	C	ρ
	Reflection coefficient to			
	mismatch loss	ρ	E D	M.L., dB
	Mismatch loss to reflection			
	coefficient	M.L., dB	D	ρ

Example 1:Convert a 6 dB SWR to σ . (2.00)

Keystrokes:

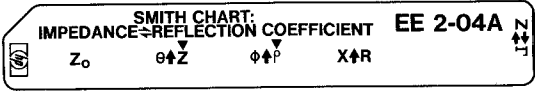
6 **A** $\longrightarrow$ 2.00**Example 2:**

Convert a standing wave ratio of 5 to mismatch loss. (2.55 dB)

Keystrokes:

5 **A** **E** **B** **E** **D** $\longrightarrow$ 2.55

SMITH CHART:
IMPEDANCE ↔ REFLECTION COEFFICIENT



Any point on a Smith Chart may be referenced in a number of different coordinates. This program converts between impedance and reflection coefficient. For a system having characteristic impedance Z_0 , the impedance and reflection coefficient are related by

$$\vec{\Gamma} = \rho \angle \phi = \frac{\frac{Z}{Z_0} - 1}{\frac{Z}{Z_0} + 1}$$

and

$$Z = Z_0 \angle \theta = Z_0 \frac{1 + \vec{\Gamma}}{1 - \vec{\Gamma}}$$

where

- $\vec{\Gamma}$ = complex reflection coefficient
- $\rho = |\vec{\Gamma}|$
- $\phi = \angle \vec{\Gamma}$
- Z = impedance
- $Z = |Z|$
- $\theta = \angle Z$

The resistive and reactive components (R, X) of Z may be input instead of Z and θ .

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter $Z \rightleftharpoons \Gamma$ (EE2-04A)			
2	Input characteristic impedance	Z_0, Ω	A	Z_0, Ω
3	Input impedance			
	Angle	θ, deg	↑	θ, deg
	Magnitude	Z, Ω	B	0.00
	or			
	Reactive component	X, Ω	↑	X, Ω
	Resistive component	R, Ω	D	
	then compute reflection coefficient			
	Magnitude		C	ρ
	Angle		R/S*	ϕ, deg
4	Input reflection coefficient			
	Angle	ϕ, deg	↑	ϕ, deg
	Magnitude	ρ	C	0.00
	then compute impedance			
	Magnitude		B	Z, Ω
	Angle		R/S*	θ, deg
	or			
	Resistive component		B	
			R→P	R, Ω
	Reactive component		R/S*	X, Ω
	* Note: Continued pressing of			
	R/S will interchange the out-			
	puts.			

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Example 1:

A 50Ω system is terminated with an impedance of $62 \angle 37^\circ$. What is the reflection coefficient? ($0.35 \angle 70.19^\circ$)

Keystrokes:

Enter $Z \neq \Gamma$ (EE2-04A)

50 **A** 37 **↑** 62 **B** **C** → 0.35
R/S → 70.19

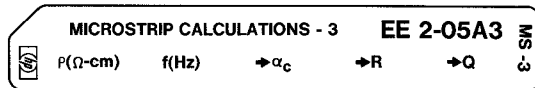
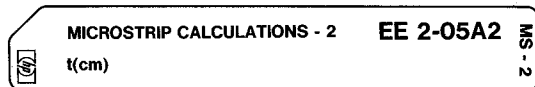
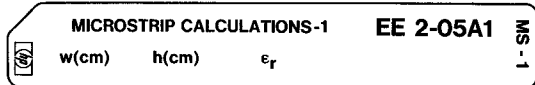
Example 2:

A reflection coefficient of $.5 \angle 7^\circ$ is observed in a 72Ω system. What are R and X? (209.75, 34.08)

Keystrokes:

72 **A** 7 **↑** .5 **C** **B** **f⁻¹** **R→P** → 209.75
R/S → 34.08

MICROSTRIP CALCULATIONS



This program is composed of three cards. The first one accepts conductor width w , dielectric thickness h , and relative permittivity ϵ_r , and computes relative phase velocity v_r and characteristic impedance Z_c for lossless line. The following formulas, accurate to $\pm 0.25\%$ for

$$0 \leq \frac{w}{h} \leq 10,$$

are used.

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 10 \frac{h}{w} \right)^{-1/2}$$

$$v_r = \frac{1}{\sqrt{\epsilon_{\text{eff}}}}$$

$$Z_0 = \begin{cases} 60 \ln \left(8 \frac{h}{w} + \frac{w}{4h} \right) & , \quad \frac{w}{h} \leq 1 \\ \frac{120\pi}{\frac{w}{h} + 2.42 - 0.44 \frac{h}{w} + \left(1 - \frac{h}{w} \right)^6} & , \quad \frac{w}{h} > 1 \end{cases}$$

$$Z_c = v_r Z_0$$

where

ϵ_r = relative permittivity of dielectric

ϵ_{eff} = effective permittivity of dielectric

h = dielectric thickness, same units as w

w = width of microstrip, same units as h

v_r = relative phase velocity of lossless line

Z_0 = characteristic impedance of corresponding air line, Ω

Z_c = characteristic impedance of lossless microstrip, Ω

The second card accepts the conductor thickness and computes a normalized conductor loss A .

$$A = \begin{cases} \frac{20}{\ln 10} \frac{h}{w Z_0} \frac{dB}{\Omega} & , \text{ uniform current distribution} \\ \frac{10}{\pi \ln 10} \frac{\left(8 \frac{h}{w} - \frac{w}{4h} \right) \left(1 + \frac{h}{w} + \frac{h}{w} \frac{\partial w}{\partial t} \right)}{Z_0 e^{Z_0/60}} \frac{dB}{\Omega} & , \quad \frac{w}{h} \leq 1 \\ \frac{Z_0}{720\pi^2 \ln 10} \left[1 + 0.44 \frac{h^2}{w^2} + \frac{6h^2}{w^2} \left(1 - \frac{h}{w} \right)^5 \right] \\ \times \left[1 + \frac{w}{h} + \frac{\partial w}{\partial t} \right] \frac{dB}{\Omega} & , \quad \frac{w}{h} > 1 \end{cases}$$

where

$$\frac{\partial w}{\partial t} = \begin{cases} \frac{1}{\pi} \ln \frac{4\pi w}{t} & , \quad \frac{w}{h} \leq \frac{1}{2\pi} \\ \frac{1}{\pi} \ln \frac{2h}{t} & , \quad \frac{w}{h} > \frac{1}{2\pi} \end{cases}$$

The third card accepts conductor resistivity ρ and frequency f and computes copper loss α_c , resistance per unit length R , and unloaded quality factor Q_0 .

$$\alpha_0 = \frac{R_S A}{h}$$

$$R_S = \sqrt{\pi f \mu_0 \rho}$$

$$\mu_0 = 4\pi \times 10^{-9} \text{ H/cm}$$

$$\alpha_c = \frac{\alpha_0}{v_r}$$

$$Q_0 = \frac{20\pi}{\ln 10} \frac{f}{c v_r \alpha}$$

$$c = 3 \times 10^8 \text{ cm/s}$$

The second card may be omitted from the series if only the uniform current distribution is desired.

Reference:

M. V. Schneider, "Microstrip Lines for Microwave Integrated Circuits," *Bell System Technical Journal*, 48, No. 5 (May-June 1969).



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter MS-1 (EE2-05A1)			
2	Input			
	Width of microstrip	w, cm	A	w, cm
	Thickness of dielectric	h, cm	B	w/h
3	Input relative permittivity and			
	compute relative phase velocity			
	of lossless line	ϵ_r	C	v_r
4	Compute characteristic imped-			
	ance of lossless line		R/S	Z_c
5	If a uniform current distribution			
	is assumed, skip to step 8			
6	For Schneider's non-uniform			
	current distribution, enter			
	MS-2 (EE2-05A2)			
7	Input line thickness	t, cm	A	A, dB/ Ω
8	Enter MS-3			
9	Input			
	Resistivity	ρ , Ω -cm	A	
	Frequency	f, Hz	B	α_c , dB/cm
10	Display as desired			
	Copper loss		C	α_c , dB/cm
	Resistance per unit length		D	R, Ω /cm
	Unloaded Q		E	Q_0
11	If card 2 has been run and it is			
	desired to recompute using the			
	uniform current assumption,			
	press T SF2 and return to step			
	9.			

Example 1:

What is the impedance of a microstrip having width 1.9 cm spaced 1.9 cm from a ground plane by a dielectric of relative permittivity $\epsilon_r = 1.032$? (125.31 Ω)

Keystrokes:

Enter MS-1 (EE2-05A1)

1.9 **A** 1.9 **B** 1.032 **C** $\longrightarrow$ 125.31

Example 2:

If the microstrip of example 1 is 0.00254 cm thick and has a bulk resistivity of 1.7 $\mu\Omega$ -cm, what is the attenuation at 30 GHz, assuming a non-uniform current distribution? (1.64×10^{-3} dB/cm)

Keystrokes:

Enter MS-1 (EE2-05A1)

1.9 **A** 1.9 **B** 1.032 **C** $\longrightarrow$ 125.31

Keystrokes:

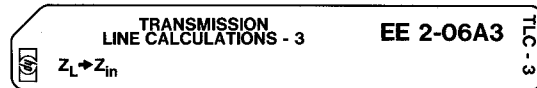
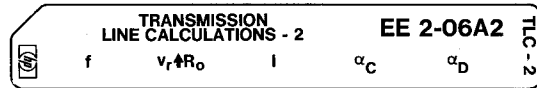
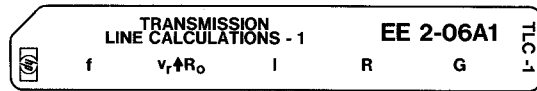
Enter MS-2 (EE2-05A2)

.00254 **A** $\longrightarrow$ 0.65

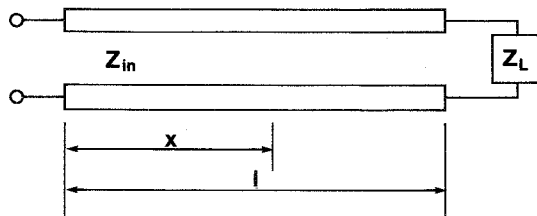
Enter MS-3 (EE2-05A3)

1.7 **EEX** **CHS** **6** **A** 30 **EEX** 9 **B** $\longrightarrow$ 1.64×10^{-3}

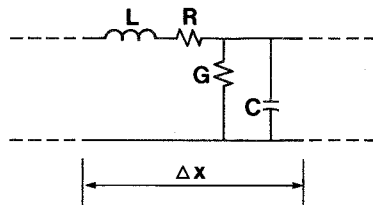
TRANSMISSION LINE CALCULATIONS



This program computes the input impedance of lossy transmission line terminated in Z_L . Cards 1 and 3 provide an exact solution when the distributed line parameters R_0 ($=\sqrt{L/C}$), R , and G are given and cards 2 and 3 provide an approximate solution when R_0 , copper loss and dielectric loss are given. The inputs to card 2 may be provided automatically by MS-3 (EE2-05A3).



MODEL



The transmission line shown has a lumped model composed of elements L , C , R , and G . From this model the following equations can be derived

Let

$$R_0 = \sqrt{\frac{L}{C}}$$

$$r = \frac{R}{L} = \frac{vR}{R_0}$$

$$g = \frac{G}{C} = v R_0 G$$

$$\omega = 2\pi f$$

where

L = inductance/unit length

C = capacitance/unit length

R = resistance/unit length

G = conductance/unit length

$$v = 3 \times 10^8 v_r$$

v_r = relative phase velocity

f = frequency, Hz

Then

$$Z_{in} = Z_0 \left(\frac{1 + \Gamma_L e^{-2\gamma l}}{1 - \Gamma_L e^{-2\gamma l}} \right)$$

where

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$

l = line length

Z_L = impedance of termination

Z_0 = characteristic impedance of line

γ = propagation constant of line

Z_0 and γ are computed differently depending on which solution is selected.

The exact solution is

$$Z_0 = \text{Re} \{Z_0\} + j \text{Im} \{Z_0\}$$

$$\text{Re} \{Z_0\} = \frac{R_0}{\sqrt{2(g^2 + \omega^2)}} \left[rg + \omega^2 + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{\frac{1}{2}}$$

$$\text{Im} \{Z_0\} = \frac{\pm R_0}{\sqrt{2(g^2 + \omega^2)}} \left[-(rg + \omega^2) + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{\frac{1}{2}}$$

in which the + sign is chosen when $g > r$

and the - sign is chosen when $g < r$

and

$$\gamma = \alpha + j\beta$$

$$\alpha = \frac{1}{\sqrt{2} v} \left[rg - \omega^2 + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{\frac{1}{2}}$$

$$\beta = \frac{1}{\sqrt{2} v} \left[\omega^2 - rg + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{\frac{1}{2}}$$

The approximate solution is

$$\text{Re} \{Z_0\} = R_0 \left[1 + \frac{1}{2} \left(\frac{\alpha_C - \alpha_D}{\beta_0} \right) \left(\frac{3\alpha_D + \alpha_C}{\beta_0} \right) \right]$$

$$\text{Im} \{Z_0\} = R_0 \left[\frac{\alpha_D - \alpha_C}{\beta_0} \right]$$

$$\alpha = \alpha_C + \alpha_D$$

$$\beta = \beta_0 \left[1 + \frac{1}{2} \left(\frac{\alpha_C - \alpha_D}{\beta_0} \right)^2 \right]$$

where

$$\alpha_C = \text{Copper loss, nepers/unit length} = \frac{1}{2} \frac{R}{R_0}$$

$$\alpha_D = \text{Dielectric loss, nepers/unit length} = \frac{1}{2} \text{ GR.}$$

$$\beta_0 = \frac{\omega}{v}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	If R and G are known, enter			
	TLC-1 (EE2-06A1)			
2	Input			
	Frequency	f, Hz	A	ω'
	Relative phase velocity	v_r	$\uparrow$	v_r
	Characteristic impedance of			
	lossless line	R_0, Ω	B	v_r
	Line length	l, cm	C	$ 2\gamma $
	Resistance of line per unit			
	length	R, Ω/cm	D	R/L
	Conductance of substrate			
	per unit length	G, S/cm	E	$L\gamma$
3	Enter TLC-3 (EE2-06A3)			
4	To compute input impedance,			
	input			
	Angle of terminating			
	impedance	$\angle Z_L, \text{deg}$	$\uparrow$	$\angle Z_L, \text{deg}$
	then Magnitude of terminating			
	impedance	$ Z_L , \Omega$	A	$ Z_{in} , \Omega$
			R/S	$\angle Z_{in}, \text{deg}$
	or			
1	If α_C and α_D are known, enter			
	TLC-2 (EE2-06A2)			
2	Input			
	Frequency	f, Hz	A	f, GHz
	Relative phase velocity	v_r	$\uparrow$	v_r
	Characteristic impedance of			
	lossless line	R_0, Ω	B	v_r
	Line length	l, cm	C	$2\beta_0 l$
	Copper loss per unit length	$\alpha_C, \Omega/\text{cm}$	D	$\alpha_C, \Omega/\text{cm}$
	Dielectric loss per unit length	$\alpha_D, \Omega/\text{cm}$	E	$L\gamma, \text{deg}$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
3	Continue with step 3 above			
	or			
1	If MS-3 (EE2-05A3) has just been run, enter TLC-2 (EE2-			
	06A2)			
2	Input			
	Line length	l, cm	C	$2\theta_0 l$
	Dielectric loss per unit length	α_D , Ω/cm	E	$L\gamma$, deg
3	Continue with step 3 above			

Example 1:

A transmission line has the following properties:

$$R = 1.2664 \Omega/\text{cm}$$

$$G = 0.000\,041\,87 \text{ S/cm}$$

$$R_0 = 55 \Omega$$

$$v_r = 0.85$$

What is the input impedance 3.5 cm of this line at 2 GHz if it is terminated in $Z_L = 75 \angle -30^\circ$? (48.0078 $\angle$ 28.4788°)

Keystrokes:

Enter TLC-1 (EE2-06A1)

2 9 A .85 55 B 3.5 C 1.2664 D
 .000 041 87 E $\longrightarrow$ (1.26)

Enter TLC-3 (EE2-06A3)

30 CHS 75 A DSP 4 $\longrightarrow$ 48.0078
 R/S $\longrightarrow$ 28.4799

Example 2:

A 4-cm gold ($\rho = 2.3 \mu\Omega\text{-cm}$) microstrip line of 50-mil width is on a 50-mil alumina ($\epsilon_r = 9.5$) substrate. Assuming a uniform current distribution and zero dielectric loss, what is the input impedance of the line at 124 MHz when it is terminated in 75Ω ? (70.66 $\angle$ -12.22)

Keystrokes:

Enter MSC-1 (EE2-05A1)

.05 + 2.54 X A B 9.5 C $\longrightarrow$ (49.54)

Enter MSC-3 (EE2-05A3)

2.3 EEX CHS 6 A 124 EEX 6 B C $\longrightarrow$ (.0046)

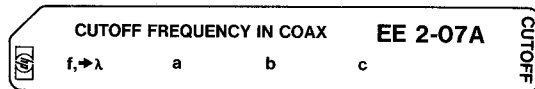
Enter TLC-2 (EE2-06A2)

4 C 0 E $\longrightarrow$ (89.54)

Enter TLC-3 (EE2-06A3)

0 75 A $\longrightarrow$ 70.66
 R/S $\longrightarrow$ -12.22

CUTOFF FREQUENCY IN COAX



This program provides an interchangeable solution to the coax cutoff equation:

$$f = \frac{c}{\pi(a + b) \sqrt{\epsilon_r}}$$

where

f = frequency in Hz

c = 3×10^{10} cm/s

a = radius of inner conductor

b = radius of outer conductor

ϵ_r = relative permittivity of dielectric

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter CUT OFF (EE2-07A)			
2	Input 3 of the following			
	Frequency	f, Hz	A	0.00
	Radius of inner conductor	a, cm	B	0.00
	Radius of outer conductor	b, cm	C	0.00
	Relative permittivity of dielectric	ϵ_r		0.00
3	Compute the unknown			
	Frequency		A	f, Hz*
	Radius of inner conductor		B	a, cm
	Radius of outer conductor		C	b, cm
	Relative permittivity of dielectric			ϵ_r
	*Note: After computing frequency, wave length may be computed also.		R/S	λ , cm

Example 1:

What is the cutoff frequency of an air line if a = 0.15 and b = 0.35? (19.1 GHz)

Keystrokes:

.15 B .35 C 1 D A DSP 2 → 1.91×10^{10}

Example 2:

What is the cutoff frequency of the same line if the dielectric has an ϵ_r of 2.7? (11.6 GHz)

Keystrokes:

.15 B .35 C 2.7 D A DSP 2 → 1.16×10^{10}

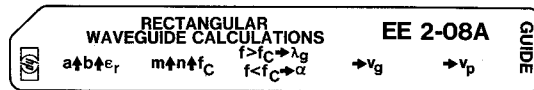
Example 3:

What outer radius is required for an air line whose inner conductor has a radius of .15 cm if a cutoff frequency of 15 GHz is desired? (.49 cm)

Keystrokes:

15 EEX 9 A .15 B 1 D C → 0.49

RECTANGULAR WAVEGUIDE CALCULATIONS



This program computes the cutoff frequency of energy propagating in the TE_{mn} mode in waveguide of dimensions $a \times b$ filled with a dielectric of relative permittivity ϵ_r . It also computes either attenuation (for frequencies below cutoff) or waveguide wavelength (for frequencies above cutoff). In addition, above cutoff, group and phase velocities may be calculated.

Cutoff frequency is given by

$$f_c = \frac{1}{2} v \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

$$v = \text{phase velocity} = \frac{c}{\sqrt{\epsilon_r}}$$

f_c = cutoff frequency in Hz

c = velocity of light in vacuum = 2.997925×10^8 m/s

m = number of half-wave variations of electric field along wide dimension of waveguide

n = number of half-wave variations of electric or magnetic field along narrow dimension of waveguide

a = wide dimension of waveguide, cm

b = narrow dimension of waveguide, cm

Below cutoff, the waveguide acts as an attenuator having attenuation

$$\alpha = \frac{2\pi f_c}{v} \sqrt{1 - \left(\frac{f}{f_c}\right)^2}$$

where

α = attenuation in nepers

f = frequency in Hz

Above cutoff, the wave will propagate with phase velocity

$$v_p = \frac{v}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}}$$

and group velocity

$$v_g = v \sqrt{1 - \left(\frac{f_c}{f}\right)^2}$$

and the guide wavelength will be $\lambda_g = \frac{v_p}{f}$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter GUIDE (EE2-08A)			
2	Input			
	Wide dimension	a, cm		a, cm
	then Narrow dimension	b, cm		b, cm
	then Relative permittivity	ϵ_r	A	v
3	To compute cutoff frequency,			
	input			
	Number of half-wave E-field			
	variations	m		m
	Number of half-wave E-or			
	H-field variations	n	B	f_c , Hz
4	To compute attenuation for			
	$f < f_c$, input			
	Frequency	f, Hz	C	α , nepers*
5	To compute guide wavelength			
	for $f > f_c$, input			
	Frequency	f, Hz	C	λ_g , cm
	then Compute group velocity		D	v_g , cm/s
	or Compute phase velocity		E	v_p , cm/s
	* To convert nepers to decibels		f^{-1} LN	

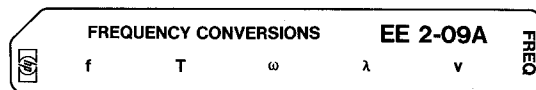
Example 1:

An air-filled waveguide has inside dimensions $2.286 \text{ cm} \times 1.016 \text{ cm}$. What is the cutoff frequency for waves propagating in the TE_{10} mode? (6.56 GHz) What is the phase velocity of a TE_{21} wave at 25 GHz? ($4.89 \times 10^{10} \text{ cm/s}$)

Keystrokes:

2.286	$\boxed{\uparrow}$	1.016	$\boxed{\uparrow}$	1	A	DSP	2	$\longrightarrow$	3.00×10^{10}	
1	$\boxed{\uparrow}$	0	B					$\longrightarrow$	6.56×10^9	
2	$\boxed{\uparrow}$	1	B					$\longrightarrow$	1.97×10^{10}	
25	EEX	9	C	E					$\longrightarrow$	4.89×10^{10}

FREQUENCY CONVERSIONS



This program allows conversion among various representations of frequency. The relations used are

$$\begin{aligned} T &= 1/f & f &= 1/T \\ \omega &= 2\pi f & f &= \omega/2\pi \\ \lambda &= v/f & f &= v/\lambda \end{aligned}$$

where

T = period

f = frequency

ω = radian frequency

λ = wavelength

v = propagation velocity

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter FREQ (EE2-09A)			
2	Input one of the following			
	Frequency	f, Hz	A	0.00
	Period	T, sec	B	0.00
	Radian frequency	ω , sec ⁻¹	C	0.00
	Wavelength	λ , m	D	0.00
3	Compute one of the following			
	Frequency		A	f, Hz
	Period		B	T, sec
	Radian frequency		C	ω , sec ⁻¹
	Wavelength		D	λ , m
4	To change the propagation			
	velocity	v, m/sec	E	v, m/sec
5	To restore default value of			
	propagation velocity		RTN R/S	

Example 1:

Convert 12 MHz to wavelength. (24.98 meters)

Keystrokes:

Enter FREQ (EE2-09A)

12 EEX 6 A D → 24.98

Example 2:

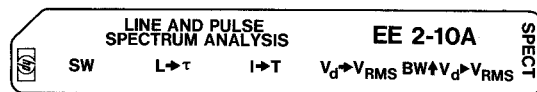
What is the period of a 10 cm wave? (334 psec)

Keystrokes:

Enter FREQ (EE2-09A)

10 EEX CHS 2 D B → 3.34 × 10⁻¹⁰

LINE AND PULSE SPECTRUM ANALYSIS



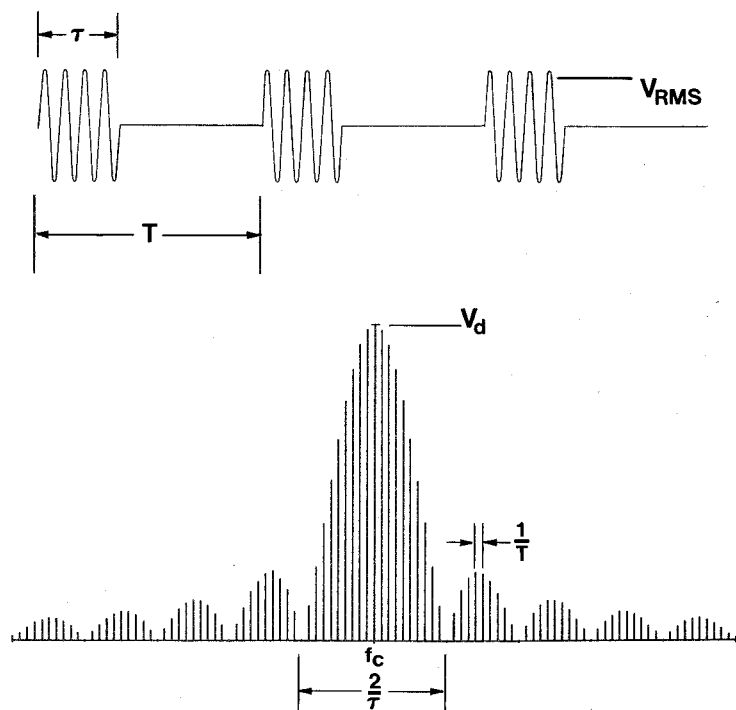
When pulsed RF is applied to the input of a spectrum analyzer, the resulting display is a line spectrum* with a

$$\frac{\sin x}{x}$$

envelope. The lines are separated by $\frac{1}{T}$

and the envelope nulls are spaced $\frac{1}{\tau}$

where T is the pulse repetition period and τ is the pulse width.



*If the i-f bandwidth is too great, the lines will not be resolved.

This program accepts and stores the spectrum analyzer display setting (MHz/cm). Lobewidth is then converted to pulse width and linespacing is converted to pulse spacing. The displayed voltage is now converted to the RMS voltage of the pulse and the peak-to-average power ratio is displayed in decibels.

The equations used are

$$\text{pulsewidth, } \tau = \frac{2}{L \times SW}$$

$$\text{pulse spacing } T = \frac{1}{\ell SW}$$

$$P_k = \text{peak-to-average power ratio} = 10 \log \frac{\tau}{T}$$

where

L = Lobewidth

ℓ = linespacing

SW = Sweep Width, $\frac{\text{MHz}}{\text{cm}}$

If the i-f bandwidth is large

$$\left(B > \frac{1}{T} \right)$$

the lines will not be resolved. In this case, the displayed level will vary with B . The voltage of the pulse will now be given by

where

$$V_{RMS} = V_d k \tau BW$$

τ = pulse width

k = an empirically derived correction factor = 1.5

BW = Bandwidth setting of spectrum analyzer, Hz

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter SPECT (EE2-10A)			
2	Input sweep width	SW, MHz/cm	A	0
3	Convert lobewidth to pulse width	L, cm	B	τ , μ s
4	If spectrum lines are not resolved, skip to step 9			
5	Convert linespacing to pulse spacing	ℓ , cm	C	T, μ s
6	Compute duty cycle		R/S	τ/T
7	Convert displayed voltage to RMS pulse voltage	V_d , V	D	V_{RMS} , V
8	Compute peak-to-average power ratio		R/S	P_k
9	If spectrum lines are not resolved then to convert displayed voltage to RMS pulse voltage			
	Input			
	Bandwidth	BW, Hz	$\uparrow$	BW, Hz
	then displayed voltage	V_d , V	E	V_{RMS} , V

Example:

A spectrum analyzer is set at 3 MHz/cm. A line spectrum has a lobewidth of 2 cm and the lines are .3 cm apart. What are τ and T? (.33 μ s, 1.11 μ s) What is the duty cycle? (0.3) If the displayed voltage is 500mV, what is the RMS voltage of the pulses? (1.67V)

Keystrokes:

Enter SPECT (EE2-10A)

3 **A** 2 **B** $\longrightarrow$ 0.33

.3 **C** $\longrightarrow$ 1.11

R/S $\longrightarrow$ 0.30

.5 **D** $\longrightarrow$ 1.67

SPURIOUS RESPONSES

SPURIOUS RESPONSES

EE 2-11A

SPURS

f_{min}↑f_{max}

M_{max}↑N_{max}

f₁↑f₂

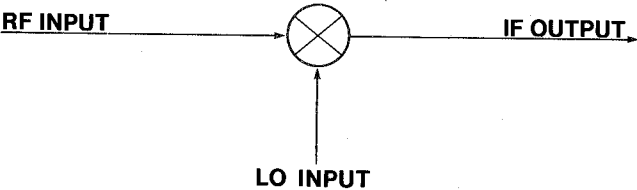
SPURS

Nonlinear elements are often used to mix RF and LO signals to produce an IF signal. The mixer may also output frequencies formed from harmonics of the inputs. This program computes values M and N which produce spurious responses falling within some specified IF band:

f_{min} < |Mf₁ ± Nf₂| < f_{max}

where

- f_{min}, f_{max} = limits of band of interest
- f₁ = RF frequency
- f₂ = LO (local oscillator) frequency
- M, N = harmonics of f₁ and f₂



A sign is attached to the output to indicate which sign satisfies the above constraint.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter SPURS (EE2-11A)			
2	Input			
	IF frequency limits			
	f _{min}	f _{min} , *	↑	f _{min} , *
	f _{max}	f _{max} , *	A	f _{min} , *
	Highest harmonics to consider			
	M _{max}	M	↑	M
	N _{max}	N	B	M
	Mixer input frequencies			
	RF frequency	f ₁ , *		f ₁ , *
	LO frequency	f ₂ , *	C	f ₁ , *
3	Compute spurious responses		D	±M.N
4	Press R/S to continue search			
	until flashing zeroes indicate			
	search is complete.		R/S	±M.N
5	Optional: After any display of			
	M.N, compute the actual fre-			
	quency of the spur.		E ±↑	f _{SPUR} , *
	then to continue search, go to			
	step 4			
	*Frequencies may be input in			
	Hz, kHz, MHz, GHz or what-			
	ever is appropriate.			
	†Use appropriate sign			

Example:

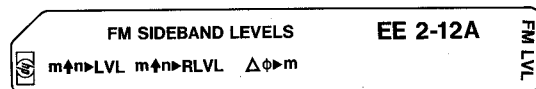
Compute the spurious outputs up to $M = 6$, $N = 7$ falling in the band .5 to 3.5 MHz if the RF frequency is 7 MHz and the LO frequency is 5 MHz.

Keystrokes:

Enter SPURS (EE2-11A)

.5	↑	3.5	A	6	↑	7	B	7	↑	5	C	D	→	-1.01
E	−	→											2.00	
R/S	→												-1.02	
E	−	→											-3.00	
R/S	→												-2.03	
E	−	→											-1.00	
R/S	→												-3.04	
E	−	→											1.00	
R/S	→												-4.05	
E	−	→											3.00	
R/S	→												-4.06	
E	−	→											-2.00	
R/S	→												flashing zeroes	

FM SIDEBAND LEVELS



This program computes sideband level in dB with respect to the level of either the modulated or unmodulated carrier. Inputs are sideband number and either modulation index or peak phase deviation in degrees.

From modulation index m and sideband number n , the sideband level with respect to unmodulated carrier is computed from an approximation to the Bessel function

$$\text{Level} = 20 \log J_n(m)$$

where

$$J_n(M) = \sum_{k=0}^{K} \frac{(-1)^k \left(\frac{m}{2}\right)^{n+2k}}{k! (n+k)!}$$

and

$$K = 15 + \text{MAX}(n, m)$$

The sideband level with respect to modulated carrier is computed by comparing two Bessel functions:

$$\text{Level} = 20 \log \frac{J_n(m)}{J_0(m)}$$

The modulation index is computed from peak phase deviation using the relation

$$m = \frac{\Delta\phi\pi}{180}$$

Note:

The program may not yield correct answers for $m > 15$.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter FM LVL (EE2-12A)			
2	To compute sideband level with respect to unmodulated carrier:			
2a	Input modulation index	m	↑	m
	then input sideband number			
	(0, 1, 2,...)	n	A	Level, dB
	or			
2b	Input peak phase deviation	ϕ , Deg	C	m
	then input sideband number			
	(0, 1, 2,...)	n	A	Level, dB
3	To compute sideband level with respect to modulated carrier:			
3a	Input modulation index	m	↑	m
	then input sideband number			
	(0, 1, 2,...)	n	B	Level, dB
	or			
3b	Input peak phase deviation	ϕ , Deg	C	m
	then input sideband number			
	(0, 1, 2,...)	n	A	Level, dB

Example:

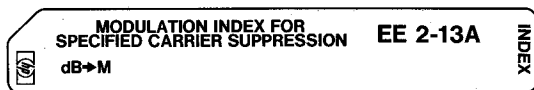
What is the carrier suppression of a frequency-modulated wave whose modulation index is 1.774? (−8.99 dB)

Keystrokes:

Enter FMLVL (EE2-12A)

1.774 0 A → −8.99

MODULATION INDEX FOR SPECIFIED CARRIER SUPPRESSION



This program computes a value of modulation index which causes a specified amount of carrier suppression. The program uses an iterative technique known as "regula falsi" to compute a root of

$$J_0(x) - y = 0$$

where

$J_0(x)$ = Bessel function of first kind of 0th order

20 log y = carrier suppression in dB

The Bessel function is computed by a method similar to that used in the FMLVL program (EE2-12A).

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter INDEX (EE2-13A)			
2	Input carrier suppression and			
	compute modulation index	y, dB	A	m

Example 1:

What modulation index is necessary if the carrier suppression is to be 5 dB? (1.41)

Keystrokes:

5 **A** —————→ 1.41

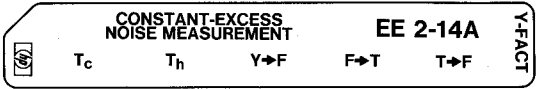
Example 2:

What modulation index will cause complete (1000 dB) carrier suppression? (2.40)

Keystrokes:

1000 **A** —————→ 2.40

CONSTANT-EXCESS NOISE MEASUREMENT



A commonly used method of determining a receiver’s noise figure is the constant-excess or Y-factor noise measurement technique. The noise at the receiver’s output when the input is connected to a cold noise source of temperature T_c is noted. The receiver is then connected to a noise source of T_h and sufficient attenuation is added to the receiver’s i-f stage to reduce the resulting output noise to its previous level. If the amount of attenuation introduced is Y , then the receiver’s noise figure is given by

$$F = 10 \log \left(1 + \frac{1}{290} \frac{T_h - Y T_c}{Y - 1} \right)$$

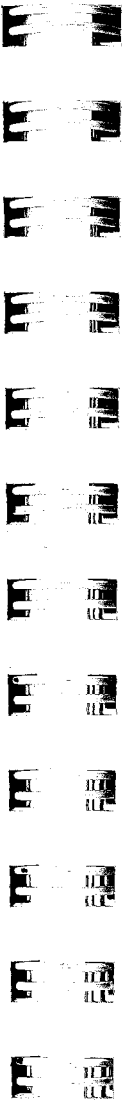
For a given T_c , T_h , and Y this program computes noise figure F . In addition, routines are provided to convert between noise figure and noise temperature:

$$T = 290 \left(10^{\frac{F}{10}} - 1 \right) = \text{noise temperature in kelvins}$$

$$F = 10 \log \left(1 + \frac{T}{290} \right) = \text{noise figure in decibels}$$

Reference

Lance, A. L., Fujimoto, P. M. Cohen, B. J., “Y-Factor Curves Simplify Noise Evaluations,” *Microwaves*, August, 1974, p. 48.



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter Y-FACT (EE2-14A)			
2	Input noise source temperatures			
	Cold	T_c , K	A	T_c , K
	Hot	T_h , K	B	T_h , K
3	Input Y-factor and compute			
	noise figures	Y , dB	C	F , dB
4	Convert noise figure to noise			
	temperature	F , dB	D	T , K
5	Convert noise temperature to			
	noise figure	T , K	E	F , dB

Example 1:

What is the noise figure of a receiver if

- $T_c = 90$ K
- $T_h = 375$ K
- $Y = 0.85$ dB

Keystrokes:

90 **A** 375 **B** .85 **C** → 7.19

Example 2:

What is the equivalent noise temperature if the noise figure is 6.3 dB? (947 K)

Keystrokes:

6.3 **D** → 947.08

NOISE FIGURE OF CASCADED NETWORKS

NOISE FIGURE OF CASCADED NETWORKS		EE 2-15A	NET F
START	F ₁ ↑G ₁ →F	F→NF	

The noise figure of a network is a measure of noise generated within that network. For cascaded networks, the overall noise figure is given by:

$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \dots$$

where $NF_i = 10^{\frac{F_i}{10}}$ = noise factor of i^{th} network

F_i = noise figure of i^{th} network in dB

G_i = gain of i^{th} network

This program accepts noise figure and gain, both expressed in dB, of an arbitrary number of networks and computes the overall noise figure in dB. It can also be used to convert a noise figure to a noise temperature using the relation

$$T = 290 \left(10^{\frac{F}{10}} - 1 \right)$$

where

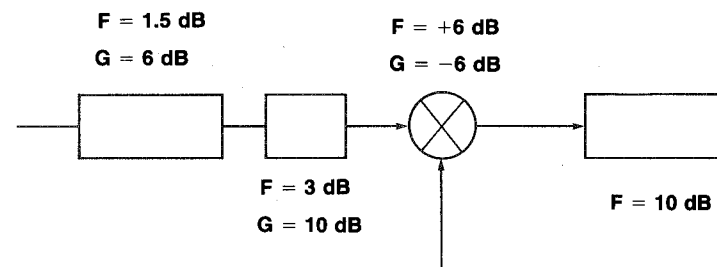
T = noise temperature in kelvins

F = noise figure in decibels

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter NET F (EE2-15A)			
2	Initialize		A	1.00
3	Input values for each stage			
	Noise figure	F _i , dB	↑	
	then Gain*	G _i , dB	B	F, dB
4	Convert noise figure to noise			
	temperature	F, dB	C	T, K
	*Note: For last stage, Gain may			
	be anything.			

Example 1:

What is the overall noise figure of the system shown? (2.58 dB)



Keystrokes:

A 1.5 ↑ 6 B 3 ↑ 10 B 6 ↑ 6 CHS B 10 ↑ B → 2.58

Example 2:

What is the noise figure in example 1 if the gain of the first stage can be increased to 9 dB? (2.05 dB)

Keystrokes:

A 1.5 ↑ 9 B 3 ↑ 10 B 6 ↑ 6 CHS B 10 ↑ B → 2.05

IMPEDANCE MATCHING

IMPEDANCE MATCHING

EE 2-16A

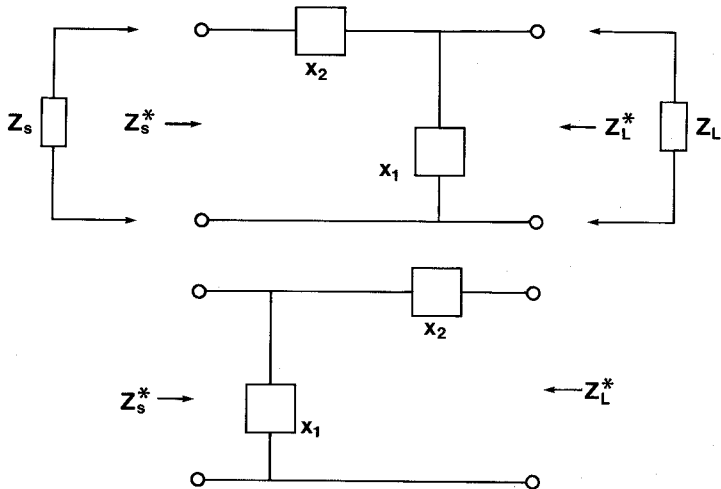
MATCH

$X_L + R_L$

$X_S + R_S$

An L-network consisting of purely reactive elements may be used to transform any complex impedance into any other complex impedance. In general there are four possible networks, but in some situations there are only two. This program accepts complex load and source impedances in rectangular form and will output all possible solutions, blinking zeros if a given topology is not suitable.

Either of these two networks is possible



For each network there are two sets of reactances (X_1, X_2) that will transform Z_L into Z_S^* . These are given by

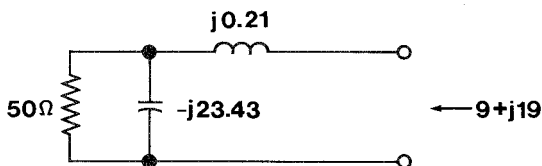
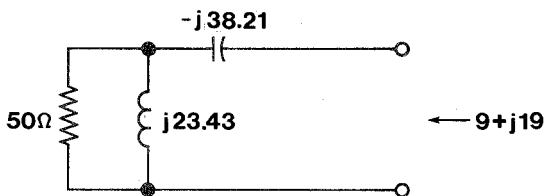
$$X_1 = \frac{R_S R_L}{R_S - R_L} \pm \sqrt{\left(\frac{R_S X_L}{R_S - R_L}\right)^2 - \frac{R_S (X_L^2 + R_L^2)}{R_S - R_L}}$$
$$X_2 = \frac{R_S (X_1 + X_L) - R_L (X_1 + X_S)}{R_L}$$

By reversing the subscripts S and L in these two equations, we get the two sets of reactances for the second network.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter MATCH (EE2-16A)			
2	Input			
	Load impedance			
	Reactive part	X_L, Ω		X_L, Ω
	then Resistive part	R_L, Ω	A	X_L, Ω
	Source impedance			
	Reactive part	X_S, Ω		X_S, Ω
	then Resistive part	R_S, Ω	B	X_S, Ω
3	Compute values for first network			
	Shunt reactance		C	X_1, Ω
	then Series reactance		R/S	X_2, Ω
	Repeat step 3 to obtain another set of values			
4	Compute values for second network			
	Shunt reactance		D	X_1, Ω
	then Series reactance		R/S	X_2, Ω
	Repeat step 4 to obtain another set of values			
	*Note: If one of the above networks is inappropriate, flashing zeroes will occur. Simply press R/S and continue.			

Example:

It has been determined that a source impedance of $9 + j19$ ohms is necessary to derive maximum gain from a particular transistor. Compute networks to transform $50 + j0$ ohms to the $9 - j19$ ohm transistor input impedance.



Keystrokes:

19 $\uparrow$ 9 **A** 0 $\uparrow$ 50 **B** **C** $\longrightarrow$ flashing zeros indicates that no solutions of this type are possible

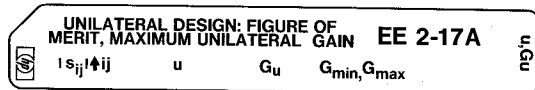
D $\longrightarrow$ 23.43

R/S $\longrightarrow$ -38.21

D $\longrightarrow$ -23.43

R/S $\longrightarrow$ 0.21

UNILATERAL DESIGN: FIGURE OF MERIT, MAXIMUM UNILATERAL GAIN



When designing a transistor amplifier with the aid of s-parameters, the often valid assumption that the reverse-transmission parameter s_{12} may be neglected leads to simplified equations. A transistor for which s_{12} is negligible is said to be a "unilateral device." The unilateral figure of merit u may be used to determine the reasonableness of the unilateral assumption:

$$u = \frac{|s_{11} s_{12} s_{21} s_{22}|}{|(1 - |s_{11}|^2)(1 - |s_{22}|^2)|}$$

Clearly, the unilateral assumption is more nearly correct for u near zero.

The maximum unilateral transducer power gain is given by

$$G_u = \frac{\text{Power delivered to load}}{\text{Power available from source}}$$

$$G_u = \frac{|s_{21}|^2}{|(1 - |s_{11}|^2)(1 - |s_{22}|^2)|}$$

Using the unilateral figure of merit we can place limits on the actual transducer power gain:

$$G_{\min} = G_u \frac{1}{(1 + u)^2}$$

$$G_{\max} = G_u \frac{1}{(1 - u)^2}$$

This program computes u , G_u , $G_{\min}$ and $G_{\max}$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter u, Gu (EE2-17A)			
2	Input magnitudes of s-parameters for i = 1, 2; j = 1, 2			
	Magnitude of parameter	s_{ij}		s_{ij}
	Designation of parameter	ij	A	s_{ij}
	or			
	store $ s_{ij} $ by hand	s_{11}	STO	
		s_{12}	STO	
		s_{21}	STO	
		s_{22}	STO	
3	Compute unilateral figure of merit			u
4	Compute maximum unilateral gain			G_u , dB
5	Compute limits on gain due to unilateral assumption.			$G_{\min}$, dB
			R/S	$G_{\max}$, dB

Example:

An HP35876E option 100 transistor operating at 4 GHz has the following s-parameters:

$$S = \begin{bmatrix} .51 \angle 154 & .09 \angle 26 \\ 1.4 \angle 22 & .60 \angle -58 \end{bmatrix}$$

What is the unilateral figure of merit? (0.08)

What is the maximum unilateral transducer power gain? (6.17 dB)

What is the range of transducer gain due to the fact that s_{12} is not zero? (5.49 dB $< G_{\text{actual}} < 6.91$ dB)

Keystrokes:

Enter u, Gu (EE2-17A)

.51 11 A .09 12 A 1.4 21 A .6

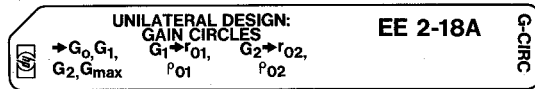
22 A B → 0.08

C → 6.17

D → 5.49

R/S → 6.91

UNILATERAL DESIGN: GAIN CIRCLES



For the unilateral circuit, transducer power gain is

$$G_T = G_0 \cdot G_1 \cdot G_2$$

where

$$G_T = \text{transducer power gain} = \frac{\text{Power delivered to load}}{\text{Power available from source}}$$

$$G_0 = |s_{21}|^2 = \text{transducer gain for } Z_0 \text{ input and output impedances}$$

$$G_{1\max} = \frac{1}{1 - |s_{11}|^2} = \text{gain contribution from change of source impedance from } Z_0 \text{ to } s_{11}^*$$

$$G_{2\max} = \frac{1}{1 - |s_{22}|^2} = \text{gain contribution from change of load impedance from } Z_0 \text{ to } s_{22}^*$$

$$s_{ij}^* = \text{complex conjugate of } s_{ij}$$

For source and load impedances other than s_{11}^* and s_{22}^* , G_1 and G_2 are less than the maximum values given above. The loci of points on a Smith chart representing values of source or load impedance which yield values of G_1 or G_2 less than $G_{1\max}$ or $G_{2\max}$ are circles. The center of a constant gain circle is in the direction of s_{ii}^* ($i = 1, 2$) at a distance

$$r_{oi} = \frac{G_i s_{ii}}{1 + G_i |s_{ii}|^2}$$

from the origin.

The radius of the circle is

$$\rho_{oi} = \frac{\sqrt{1 - G_i (1 - |s_{ii}|^2)}}{1 + G_i |s_{ii}|^2}$$

Note:

No intermediate calculations may be done while computing $G_{\max}$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Run u, Gu (EE2-17A)			
	or			
	Store s _{ij} ; ij = 11, 21, 22 by			
	hand	s ₁₁	STO 1	
		s ₂₁	STO 3	
		s ₂₂	STO 4	
2	Enter G-CIRC (EE2-18A)			
3	Compute			
	Transducer power gain with			
	R ₁ = R ₂ = Z ₀		A	G ₀ , dB
	then Power gain contribution			
	from R ₁ = s ₁₁ [*]		R/S	G _{1 max} , dB
	then Power gain contribution			
	from R ₂ = s ₂₂ [*]		R/S	G _{2 max} , dB
	then Transducer power gain		R/S	G _T , dB
4	Input desired gain (≤G _{1 max})			
	compute location† of center of			
	gain circle	G ₁ , dB	B	r ₀₁
	then compute radius of gain			
	circle		R/S	ρ ₀₁
5	Input desired gain (≤G _{2 max})			
	and compute location† of cen-			
	ter of gain circle	G ₂ , dB	C	r ₀₂
	then compute radius of gain			
	circle		R/S	ρ ₀₂
	†Note: These points are located			
	at a distance r _{0i} from the origin			
	of the Smith chart in the dir-			
	ection of s _{ij} [*] .			

Example:

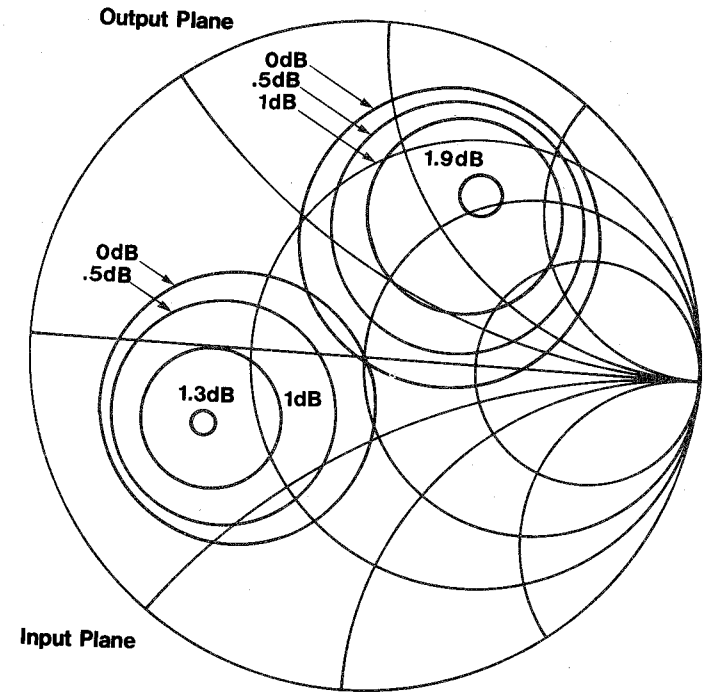
For the transistor described in the example for EE2-17A what are G_0 , $G_{1\max}$, and $G_{2\max}$? (2.92 dB, 1.31 dB, 1.94 dB 6.17 dB)

Draw 0 dB, .5 dB, and 1 dB constant gain circles on input and output planes.

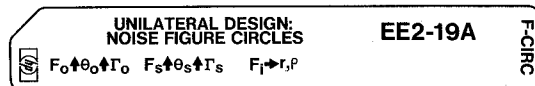
input plane				output plane			
	r_{01}		ρ_{01}		r_{02}		ρ_{02}
0 dB	.40	$\angle -154$	.40		.44	$\angle 58$	.44
.5 dB	.44	$\angle -154$	.32		.48	$\angle 58$	.38
1 dB	.48	$\angle -154$	.20		.52	$\angle 58$	.30

Keystrokes

.51	STO	1	1.4	STO	3	.6	STO	4	A	→	2.92
R/S	→ 1.31										
R/S	→ 1.94										
R/S	→ 6.17										
0	B	→ .40									
R/S	→ .40										
.5	B	→ .44									
R/S	→ .32										
1	B	→ .48									
R/S	→ 12										
0	C	→ .44									
R/S	→ .44										
.5	C	→ .48									
R/S	→ .38										
1	C	→ .52									
R/S	→ .30										



UNILATERAL DESIGN: NOISE FIGURE CIRCLES



This program computes the location and radius of a circle on a Smith chart which defines the values of source reflection coefficient which will produce a noise figure F_i .

If Γ_0 is the source reflection coefficient for which the transistor's noise figure is minimum (F_0) and Γ_S is an arbitrary source reflection coefficient for which the noise figure measures F_S , then the locus of Γ_i for which the noise figure is F_i is a circle of radius ρ centered at distance r from the origin at an angle $\angle\Gamma_0$.

$$r = \frac{|\Gamma_0|}{1 + N}$$

$$\rho = \frac{\sqrt{N^2 + N(1 - |\Gamma_0|^2)}}{1 + N}$$

where

$$N = \frac{NF_i - NF_0}{NF_S - NF_0} \frac{|\Gamma_S - \Gamma_0|^2}{1 - |\Gamma_S|^2}$$

$$NF = 10^{\frac{F}{10}} = \text{noise factor}$$

F = noise figure in dB

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter F-CIRC (EE2-19A)			
2	Input			
	Minimum noise figure	F_0 , dB		F_0 , dB
	Angle of corresponding			
	source reflection coefficient	$\angle\Gamma_0$		$\angle\Gamma_0$
	Magnitude of source reflection coefficient	Γ_0		
3	Input			
	Measured noise figure	F_S , dB		F_S , dB
	Angle of corresponding			
	source reflection coefficient	$\angle\Gamma_S$		$\angle\Gamma_S$
	Magnitude of source reflection coefficient	Γ_S		
4	Input arbitrary noise figure and			
	compute location* of noise			
	figure circle and radius of noise			
	figure circle	F_i , dB		r
				ρ
	*Note: This point is located at			
	a distance r from the origin of			
	the Smith chart in the direction			
	of Γ_0 .			

Example:

An HP-21 transistor has an optimum (minimum) noise figure of 3.3 dB at 1000 MHz when the source reflection coefficient, $\Gamma_0 = .22 \angle 170^\circ$, $V_{CB} = 10V$, and $I_c = 3$ ma. A 5.8 dB noise figure was measured at an arbitrary source reflection coefficient $\Gamma_S = .5 \angle -43^\circ$. Find all possible reflection coefficients where the noise figure is 3.5 dB, 4 dB, and 7 dB.

Input: $F_S = 5.8$ dB

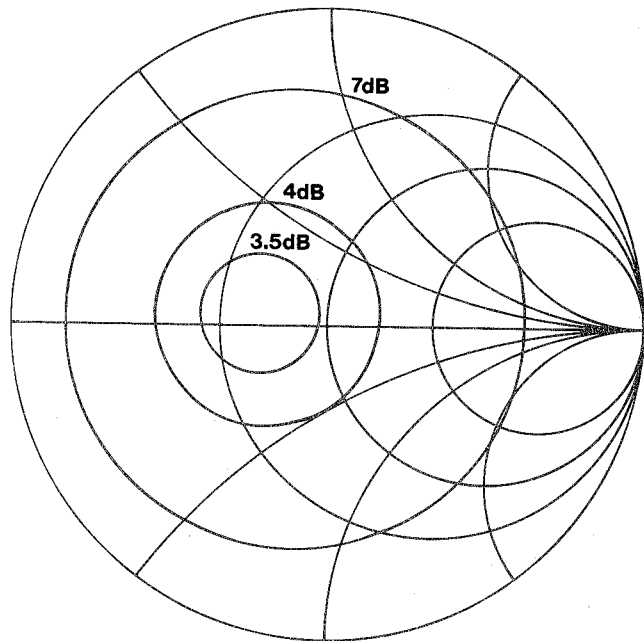
$\Gamma_S = .5 \angle -43^\circ$

$F_0 = 3.3$ dB

$\Gamma_0 = .22 \angle 170^\circ$

$F_i = 3.5, 4, \text{ and } 7$ dB

Output:



Keystrokes:

Enter F-CIRC (EE2-19A)

3.3 $\uparrow$ 170 $\uparrow$.22 **A** 5.8 $\uparrow$ 43 **CHS** $\uparrow$.5 **B**3.5 **C** $\longrightarrow$.21**R/S** $\longrightarrow$.194 **C** $\longrightarrow$.19**R/S** $\longrightarrow$.357 **C** $\longrightarrow$.10**R/S** $\longrightarrow$.72

BILATERAL DESIGN: STABILITY FACTOR, MAXIMUM GAIN , OPTIMUM MATCHING

BILATERAL DESIGN: INPUT
S-PARAMETERS AND COMPUTE Δ EE 2-20A1 $S \leftrightarrow \Delta$
 $\theta_{ij} \leftrightarrow s_{ij} \leftrightarrow ij$ COMPUTE

BILATERAL DESIGN:
STABILITY FACTOR, MAXIMUM GAIN EE 2-20A2 $K, G_{\max}$
 $\rightarrow K \rightarrow G_{\max} G_p \rightarrow G$

BILATERAL DESIGN:
OPTIMUM MATCHING EE 2-20A3 OPTMCH
 $\rightarrow \Gamma_{ms}, \theta_{ms} \rightarrow \Gamma_{ml}, \theta_{ml}$

Sometimes s_{12} is not sufficiently small that it may be neglected in transistor amplifier design. In this case it is necessary to compute a stability factor K and use different design approaches depending on its value. The stability factor is defined by the equation

$$K = \frac{1 + |\Delta|^2 - |s_{11}|^2 - |s_{22}|^2}{2 |s_{21} s_{12}|}$$

where

s_{ij} are s-parameters

and

$$\Delta = s_{11} s_{22} - s_{21} s_{12}$$

For $K < 1$ the amplifier is potentially unstable and the designer must choose input and output matching networks very carefully (see STABILITY CIRCLE program (EE2-22A)). For $K > 1$ the amplifier is unconditionally stable and this program may be used to compute the maximum gain available and the load and source reflection coefficients which yield the maximum gain.

Maximum gain is computed using the relation

$$G_{\max} = \frac{|s_{21}|}{|s_{12}|} \left(K \pm \sqrt{K^2 - 1} \right)$$

in which the plus sign is used when the quantity

$$B_1 = 1 + |s_{11}|^2 - |s_{22}|^2 - |\Delta|^2$$

is negative and the minus sign is used when B_1 is positive.

The third card of this series computes values of source and load reflection coefficient required to conjugately match the transistor using the equations

$$\Gamma_{ms} = C_1 * \left[\frac{B_1 \pm \sqrt{B_1^2 - 4 |C_1|^2}}{2 |C_1|^2} \right]$$

$$\Gamma_{ml} = C_2 * \left[\frac{B_2 \pm \sqrt{B_2^2 - 4 |C_2|^2}}{2 |C_2|^2} \right]$$

where

$$C_1 = s_{11} - \Delta s_{22}^*$$

C_1^* = complex conjugate of C_1

$$C_2 = s_{22} - \Delta s_{11}^*$$

C_2^* = complex conjugate of C_2

$$B_1 = 1 + |s_{11}|^2 - |s_{22}|^2 - |\Delta|^2$$

$$B_2 = 1 + |s_{22}|^2 - |s_{11}|^2 - |\Delta|^2$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter S→Δ (EE2-20A1)			
2	Input s-parameter matrix (ij = 11, 12, 21, 22)			
	Angle of desired s-parameter	∠s _{ij}	↑	
	then Magnitude of desired s-parameter	s _{ij}	↑	
	then Designation of desired s-parameter	ij	A	s _{ij}
3	Compute determinant of S		B	Δ
4	Enter K, GMAX (EE2-20A2)			
5	Compute stability factor		A	K
6	Compute maximum gain*		B	G _{max} , dB
7	Compute G for G _p < G _{max}	G _p , dB	C	G, dB
8	Enter OPTMCH (EE2-20A3)			
9	Compute Magnitude of source reflection coefficient		A	Γ _{ms}
	then Angle of source reflection coefficient		R/S	θ _{ms}
10	Compute Magnitude of load reflection coefficient		B	Γ _{ml}
	then Angle of load reflection coefficient		R/S	θ _{ml}
	Note: Continued pressing of R/S will result in exchanging Γ and θ.			
	*If K < 1, this step will cause flashing zeroes. Press R/S and continue with step 7.			

Example:

Design a maximum-gain amplifier using a transistor having the following s-parameters.

$$s_{11} = 0.277 \angle -59^\circ$$

$$s_{12} = 0.078 \angle 93.0^\circ$$

$$s_{21} = 1.920 \angle 64^\circ$$

$$s_{22} = 0.848 \angle -31^\circ$$

$$(K = 1.03, G_{\max} = 12.8 \text{ dB}, \Gamma_{ms} = 0.73 \angle 135.44^\circ,$$

$$\Gamma_{ml} = 0.95 \angle 33.85^\circ, Z_s = 9.08 + j 19.91, Z_L = 15.02 + j 163.05)$$

Keystrokes:

Enter S→Δ (EE2-20A1)

59 **CHS** .277 11 **A** 93 .078 12 **A**

64 1.92 21 **A** 31 **CHS** .848 22 **A**

B → (-64.83)

Enter K GMAX (EE2-20A2)

A → 1.03

B → 12.81

Enter OPTMCH (EE2-20A3)

A → 0.73

R/S → 135.44

B → 0.95

R/S → 33.85

Enter Z↔Γ (EE2-04A)

50 **A** 135.44 .73 **C** **B** **f⁻¹** **R→P** → 9.08

R/S → 19.91

33.85 .95 **C** **B** **f⁻¹** **R→P** → 15.02

R/S → 163.05

BILATERAL DESIGN: GAIN CIRCLES



If it is desired to build an amplifier having gain less than the maximum possible for the transistor to be used, a gain circle is constructed. This circle shows all possible loads for the output that yield the desired power gain. When a load on this gain circle is selected, the load and source mapping program (EE2-23A) may be used to compute the new source reflection coefficient required.

This program computes the center

$$r_{02} = \left[\frac{G}{1 + D_2 G} \right] C_2^*$$

and radius

$$\rho_{02} = \frac{(1 - 2k |s_{12} s_{21}| G + |s_{12} s_{21}|^2 G^2)^{1/2}}{1 + D_2 G}$$

where

$$G = \frac{G_p}{G_0}$$

G_p = desired gain

G_0 = maximum transducer gain

$$C_2 = s_{22} - s_{11}^*$$

$$D_2 = |s_{22}|^2 - |\Delta|^2$$

$$\Delta = s_{22} s_{11} - s_{21} s_{22}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Run S→Δ (EE2-20A1)			
2	Enter BG-CIRC (EE2-21A)			
3	Begin computation		A	C ₂ *
4	Key in desired total amplifier			
	gain and compute			
	Distance to center of constant			
	gain circle	G _p , dB	R/S	r ₀
	Angle to center of constant			
	gain circle		R/S	θ ₀
	Radius of constant gain circle		B	ρ ₀

Example:

A gain of 10 dB is desired from an amplifier using a transistor whose s-parameter matrix is

$$S = \begin{bmatrix} .277 \angle -59 & .078 \angle 93 \\ 1.92 \angle 64 & .848 \angle -31 \end{bmatrix}$$

Plot the 10 dB gain circle on a Smith chart.

$$r_{02} = .781 \angle 33.85 \quad \rho_{02} = .214$$

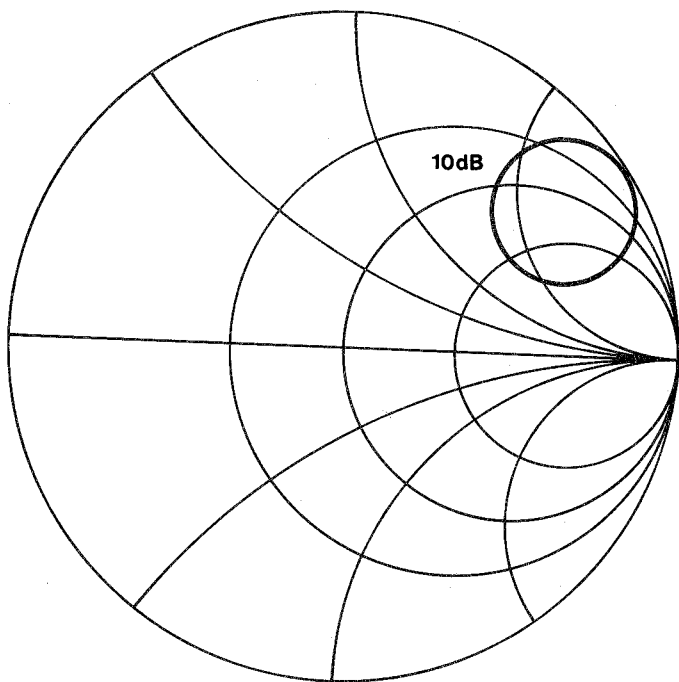
Keystrokes:

Enter S→Δ (EE2-20A1)

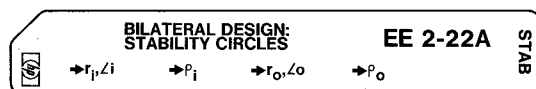
59 **CHS** **↑** .277 **↑** 11 **A** 93 **↑** .078 **↑** 12 **A**
 64 **↑** 1.92 **↑** 21 **A** 31 **CHS** **↑** .848 **↑** 22 **A** **B** → (-64.83)

Enter BG-CIRC (EE2-21A)

A 10 **R/S** → .781
R/S → 33.85
B → .214



BILATERAL DESIGN: STABILITY CIRCLES



For the potentially unstable amplifier (stability factor $K < 1$), it is necessary to avoid values of source and load reflection coefficients which could cause oscillations. The boundaries between stable and unstable regions are circles on the input and output planes.

The centers of the stability circles are located at:

$$r_{si} = \frac{C_1^*}{|s_{ii}|^2 - |\Delta|^2}$$

where

r_{s1} = location of center of stability circle on input plane

r_{s2} = location of center of stability circle on output plane

$$C_1 = s_{11} - \Delta s_{22}^*$$

$$C_2 = s_{22} - \Delta s_{11}^*$$

$$\Delta = s_{11} s_{22} - s_{21} s_{12}$$

The radii of the stability circles are:

$$\rho_{si} = \frac{|s_{12} s_{21}|}{|s_{ii}|^2 - |\Delta|^2}$$

where

ρ_{s1} = radius of stability circle on input plane

ρ_{s2} = radius of stability circle on output plane

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Run S→Δ (EE2-20A1)			
2	Enter STAB (EE2-22A)			
3	Compute distance of center of stability circle on input plane,			r_{s1}
	then Compute its direction,			$\angle r_{s1}$
	then Compute the radius of the stability circle			ρ_{s1}
4	Compute distance of center of stability circle on output plane,			r_{s2}
	then Compute its direction,			$\angle r_{s2}$
	then Compute the radius of the stability circle			ρ_{s2}

Example:

Construct stability circles for a transistor having the following s-matrix.

$$S = \begin{bmatrix} .385 \angle -55 & .045 \angle 90 \\ 2.7 \angle 78 & .89 \angle -26.5 \end{bmatrix}$$

$$(K = .91, r_{s1} = -8.37 \angle 122.4, \rho_{s1} = -9.27$$

$$r_{s2} = 1.18 \angle 29.88, \rho_{s2} = 0.19)$$

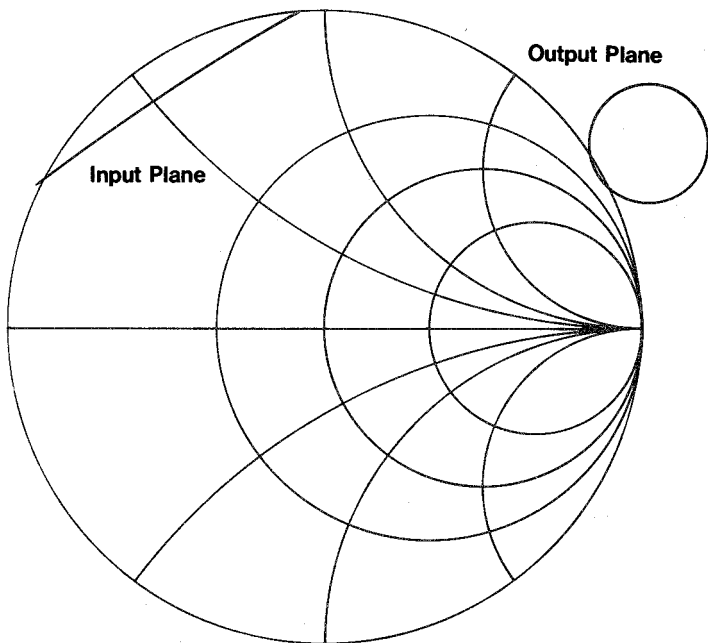
Keystrokes:

Enter S→Δ (EE2-20A1)

55 **CHS** **↑** .385 **↑** 11 **A** 90 **↑** .045 **↑** 12 **A**
 78 **↑** 2.7 21 **A** 26.5 **CHS** **↑** .89 **↑** 22 **A** **B** → (65.4)

Enter STAB (EE1-22A)

A → -8.37
R/S → 122.4
B → -9.27
C → 1.18
R/S → 29.88
D → 0.19



LOAD AND SOURCE MAPPING

LOAD AND SOURCE MAPPING

EE 2-23A

MAP

 $\Gamma_L \rightarrow s'_{11}$ $\Gamma_S \rightarrow s'_{22}$

When a two-port network is terminated in a load having reflection coefficient Γ_L the source reflection coefficient for a conjugate input match becomes

$$\Gamma_{ms} = \left[s_{11} + \frac{s_{12} s_{21}}{\frac{1}{\Gamma_L} - s_{22}} \right]^*$$

Similarly, when the source reflection coefficient of a two-port network is Γ_S , the output reflection coefficient for a conjugate output match becomes

$$\Gamma_{ml} = \left[s_{22} + \frac{s_{12} s_{21}}{\frac{1}{\Gamma_S} - s_{11}} \right]^*$$

This program accepts Γ_L or Γ_S and computes the corresponding source or load reflection coefficient. A typical use is to determine which area defined by a stability circle is the stable or unstable region (for stable operation, Γ_L must be such that $|\Gamma_{ms}| < 1$ and Γ_S must be such that $|\Gamma_{ml}| < 1$).

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Run S $\rightarrow\Delta$ (EE2-20A1)			
2	Run K, GMAX (EE2-20A2)			
3	Enter MAP (EE2-23A)			
4	To calculate load reflection coefficient, go to step 6			
5	Input angle of load reflection coefficient	$\angle\Gamma_L$		$\angle\Gamma_L$
	then Input magnitude of load reflection coefficient and calculate magnitude of source			

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
	reflection coefficient	$ \Gamma_L $	A	$ \Gamma_{ms} $
	then Calculate angle of source			
	reflection coefficient		R/S	$\angle\Gamma_{ms}$
6	Input angle of source reflection coefficient	$\angle\Gamma_S$		$\angle\Gamma_S$
	then Input magnitude of source reflection coefficient and calculate magnitude of load reflection coefficient	$ \Gamma_S $	A	$ \Gamma_{ml} $
	then Calculate angle of load reflection coefficient			
	reflection coefficient		R/S	$\angle\Gamma_{ml}$

Example:

For the transistor whose s-parameter matrix is

$$S = \begin{bmatrix} .277 \angle -59 & .078 \angle 93 \\ 1.92 \angle 64 & .848 \angle -31 \end{bmatrix}$$

we have determined that the output stability circle is located at $r_{s2} = 1.18 \angle 29.88$ and that its 10 dB gain circle is located at $r_{02} = .781 \angle 33.85$ with a radius of $\rho_{02} = .214$. If we pick a load reflection coefficient of $(|r_{02}| - \rho_{02}) \angle r_{02} = .567 \angle 33.85$, what source reflection coefficient is required? ($.276 \angle 93.3$)

Keystrokes:

Enter S $\rightarrow|\Delta|^2$ (EE2-20A1)

59 **CHS** $\uparrow$.277 $\uparrow$ 11 **A** 93 $\uparrow$.078 $\uparrow$ 12 **A**

64 $\uparrow$ 1.92 $\uparrow$ 21 **A** 31 **CHS** $\uparrow$.848 $\uparrow$ 22 **A** **B** $\rightarrow$ -64.83

Enter K, GMAX (EE2-20A2)

A $\rightarrow$ 1.03

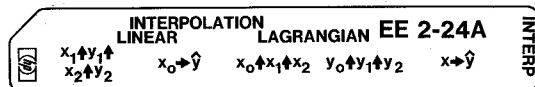
B $\rightarrow$ 12.81

Enter MAP (EE2-23A)

33.85 $\uparrow$.567 **A** **DSP** $\square$ 3 $\rightarrow$ 0.276

R/S $\rightarrow$ 93.330

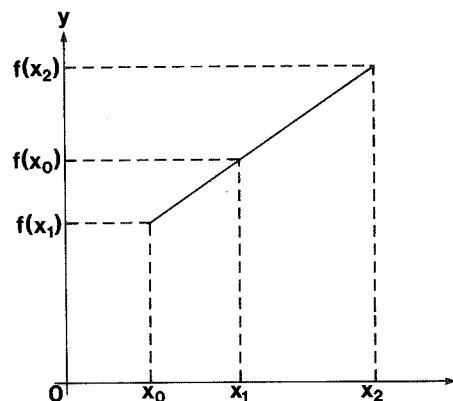
LINEAR AND LAGRANGIAN INTERPOLATIONS



Linear Interpolation

If $f(x)$ is a function of x and $x_1 < x_0 < x_2$, $f(x_0)$ can be approximated by

$$f(x_0) \cong \frac{(x_2 - x_0)f(x_1) + (x_0 - x_1)f(x_2)}{x_2 - x_1}$$



Lagrangian Interpolation

This program also evaluates for interpolation argument x the Lagrangian interpolating polynomial $P_2(x)$ of degree two passing through the points (x_0, y_0) , (x_1, y_1) , (x_2, y_2) .

$$P_2(x) = \sum_{i=0}^2 L_i(x) y_i$$

where

$$L_i(x) = \prod_{\substack{j=0 \\ j \neq i}}^2 \frac{(x - x_j)}{(x_i - x_j)}, i = 0, 1, 2$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter interp. (EE 2-24A)			
2	For linear interpolation	x_1		
3		$f(x_1)$		
4		x_2		
5		$f(x_2)$		
6		x_0		$f(x_0)$
	(For a new value of x_0 , go to 6.)			
7	For Lagrangian interpolation	x_0		
8		x_1		
9		x_2		
10		y_0		
11		y_1		
12		y_2		
13		x		y
	(For a new x , go to 13.)			

Examples:

i	1	2
x	1.2	1.3
f(x)	0.30119	0.27253

Keystrokes:

1.2 .30110 1.3 .27253 **A** 1.27 **B** $\longrightarrow$.28113
 1.29 **B** $\longrightarrow$.27540

i	0	1	2
x	1	3	10
y	-5	1	25

Keystrokes:

1 3 10 **C** 5 **CHS** 1 25 **D** 1.7 **E** $\longrightarrow$ -2.94
 9 **E** $\longrightarrow$ 21.29

PARAMETER CONVERSION: S↔Y, Z, G, H

S to Y, Z, G, H: INPUT
S-PARAMETERS AND PRECONDITION EE 2-25A1 S(N)

$\theta_{ij} \leftrightarrow s_{ij} \leftrightarrow ij$ S to Y S to Z S to G S to H

Y, Z, G, H to S: INPUT
Y, Z, G, OR H AND PRECONDITION EE 2-25A2 S(N)

$\theta_{ij} \leftrightarrow m_{ij} \leftrightarrow ij$ Y to S Z to S G to S H to S
 Z_0 Z_0 Z_0 Z_0

COMPUTE T' - CARD 1 EE 2-25A3 T' - 1

START

COMPUTE T' - CARD 2 EE 2-25A4 T' - 2

START

S to Y, Z, G, H
POSTCONDITION EE 2-25A5 S(OUT)

Z_0 $ij \leftrightarrow y_{ij}$ $ij \leftrightarrow z_{ij}$ $ij \leftrightarrow g_{ij}$ $ij \leftrightarrow h_{ij}$

Y, Z, G, H to S
POSTCONDITION EE 2-25A6 S(OUT)

Y to S Z to S G to S H to S $ij \leftrightarrow s_{ij}$

Two-port s-parameters may be converted to and from any of Y-, Z-, G-, or H-parameters using a single matrix equation. Appropriate pre- and postconditioning operations must be performed depending on which conversion is desired. The basic transformation is

$$T' = (I + T)^{-1} (I - T)$$

$$= \frac{2}{(1 + T_{11})(1 + T_{22}) - T_{12} T_{21}} \begin{bmatrix} 1 + T_{22} & -T_{12} \\ -T_{21} & 1 + T_{11} \end{bmatrix} - I$$

which is programmed on two magnetic cards.

To generate the T matrix, two preconditioning cards are provided. The first of these accepts S and generates T as follows:

conversion desired	S→Y	S→Z	S→G	S→H
preconditioning operation	$T = S$	$T = -S$	$T = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} S$	$T = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} S$

The other preconditioning card accepts Y, Z, G, or H and generates T by one of these operations:

conversion desired	Y→S	Z→S
preconditioning operation	$T = Z_0 Y$	$T = \frac{Z}{Z_0}$

conversion desired	G→S	H→S
preconditioning operation	$T = \begin{bmatrix} Z_0 g_{11} & g_{12} \\ g_{21} & \frac{g_{22}}{Z_0} \end{bmatrix}$	$T = \begin{bmatrix} \frac{h_{11}}{Z_0} & h_{12} \\ h_{21} & h_{22} Z_0 \end{bmatrix}$

After the T' matrix has been computed, the following postconditioning operations must be performed:

conversion desired	S→Y	S→Z
postconditioning operation	$Y = \frac{T'}{Z_0}$	$Z = Z_0 T'$

conversion desired	S→G	S→H
postconditioning operation	$G = \begin{bmatrix} \frac{g_{11}}{Z_0} & g_{12} \\ g_{21} & g_{22} Z_0 \end{bmatrix}$	$H = \begin{bmatrix} h_{11} Z_0 & h_{12} \\ h_{21} & \frac{h_{22}}{Z_0} \end{bmatrix}$

conversion desired	Y→S	Z→S	G→S	H→S
postconditioning operation	$S = T'$	$S = -T'$	$S = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} T'$	$S = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} T'$

Preconditioning operation
for converting from s-parameters

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter $S \rightarrow (IN)$ (EE2-25A1)			
2	Input s-parameters for $i = 1, 2$; $j = 1, 2$			
	Angle of parameter	θ_{ij} , deg		
	Magnitude of parameter	M_{ij}		
	Designation of parameter	ij		M_{ij}
3	Precondition as appropriate			
	$S \rightarrow Y$			
	$S \rightarrow Z$			-1
	$S \rightarrow G$			-1
	$S \rightarrow H$			-1

Preconditioning operation
for converting to s-parameters

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter $\rightarrow S$ (IN) (EE2-25A2)			
2	Input Y -, Z -, G -, or H -parameters for $i = 1, 2$; $j = 1, 2$.			
	Angle of parameter	θ_{ij} , deg		
	Magnitude of parameter	M_{ij}		
	Designation of parameter	ij		M_{ij}
3	Input characteristic impedance and precondition as appropriate			
	$Y \rightarrow T$	Z_0, Ω^*		Z_0
	$Z \rightarrow T$	Z_0, Ω^*		$1/Z_0$
	$G \rightarrow T$	Z_0, Ω^*		Z_0
	$H \rightarrow T$	Z_0, Ω^*		$1/Z_0$
4	Run T'^{-1} , and T'^{-2} , and $\rightarrow S$ (OUT) (EE2-25A3, 4, and 6)			
	* (Use $Z_0 = 1$ if normalized s-parameters are desired).			

Matrix transformation

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Run $S \rightarrow (IN)$ or $\rightarrow S$ (IN) (EE2-25A1 or 2)			
2	Enter T'^{-1} (EE2-25A3)			
3	Begin computation of T'		A	
4	Enter T'^{-2} (EE2-25A4)			
5	Complete computation of T'		A	
6	Run $S \rightarrow (OUT)$ or $\rightarrow S$ (OUT) (EE2-25A5 or 6)			

Postconditioning operation
for converting from s-parameters

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Run $S \rightarrow (IN)$ (EE2-25A1)			
2	Run T'^{-1} and T'^{-2} (EE2-25A3 and 4)			
3	Enter $S \rightarrow (OUT)$ (EE2-25A5)			
4	Input characteristic impedance	Z_0, Ω^*	A	Z_0, Ω
5	Display parameters as appropriate for $i = 1, 2$; $j = 1, 2$.			
	$S \rightarrow Y$	ij	B	$ y_{ij} $
			R/S	$\angle y_{ij}$
	$S \rightarrow Z$	ij	C	$ z_{ij} $
			R/S	$\angle z_{ij}$
	$S \rightarrow G$	ij	D	$ g_{ij} $
			R/S	$\angle g_{ij}$
	$S \rightarrow H$	ij	E	$ h_{ij} $
			R/S	$\angle h_{ij}$
	* ($Z_0 = 1$ if normalized s-parameters were used)			

Postconditioning operation
for converting to s-parameters

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Run →S (IN) (EE2-25A2)			
2	Run T'-1 and T'-2 (EE2-25A3 and 4)			
3	Enter →S (OUT) (EE2-25A6)			
4	Postcondition as appropriate			
	Y→S		A	
	Z→S		B	
	G→S		C	
	H→S		D	
5	Display s-parameters for i = 1, 2;			
	j = 1, 2.			
	Parameter designation	ij	E	s _{ij}
			R/S	θ _{ij}

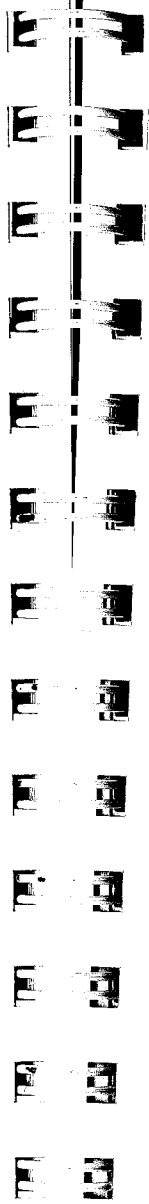
Example 1:

The s-parameter matrix of a 2N3571 transistor is

$$S = \begin{bmatrix} 0.62 \angle -44.0 & 0.0115 \angle 75.0 \\ 9.0 \angle 130 & 0.955 \angle -6.0 \end{bmatrix}$$

What is the h-parameter matrix?

$$\left(H = \begin{bmatrix} 119 \angle -53.9 & 0.02 \angle 39.3 \\ 14.2 \angle -85.7 & 0.002 \angle 21.2 \end{bmatrix} \right)$$



Keystrokes:

Enter: S→(IN) (EE2-25A1)

44 **CHS** **↑** .62 **↑** 11 **A** 75 **↑** .0115 **↑**
12 **A** 130 **↑** 9 **↑** 21 **A** 6 **CHS** **↑** .955
↑ 22 **A** **E**

Enter T' - 1 (EE2-25A3)

A

Enter T' - 2 (EE2-25A4)

A

Enter S→(OUT) (EE2-25A5)

50 A	→	50
11 E	→	119.08
R/S	→	-53.88
12 E	→	0.02
R/S	→	39.26
21 E	→	14.19
R/S	→	-85.74
22 E	→	0.002
R/S	→	21.173

PARAMETER CONVERSIONS: S ↔ T

S to T PARAMETER CONVERSION EE 2-26A1

START t₁₁, t₁₂ t₂₁, t₂₂

S
↓
T

T to S PARAMETER CONVERSION EE 2-26A2

START s₁₁, s₁₂ s₂₁, s₂₂

T
↓
S

These two programs allow interconversion of scattering parameters and transmission parameters using the following relationships.

s₁₁

s₂₁

s₁₂

s₂₂

=

t₁₂

t₂₂

t₁₁ t₂₂ - t₁₂ t₂₁

t₂₂

1

t₂₂

t₂₁

t₂₂

t₁₁

t₂₁

=

s₁₁ s₂₂ - s₁₂ s₂₁

s₂₁

s₂₂

s₂₁

s₁₁

s₂₁

1

s₂₁

The data is stored such that these programs are compatible with the S→(IN) program (EE2-25A1).

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter S→ (IN) (EE2-25A1)			
2	Input s-parameters for i = 1, 2:			
	j = 1, 2.			
	Angle of parameter	θ _{ij} , deg		θ _{ij}
	Magnitude of parameter	M _{ij}		M _{ij}
	Designation of parameter	ij		M _{ij}
3	Enter S→T (EE2-26A1)			
4	Begin computation			
5	Compute			
	Magnitude of t ₁₁			t ₁₁
	Angle of t ₁₁			∠t ₁₁
	Magnitude of t ₁₂			t ₁₂
	Angle of t ₁₂			∠t ₁₂
6	Compute			
	Magnitude of t ₂₁			t ₂₁
	Angle of t ₂₁			∠t ₂₁
	Magnitude of t ₂₂			t ₂₂
	Angle of t ₂₂			∠t ₂₂
	or			
1	Store s-parameters as shown			
	and continue with step 3 above	s ₁₁		
		s ₁₂		
		s ₂₁		
		s ₂₂		
		∠s ₁₁		
		∠s ₁₂		
		∠s ₂₁		
		∠s ₂₂		

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter S→ (IN) (EE2-26A1)			
2	Input T-parameters for i = 1, 2; j = 1, 2.			
	Angle	θ_{ij} , deg		θ_{ij}
	Magnitude	M_{ij}		M_{ij}
	Designation	ij		M_{ij}
3	Enter T→S (EE2-26A2)			
4	Begin computation			
5	Compute			
	Magnitude of s_{11}			$ s_{11} $
	Angle of s_{11}			$\angle s_{11}$
	Magnitude of s_{12}			$ s_{12} $
	Angle of s_{12}			$\angle s_{12}$
	Magnitude of s_{21}			$ s_{21} $
	Angle of s_{21}			$\angle s_{21}$
	Magnitude of s_{22}			$ s_{22} $
	Angle of s_{22}			$\angle s_{22}$

Example:

Convert the following s-parameter matrix to T-parameters.

$$S = \begin{bmatrix} 0.62 \angle -44 & 0.0115 \angle 75 \\ 9 \angle 130 & 0.955 \angle -6 \end{bmatrix}$$

$$T = \begin{bmatrix} 0.07 \angle 9.18 & 0.07 \angle -174 \\ 0.11 \angle 44 & 0.11 \angle -130 \end{bmatrix}$$

Keystrokes:

Enter S→T (EE2-26A1)

.62 **STO** **1** .0115 **STO** **2** 9 **STO** **3** .955 **STO****4** 44 **CHS** **STO** **5** 75 **STO** **6** 130 **STO** **7**630 **CHS** **STO** **8** **A** **B** → .07**R/S** → 9.18**R/S** → .07**R/S** → -174**C** → 0.11**R/S** → 44**R/S** → 0.11**R/S** → -130

COMPLEX MATRIX OPERATIONS

COMPLEX MATRIX OPERATIONS CARD 1	EE 2-27A1	CMO - 1
PACK	UNPACK	

COMPLEX MATRIX OPERATIONS CARD 2	EE 2-27A2	CMO - 2
START		

These two cards will either multiply or add 2×2 complex matrices. The matrix elements are packed such that magnitude and angle are stored simultaneously in the same location. The user stores each matrix element appropriately after the program packs it for him. These programs are useful for adding Z- or Y-parameter matrices and for multiplying T-parameter matrices.

The product of matrices A and B is formed as follows:

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} a_{11} b_{11} + a_{12} b_{21} & a_{11} b_{12} + a_{12} b_{22} \\ a_{21} b_{11} + a_{22} b_{21} & a_{21} b_{12} + a_{22} b_{22} \end{bmatrix}$$

Note:

It is necessary that magnitudes not contain more than three digits beyond the decimal point.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter CMO-1 (EE2-27A1)			
2	Pack left-hand matrix elements			
	a_{ij}			
	Input angle of element	θ_{ij}, deg		
	then magnitude of element	M_{ij}		
	and store in appropriate register			
	ij 11 12 21 22			
	n 1 2 3 4			
3	Repeat step 2 for $i = 1, 2; j = 1,$			
	2.			
4a	For multiplication			
	Input angle of element b_{11}	θ_{11}, deg		
	Magnitude of element b_{11}	M_{11}		
	Input angle of element b_{12}	θ_{12}, deg		
	Magnitude of element b_{12}	M_{12}		
	Input angle of element b_{21}	θ_{21}, deg		
	Magnitude of element b_{21}	M_{21}		
	Input angle of element b_{22}	θ_{22}, deg		
	Magnitude of element b_{22}	M_{22}		
4b	For addition (repeat for $i = 1, 2;$			
	$j = 1, 2.)$			
	Input angle of element a_{ij}	θ_{ij}, deg		
	then magnitude of element a_{ij}	M_{ij}		
	and store in appropriate register			
	ij 11 12 21 22			
	n 5 6 7 8			
5	Enter CMO-2 (EE2-27A2)			
	Compute answer matrix			$ c_{11} $
				$\angle c_{11}$
				$ c_{12} $
				$\angle c_{12}$
				$ c_{21} $
				$\angle c_{21}$
				$ c_{22} $
				$\angle c_{22}$

Example:

Multiply

$$\begin{bmatrix} 1.02 \angle -38^\circ & .197 \angle 180^\circ \\ .197 \angle 180^\circ & 1.02 \angle 38^\circ \end{bmatrix} \times \begin{bmatrix} .192 \angle -14.7^\circ & .203 \angle -261.9^\circ \\ .0612 \angle 74.3^\circ & .422 \angle -130.4^\circ \end{bmatrix}$$

$$\begin{bmatrix} 0.203 \angle -55.4^\circ & 0.289 \angle 57.1^\circ \\ 0.090 \angle 131.8^\circ & 0.470 \angle -91.5^\circ \end{bmatrix}$$

Keystrokes

Enter: CMO-1 (EE2-27A1)

38 [CHS] [↑] 1.02 [A] [STO] [1] 180 [↑] .197 [A] [STO]
 [2] [STO] [3] 38 [↑] 1.02 [A] [STO] [4] 14.7 [CHS]
 [↑] .192 [RTN] [R/S] 261.9 [CHS] [↑] .203 [R/S] 74.3
 [↑] .0612 [R/S] 130.4 [CHS] [↑] .422 [R/S] [DSP] [◻] 3

Enter CMO-2 (EE2-27 A2)

[A] → .203
 [R/S] → -55.393
 [R/S] → .289
 [R/S] → 57.097
 [R/S] → .090
 [R/S] → 131.826
 [R/S] → .470
 [R/S] → -91.513

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REGISTER ALLOCATION

		R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9
MEL	EE2-01A	ρ_1	ρ_2							
MMEL	EE2-02A	ρ_s	ρ_L	ρ_1	ρ_2	T^2	$\rho_s \rho_1$	$\rho_L \rho_2$	$\rho_s \rho_L$	
$\sigma \Rightarrow \rho$	EE2-03A								Shift Flag	
$Z \Rightarrow \Gamma$	EE2-04A	Z_0	$ Z/Z_0 $	θ	ρ	ϕ	$ 1-\Gamma , Z/Z_0+1 $			
MS-1	EE2-05A1	Z_c	v_r				w	h	w/h	
MS-2	EE2-05A2	Z_c	v_r		$2\pi \ln 10 A/v_r$		w	h	w/h	
MS-3	EE2-05A3	Z_c	v_r	α_c	$2\pi \ln 10 A/v_r$	f	w	h	w/h	
TLC-1	EE2-06A1	$R_0, Z_d $	$v_r, L Z_0$	Used	$L \gamma$	R/L		$ 2\gamma $	ω'	
TLC-2	EE2-06A2	$R_0, Z_0 $	$v_r, L Z_0$	α_c	$L, L \gamma$	$f, (\alpha_0 - \alpha_c)/\beta_0$	β_0	$2\beta_0, 2\gamma $	α_D	
TLC-3	EE2-06A3	$ Z_0 $	$L Z_0$	α_c	$L \gamma$	$ Z_L $	$L Z_L$	$ 2\gamma $	$2\beta_l$	
CUTOFF	EE2-07A	f	a	b	ϵ_r					
GUIDE	EE2-08A	a	b	$c/\sqrt{\epsilon_r}$	f_c	f	λ_g	v_g	v_p	
FREQ	EE2-09A						v	f	$1/2\pi$	
SPECT	EE2-10A	MHz/cm		τ	T	V				
SPURS	EE2-11A	$f_{\max}$	$f_{\min}$	$N_{\max}$	$M_{\max}$	f_1	f_2	M	N	
FM LVL	EE2-12A			M	$\sum$		J_n	k+1	k	
INDEX	EE2-13A	x_1	x_0	x	$f(x), f(x)-y$	y	$f(x_0)$	$f(x_1)$	# iter	
Y-FACT	EE2-14A	T_c	T_h	$10 \uparrow Y/10$						
NET-F	EE2-15A	IIG _i	G _i	NF						
MATCH	EE2-16A	R_L	X_L	R_s	X_s	Used	Used	Used		

u, G _u	EE2-17A	S ₁₁	S ₁₂	S ₂₁	S ₂₂		S ₂₁ ² /G _u	u		
G-CIRC	EE2-18A	S ₁₁	S ₁₂	S ₂₁	S ₂₂		denominator	G _i		S _{ij}
F-CIRC	EE2-19A	Γ ₀	∠Γ ₀	NF ₀	Γ _s	∠Γ _s	NF _s	NF _i	N	
S→Δ	EE2-20A1	S ₁₁	S ₁₂	S ₂₁	S ₂₂	θ ₁₁	θ ₁₂ , Δ	θ ₂₁ , Δ	θ ₂₂	
K, GMAX	EE2-20A2	S ₁₁	S ₁₂	S ₂₁	S ₂₂	θ ₁₁	Δ	∠Δ	θ ₂₂	K
PTMCH	EE2-20A3	S ₁₁	S ₁₂	S ₂₁	S ₂₂	θ ₁₁	Δ	∠Δ	θ ₂₂	C*
B:G-CIRC	EE2-21A	S ₁₁	S ₁₂	S ₂₁	S ₂₂	θ ₁₁	Δ	∠Δ	θ ₂₂	G
STAB	EE2-22A	S ₁₁	S ₁₂	S ₂₁	S ₂₂	θ ₁₁	Δ	∠Δ	θ ₂₂	
MAP	EE2-23A	S ₁₁	S ₁₂ , Γ	S ₂₁ , ∠Γ	S ₂₂	θ ₁₁	Δ	Δ	θ ₂₂	
INTERP	EE2-24A	x ₁ , x ₀	y ₁ , x ₁	x ₁ , x ₂	y ₂	x	(x ₂ -x ₁)(x ₂ -x ₀)	x		
S→(IN)	EE2-25A1	T ₁₁	T ₁₂	T ₂₁	T ₂₂	∠T ₁₁	∠T ₁₂	T ₂₁	T ₂₂	
→S(IN)	EE2-25A2	T ₁₁	T ₁₂	T ₂₁	T ₂₂	∠T ₁₁	∠T ₁₂	T ₂₁	T ₂₂	
T'-1	EE2-25A3	T ₁₁ , T ₁₂	T ₁₂	T ₂₁	T ₂₂ , T ₁₁	∠T ₁₁ , ∠T ₂₂	∠T ₁₂	T ₂₁	T ₂₂ , T ₁₁	
T'-2	EE2-25A4	T ₁₁ '	T ₁₂ '	T ₂₁ '	T ₂₂ '	∠T ₁₁ '	∠T ₁₂ '	T ₂₁ '	T ₂₂ '	
S→(OUT)	EE2-26A5	T ₁₁ '	T ₁₂ '	T ₂₁ '	T ₂₂ '	∠T ₁₁ '	∠T ₁₂ '	T ₂₁ '	T ₂₂ '	
→S(OUT)	EE2-25A6	T ₁₁ '	T ₁₂ '	T ₂₁ '	T ₂₂ '	∠T ₁₁ '	∠T ₁₂ '	T ₂₁ '	T ₂₂ '	
S→T	EE2-26A1	S ₁₁	S ₁₂	S ₂₁	S ₂₂	∠S ₁₁	∠S ₁₂	S ₂₁	S ₂₂	
T→S	EE2-26A2	t ₁₁	t ₁₂	t ₂₁	t ₂₂	∠t ₁₁	∠t ₁₂	t ₂₁	t ₂₂	
CM0-1	EE2-27A1	a ₁₁ , a ₁₂ b ₂₁	a ₁₂ , a ₁₂ b ₂₂	a ₂₁ , a ₂₂ b ₂₁	a ₂₁ , a ₂₂ b ₂₂	a ₁₁ b ₁₁	a ₁₁ b ₁₂	a ₂₁ b ₁₁	a ₂₁ b ₁₂	
CM0-2	EE2-27A2	∠c ₁₁	∠c ₁₂	∠c ₂₁	∠c ₂₂	c ₁₁	c ₁₂	c ₂₁	c ₂₂	

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MISMATCH ERROR LIMITS

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	x	71	g NOP	35 01
A	11	RTN	24	g NOP	35 01
↑	41	LBL	23	g NOP	35 01
↑	41	D	14	g NOP	35 01
1	01	1	01	g NOP	35 01
—	51	RCL 1	34 01	g NOP	35 01
$g x \div y$	35 07	RCL 2	34 02	g NOP	35 01
1	01	x	71	g NOP	35 01
+	61	—	51	g NOP	35 01
÷	81	f	31	g NOP	35 01
STO 1	33 01	LOG	08	g NOP	35 01
RTN	24	2	02	g NOP	35 01
LBL	23	0	00	g NOP	35 01
B	12	x	71	g NOP	35 01
↑	41	RTN	24	g NOP	35 01
↑	41	LBL	23	g NOP	35 01
1	01	E	15	g NOP	35 01
—	51	RCL 1	34 01	g NOP	35 01
$g x \div y$	35 07	RCL 2	34 02	g NOP	35 01
1	01	x	71	g NOP	35 01
+	61	f^{-1}	32	g NOP	35 01
÷	81	SIN	04	g NOP	35 01
STO 2	33 02	RTN	24	g NOP	35 01
RTN	24	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01
C	13	g NOP	35 01	g NOP	35 01
1	01	g NOP	35 01	g NOP	35 01
RCL 1	34 01	g NOP	35 01	g NOP	35 01
RCL 2	34 02	g NOP	35 01	g NOP	35 01
x	71	g NOP	35 01	g NOP	35 01
+	61	g NOP	35 01	g NOP	35 01
f	31	g NOP	35 01	g NOP	35 01
LOG	08	g NOP	35 01	g NOP	35 01
2	02	g NOP	35 01	g NOP	35 01
0	00	g NOP	35 01	g NOP	35 01

$R_1 \rho_1$	R_4	R_7
$R_2 \rho_2$	R_5	R_8
R_3	R_6	R_9

MULTIPLE MISMATCH ERROR LIMITS

KEYS	CODE	KEYS	CODE	KEYS	CODE
E	15	STO 6	33 06	RCL 7	34 07
STO 2	33 02	—	51	x	71
$g x \div y$	35 07	RCL 2	34 02	—	51
E	15	RCL 4	34 04	÷	81
STO 1	33 01	x	71	f	31
RTN	24	STO 7	33 07	LOG	08
LBL	23	—	51	2	02
B	12	RCL 8	34 08	0	00
E	15	RCL 5	34 05	x	71
STO 4	33 04	x	71	RTN	24
$g x \div y$	35 07	—	51	LBL	23
E	15	RCL 6	34 06	E	15
STO 3	33 03	RCL 7	34 07	↑	41
RTN	24	x	71	↑	41
LBL	23	+	61	1	01
C	13	÷	81	—	51
CHS	42	f	31	$g x \div y$	35 07
5	05	LOG	08	1	01
÷	81	2	02	+	61
f^{-1}	32	0	00	÷	81
LOG	08	x	71	RTN	24
STO 5	33 05	R/S	84	g NOP	35 01
RTN	24	1	01	g NOP	35 01
LBL	23	RCL 8	34 08	g NOP	35 01
D	14	—	51	g NOP	35 01
1	01	1	01	g NOP	35 01
RCL 1	34 01	RCL 6	34 06	g NOP	35 01
RCL 2	34 02	+	61	g NOP	35 01
x	71	RCL 7	34 07	g NOP	35 01
STO 8	33 08	+	61	g NOP	35 01
+	61	RCL 8	34 08	g NOP	35 01
1	01	RCL 5	34 05	g NOP	35 01
RCL 1	34 01	x	71	g NOP	35 01
RCL 3	34 03	+	61	g NOP	35 01
x	71	RCL 6	34 06	g NOP	35 01

$R_1 \rho_S$	$R_4 \rho_2$	$R_7 \rho_L \rho_2$
$R_2 \rho_L$	$R_5 T^2$	$R_8 \rho_S \rho_L$
$R_3 \rho_1$	$R_6 \rho_S \rho_1$	R_9

SMITH CHART: IMPEDANCE REFLECTION COEFFICIENT

KEYS	CODE	KEYS	CODE	KEYS	CODE
0	00	STO 2	33 02	R→P	01
g x=y	35 23	g R↓	35 08	STO 6	33 06
GTO	22	—	51	g R↓	35 08
1	01	CHS	42	RCL 3	34 03
g R↓	35 08	STO 3	33 03	RCL 2	34 02
RCL 1	34 01	RCL 2	34 02	f ⁻¹	32
÷	81	RCL 1	34 01	R→P	01
STO 2	33 02	x	71	1	01
g R↓	35 08	GTO	22	—	51
STO 3	33 03	9	09	f	31
0	00	LBL	23	R→P	01
RTN	24	A	11	RCL 6	34 06
LBL	23	STO 1	33 01	÷	81
1	01	RTN	24	STO 4	33 04
RCL 5	34 05	LBL	23	g R↓	35 08
RCL 4	34 04	C	13	—	51
CHS	42	0	00	CHS	42
f ⁻¹	32	g x=y	35 23	STO 5	33 05
R→P	01	GTO	22	RCL 4	34 04
1	01	2	02	LBL	23
+	61	g R↓	35 08	9	09
f	31	STO 4	33 04	R/S	84
R→P	01	g R↓	35 08	g x↔y	35 07
STO 6	33 06	STO 5	33 05	GTO	22
g R↓	35 08	0	00	9	09
RCL 5	34 05	RTN	24	LBL	23
RCL 4	34 04	LBL	23	D	14
f ⁻¹	32	2	02	f	31
R→P	01	RCL 3	34 03	R→P	01
1	01	RCL 2	34 02	g LST X	35 00
+	61	f ⁻¹	32		
f	31	R→P	01		
R→P	01	1	01		
RCL 6	34 06	+	61		
÷	81	f	31		

R ₁ Z ₀	R ₄ ρ	R ₇
R ₂ Z/Z ₀	R ₅ φ	R ₈
R ₃ θ	R ₆ 1-Γ , Z/Z ₀ +1	R ₉

SMITH CHART: RADIALLY SCALED PARAMETERS

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	1	01	0	00
4	04	g LST X	35 00	x	71
CHS	42	—	51	CHS	42
GTO	22	÷	81	RTN	24
3	03	RTN	24	LBL	23
LBL	23	LBL	23	2	02
A	11	C	13	1	01
g	35	g	35	g x↔y	35 07
DSZ	83	DSZ	83	1	01
GTO	22	GTO	22	0	00
3	03	4	04	CHS	42
GTO	22	g	35	÷	81
5	05	1/x	04	f ⁻¹	32
LBL	23	LBL	23	LOG	08
3	03	5	05	—	51
2	02	f	31	f	31
0	00	LOG	08	√x	09
÷	81	2	02	RTN	24
f ⁻¹	32	0	00	LBL	23
LOG	08	x	71	E	15
RTN	24	RTN	24	1	01
LBL	23	LBL	23	STO 8	33 08
B	12	D	14	g R↓	35 08
g	35	g	35	RTN	24
DSZ	83	DSZ	83	g NOP	35 01
GTO	22	GTO	22	g NOP	35 01
1	01	2	02	g NOP	35 01
g	35	1	01	g NOP	35 01
1/x	04	g x↔y	35 07	g NOP	35 01
CHS	42	↑	41	g NOP	35 01
LBL	23	x	71		
1	01	—	51		
1	01	f	31		
g x↔y	35 07	LOG	08		
+	61	1	01		

R ₁	R ₄	R ₇
R ₂	R ₅	R ₈ Shift Flag
R ₃	R ₆	R ₉

MICROSTRIP CALCULATIONS – CARD 1

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	÷	81	g	35
A	11	+	61	π	02
f	31	2	02	x	71
SF1	51	÷	81	$g x \rightleftharpoons y$	35 07
f	31	f	31	÷	81
SF2	71	$\sqrt{x}$	09	GTO	22
STO 6	33 06	g	35	2	02
R/S	84	$1/x$	04	LBL	23
LBL	23	STO 2	33 02	1	01
B	12	f	31	8	08
STO 7	33 07	TF1	61	RCL 8	34 08
RCL 6	34 06	GTO	22	÷	81
$g x > y$	35 24	1	01	$g \text{ LST } X$	35 00
f^{-1}	32	1	01	4	04
SF1	51	RCL 8	34 08	÷	81
$g x \rightleftharpoons y$	35 07	g	35	+	61
÷	81	$1/x$	04	f	31
STO 8	33 08	—	51	LN	07
R/S	84	6	06	LBL	23
LBL	23	g	35	2	02
C	13	y^x	05	6	06
1	01	·	83	0	00
$g x \rightleftharpoons y$	35 07	4	04	x	71
+	61	4	04	x	71
$g \text{ LST } X$	35 00	RCL 8	34 08	STO 1	33 01
1	01	÷	81	$g x \rightleftharpoons y$	35 07
—	51	—	51	R/S	84
1	01	2	02	$g x \rightleftharpoons y$	35 07
0	00	·	83	R/S	84
RCL 8	34 08	4	04	$g \text{ NOP}$	35 01
÷	81	2	02		
1	01	+	61		
+	61	RCL 8	34 08		
f	31	+	61		
$\sqrt{x}$	09	2	02		

R_1 Z_C	R_4	R_7 h
R_2 v_r	R_5	R_8 w/h
R_3	R_6 w	R_9

MICROSTRIP CALCULATIONS – CARD 2

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	RCL 8	34 08	·	83
A	11	f^{-1}	32	4	04
f^{-1}	32	$\sqrt{x}$	09	4	04
SF2	71	÷	81	+	61
RCL 7	34 07	1	01	RCL 8	34 08
2	02	—	51	f^{-1}	32
x	71	RCL 4	34 04	$\sqrt{x}$	09
$g x \rightleftharpoons y$	35 07	x	71	÷	81
÷	81	RCL 1	34 01	1	01
RCL 8	34 08	RCL 2	34 02	+	61
g	35	÷	81	RCL 4	34 04
π	02	6	06	x	71
2	02	0	00	RCL 1	34 01
x	71	÷	81	x	71
x	71	f^{-1}	32	RCL 2	34 02
x	71	LN	07	f^{-1}	32
$g x > y$	35 24	RCL 1	34 01	$\sqrt{x}$	09
$g x \rightleftharpoons y$	35 07	x	71	÷	81
$g \text{ NOP}$	35 01	÷	81	3	03
f	31	5	05	6	06
LN	07	x	71	0	00
g	35	GTO	22	g	35
π	02	2	02	π	02
÷	81	LBL	23	x	71
RCL 8	34 08	1	01	÷	81
+	61	1	01	LBL	23
1	01	RCL 8	34 08	2	02
+	61	g	35	STO 4	33 04
STO 4	33 04	$1/x$	04	R/S	84
f^{-1}	32	—	51	$g \text{ NOP}$	35 01
TF1	61	5	05		
GTO	22	g	35		
1	01	y^x	05		
3	03	6	06		
2	02	x	71		

R_1 Z_C	R_4 $2\pi \ln 10 A/v_r$	R_7 h
R_2 v_r	R_5	R_8 w/h
R_3	R_6 w	R_9

MICROSTRIP CALCULATIONS – CARD 3

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	LBL	23	GTO	22
A	11	B	12	2	02
1	01	EEX	43	LBL	23
STO 5	33 05	9	09	E	15
$g \times \div y$	35 07	$\div$	81	RCL 5	34 05
f	31	RCL 5	34 05	3	03
$\sqrt{x}$	09	$g \times \div y$	35 07	$\div$	81
f^{-1}	32	$\div$	81	RCL 2	34 02
TF2	81	g LST X	35 00	$\div$	81
GTO	22	STO 5	33 05	RCL 3	34 03
1	01	$g \times \div y$	35 07	$\div$	81
4	04	f	31	2	02
0	00	$\sqrt{x}$	09	x	71
g	35	STO	33	g	35
π	02	$\div$	81	π	02
x	71	3	03	x	71
RCL 1	34 01	LBL	23	1	01
$\div$	81	C	13	0	00
RCL 8	34 08	RCL 3	34 03	f	31
$\div$	81	R/S	84	LN	07
STO 4	33 04	GTO	22	$\div$	81
$g R \downarrow$	35 08	2	02	R/S	84
LBL	23	LBL	23	LBL	23
1	01	D	14	2	02
RCL 4	34 04	1	01	R/S	84
x	71	0	00	GTO	22
RCL 7	34 07	f	31	2	02
1	01	LN	07	g NOP	35 01
0	00	g LST X	35 00	g NOP	35 01
f	31	$\div$	81	g NOP	35 01
LN	07	RCL 1	34 01		
x	71	x	71		
$\div$	81	RCL 3	34 03		
STO 3	33 03	x	71		
R/S	84	R/S	84		

$R_1 Z_C$	$R_4 2\pi \ln 10 A/v_r$	$R_7 h$
$R_2 v_r$	$R_5 f$	$R_8 w/h$
$R_3 \alpha_C$	$R_6 w$	R_9

TRANSMISSION LINE CALCULATIONS—CARD 1

KEYS	CODE	KEYS	CODE	KEYS	CODE
EEX	43	R/S	84	—	51
1	01	LBL	23	STO 2	33 02
0	00	E	15	RCL 5	34 05
$\div$	81	RCL 1	34 01	RCL 3	34 03
2	02	x	71	$\div$	81
x	71	STO	33	STO	33
g	35	x	71	x	71
π	02	3	03	1	01
x	71	RCL 8	34 08	RCL 5	34 05
STO 8	33 08	RCL 5	34 05	RCL 3	34 03
R/S	84	f	31	x	71
LBL	23	R→P	01	STO	33
B	12	f	31	x	71
STO 1	33 01	$\sqrt{x}$	09	7	07
$g \times \div y$	35 07	STO 5	33 05	R/S	84
STO 2	33 02	$g \times \div y$	35 07	g NOP	35 01
R/S	84	2	02	g NOP	35 01
LBL	23	$\div$	81	g NOP	35 01
C	13	STO 6	33 06	g NOP	35 01
2	02	RCL 8	34 08	g NOP	35 01
x	71	RCL 3	34 03	g NOP	35 01
3	03	f	31	g NOP	35 01
RCL 2	34 02	R→P	01	g NOP	35 01
x	71	f	31	g NOP	35 01
STO 3	33 03	$\sqrt{x}$	09	g NOP	35 01
$\div$	81	STO 3	33 03	g NOP	35 01
STO 7	33 07	$g \times \div y$	35 07	g NOP	35 01
R/S	84	2	02	g NOP	35 01
LBL	23	$\div$	81	g NOP	35 01
D	14	STO 8	33 08	g NOP	35 01
RCL 3	34 03	RCL 6	34 06	g NOP	35 01
x	71	+	61		
RCL 1	34 01	STO 4	33 04		
$\div$	81	RCL 6	34 06		
STO 5	33 05	RCL 8	34 08		

$R_1 R_0, Z_0 $	$R_4 L\gamma$	$R_7 2l/cv_r, 2\gamma l $
$R_2 v_r, L/Z_0$	$R_5 R/L$	$R_8 \omega'$
$R_3 \text{ Used}$	R_6	R_9

TRANSMISSION LINE CALCULATIONS – CARD 2

KEYS	CODE	KEYS	CODE	KEYS	CODE
EEX	43	STO 8	33 08	x	71
9	09	1	01	1	01
÷	81	0	00	$g \times \div y$	35 07
STO 5	33 05	f	31	STO 2	33 02
R/S	84	LN	07	RCL 5	34 05
LBL	23	2	02	f^{-1}	32
B	12	0	00	$\sqrt{x}$	09
STO 1	33 01	÷	81	2	02
$g \times \div y$	35 07	RCL 6	34 06	÷	81
STO 2	33 02	÷	81	1	01
R/S	84	STO	33	+	61
LBL	23	x	71	RCL 3	34 03
C	13	3	03	RCL 8	34 08
RCL 2	34 02	STO	33	+	61
RCL 5	34 05	x	71	f	31
g	35	8	08	R→P	01
π	02	RCL 8	34 08	STO	33
x	71	RCL 3	34 03	x	71
1	01	—	51	7	07
5	05	↑	41	$g \times \div y$	35 07
÷	81	STO 5	33 05	STO 4	33 04
$g \times \div y$	35 07	RCL 8	34 08	R/S	84
÷	81	3	03	g NOP	35 01
STO 6	33 06	x	71	g NOP	35 01
x	71	RCL 3	34 03	g NOP	35 01
2	02	+	61	g NOP	35 01
x	71	x	71	g NOP	35 01
STO 7	33 07	2	02	g NOP	35 01
R/S	84	÷	81	g NOP	35 01
LBL	23	CHS	42	g NOP	35 01
D	14	1	01	g NOP	35 01
STO 3	33 03	+	61	g NOP	35 01
R/S	84	f	31	g NOP	35 01
LBL	23	R→P	01	g NOP	35 01
E	15	STO	33	g NOP	35 01

R ₁ R ₀ , Z ₀	R ₄ l, Lγ	R ₇ 2β ₀ l, 2γl
R ₂ v _r , LZ ₀	R ₅ f, (α ₀ - α _C)/β ₀	R ₈ α _D
R ₃ α _C	R ₆ β ₀	R ₉

TRANSMISSION LINE CALCULATIONS – CARD 3

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	$1/x$	04	f^{-1}	32
A	11	2	02	R→P	01
STO 5	33 05	CHS	42	1	01
$g \times \div y$	35 07	x	71	+	61
STO 6	33 06	$g \times \div y$	35 07	f	31
RCL 4	34 04	CHS	42	R→P	01
RCL 7	34 07	$g \times \div y$	35 07	RCL 1	34 01
f^{-1}	32	f^{-1}	32	x	71
R→P	01	R→P	01	$g \times \div y$	35 07
CHS	42	1	01	RCL 2	34 02
f^{-1}	32	+	61	+	61
LN	07	f	31	LBL	23
STO 7	33 07	R→P	01	1	01
$g \times \div y$	35 07	RCL 7	34 07	$g \times \div y$	35 07
1	01	x	71	R/S	84
8	08	g	35	GTO	22
0	00	$1/x$	04	1	01
x	71	$g \times \div y$	35 07	g NOP	35 01
g	35	RCL 8	34 08	g NOP	35 01
π	02	—	51	g NOP	35 01
÷	81	CHS	42	g NOP	35 01
STO 8	33 08	$g \times \div y$	35 07	g NOP	35 01
RCL 6	34 06	f^{-1}	32	g NOP	35 01
RCL 2	34 02	R→P	01	g NOP	35 01
—	51	1	01	g NOP	35 01
RCL 5	34 05	—	51	g NOP	35 01
RCL 1	34 01	f	31	g NOP	35 01
÷	81	R→P	01	g NOP	35 01
f^{-1}	32	g	35	g NOP	35 01
R→P	01	$1/x$	04	g NOP	35 01
1	01	2	02	g NOP	35 01
+	61	x	71	g NOP	35 01
f	31	$g \times \div y$	35 07	g NOP	35 01
R→P	01	CHS	42	g NOP	35 01
g	35	$g \times \div y$	35 07	g NOP	35 01

R ₁ Z ₀	R ₄ Lγ	R ₇ 2γl
R ₂ LZ ₀	R ₅ Z _L	R ₈ 2βl
R ₃ α _C	R ₆ LZ _L	R ₉

CUTOFF FREQUENCY IN COAX

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	LBL	23	D	14
E	15	B	12	STO 4	33 04
3	03	STO 2	33 02	0	00
EEX	43	0	00	$g x \neq y$	35 21
1	01	$g x \neq y$	35 21	0	00
0	00	0	00	RTN	24
g	35	RTN	24	E	15
π	02	E	15	RCL 2	34 02
$\div$	81	RCL 1	34 01	RCL 3	34 03
RTN	24	$\div$	81	+	61
LBL	23	RCL 4	34 04	$\div$	81
A	11	f	31	RCL 1	34 01
STO 1	33 01	$\sqrt{x}$	09	$\div$	81
0	00	$\div$	81	f^{-1}	32
$g x \neq y$	35 21	RCL 3	34 03	$\sqrt{x}$	09
0	00	-	51	RTN	24
RTN	24	RTN	24	g NOP	35 01
E	15	LBL	23	g NOP	35 01
RCL 2	34 02	C	13	g NOP	35 01
RCL 3	34 03	STO 3	33 03	g NOP	35 01
+	61	0	00	g NOP	35 01
$\div$	81	$g x \neq y$	35 21	g NOP	35 01
RCL 4	34 04	0	00	g NOP	35 01
f	31	RTN	24	g NOP	35 01
$\sqrt{x}$	09	E	15	g NOP	35 01
$\div$	81	RCL 1	34 01	g NOP	35 01
RTN	24	$\div$	81	g NOP	35 01
3	03	RCL 4	34 04	g NOP	35 01
EEX	43	f	31	g NOP	35 01
1	01	$\sqrt{x}$	09	g NOP	35 01
0	00	$\div$	81	g NOP	35 01
$\div$	81	RCL 2	34 02	g NOP	35 01
g	35	-	51	g NOP	35 01
$1/x$	04	RTN	24	g NOP	35 01
R/S	84	LBL	23	g NOP	35 01

RECTANGULAR WAVEGUIDE CALCULATIONS

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 3	33 03	2	02	x	71
$g R \downarrow$	35 08	$\div$	81	7	07
STO 2	33 02	RCL 3	34 03	$g x \neq y$	35 07
$g R \downarrow$	35 08	x	71	$\div$	81
STO 1	33 01	STO 4	33 04	STO 8	33 08
RCL 3	34 03	R/S	84	RCL 5	34 05
f	31	LBL	23	$\div$	81
$\sqrt{x}$	09	C	13	STO 6	33 06
2	02	STO 5	33 05	R/S	84
9	09	f^{-1}	32	LBL	23
9	09	SF1	51	D	14
7	07	RCL 4	34 04	RCL 7	34 07
9	09	$g x > y$	35 24	R/S	84
2	02	GTO	22	LBL	23
5	05	1	01	E	15
EEX	43	f	31	RCL 8	34 08
4	04	SF1	51	R/S	84
$g x \neq y$	35 07	$g x \neq y$	35 07	LBL	23
$\div$	81	LBL	23	2	02
STO 3	33 03	1	01	RCL 7	34 07
R/S	84	$\div$	81	RCL 4	34 04
LBL	23	f^{-1}	32	x	71
B	12	$\sqrt{x}$	09	RCL 3	34 03
RCL 2	34 02	1	01	$\div$	81
$\div$	81	$g x \neq y$	35 07	g	35
f^{-1}	32	-	51	π	02
$\sqrt{x}$	09	f	31	x	71
$g x \neq y$	35 07	$\sqrt{x}$	09	2	02
RCL 1	34 01	STO 7	33 07	x	71
$\div$	81	f^{-1}	32	R/S	84
f^{-1}	32	TF1	61		
$\sqrt{x}$	09	GTO	22		
+	61	2	02		
f	31	RCL 3	34 03		
$\sqrt{x}$	09	STO	33		

R_1 f	R_4 ϵ_r	R_7
R_2 a	R_5	R_8
R_3 b	R_6	R_9

R_1 a	R_4 f_c	R_7 v_g
R_2 b	R_5 f	R_8 v_p
R_3 $c/\sqrt{\epsilon_r}$	R_6 λ_g	R_9

FREQUENCY CONVERSIONS

KEYS	CODE	KEYS	CODE	KEYS	CODE
f^{-1}	32	g	35	g R↓	35 08
SF1	51	π	02	LBL	23
R/S	84	↑	41	1	01
LBL	23	+	61	0	00
A	11	g	35	g $x \neq y$	35 21
0	00	$1/x$	04	GTO	22
g $x=y$	35 23	STO 8	33 08	2	02
RCL 7	34 07	x	71	RCL 6	34 06
R/S	84	0	00	RCL 7	34 07
g R↓	35 08	g $x \neq y$	35 21	÷	81
STO 7	33 07	g R↓	35 08	RTN	24
0	00	A	11	LBL	23
↑	41	RCL 8	34 08	2	02
R/S	84	STO	33	g R↓	35 08
LBL	23	÷	81	RCL 6	34 06
B	12	7	07	g $x \neq y$	35 07
0	00	g R↓	35 08	÷	81
g $x \neq y$	35 21	A	11	STO 7	33 07
GTO	22	LBL	23	0	00
0	00	D	14	↑	41
RCL 7	34 07	f	31	RTN	24
g	35	TF1	61	LBL	23
$1/x$	04	GTO	22	E	15
RTN	24	1	01	STO 6	33 06
LBL	23	2	02	f	31
0	00	·	83	SF1	51
g R↓	35 08	9	09	RTN	24
g	35	9	09	g NOP	35 01
$1/x$	04	7	07	g NOP	35 01
STO 7	33 07	9	09	g NOP	35 01
0	00	2	02		
↑	41	5	05		
RTN	24	EEX	43		
LBL	23	8	08		
C	13	STO 6	33 06		

R ₁	R ₄	R ₇ Frequency
R ₂	R ₅	R ₈ $1/2\pi$
R ₃	R ₆ Velocity	R ₉ Used

LINE AND PULSE SPECTRUM ANALYSIS

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 1	33 01	÷	81	g NOP	35 01
CLX	44	f	31	g NOP	35 01
R/S	84	LOG	08	g NOP	35 01
LBL	23	1	01	g NOP	35 01
B	12	0	00	g NOP	35 01
RCL 1	34 01	x	71	g NOP	35 01
x	71	R/S	84	g NOP	35 01
2	02	LBL	23	g NOP	35 01
÷	81	E	15	g NOP	35 01
g	35	g $x \neq y$	35 07	g NOP	35 01
$1/x$	04	RCL 3	33 04	g NOP	35 01
STO 3	33 03	x	71	g NOP	35 01
R/S	84	1	01	g NOP	35 01
LBL	23	·	83	g NOP	35 01
C	13	5	05	g NOP	35 01
RCL 1	34 01	x	71	g NOP	35 01
x	71	x	71	g NOP	35 01
g	35	STO 5	33 05	g NOP	35 01
$1/x$	04	R/S	84	g NOP	35 01
STO 4	33 04	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
RCL 3	34 03	g NOP	35 01	g NOP	35 01
RCL 4	34 04	g NOP	35 01	g NOP	35 01
÷	81	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01
D	14	g NOP	35 01	g NOP	35 01
RCL 4	34 04	g NOP	35 01	g NOP	35 01
RCL 3	34 03	g NOP	35 01	g NOP	35 01
÷	81	g NOP	35 01	g NOP	35 01
x	71	g NOP	35 01	g NOP	35 01
STO 5	33 05	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
RCL 3	34 03	g NOP	35 01	g NOP	35 01
RCL 4	34 04	g NOP	35 01	g NOP	35 01

R ₁ MHz/cm	R ₄ T	R ₇
R ₂	R ₅ V	R ₈
R ₃ τ	R ₆	R ₉

SPURIOUS RESPONSES

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 1	33 01	E	15	EEX	43
g R↓	35 08	—	51	2	02
STO 2	33 02	g	35	÷	81
R/S	84	ABS	06	+	61
LBL	23	g x>y	35 24	R/S	84
B	12	GTO	22	GTO	22
STO 3	33 03	3	03	4	04
g R↓	35 08	RCL 2	34 02	LBL	23
STO 4	33 04	g x>y	35 24	E	15
R/S	84	GTO	22	RCL 5	34 05
LBL	23	3	03	RCL 7	34 07
C	13	RCL 7	34 07	x	71
STO 6	33 06	RCL 8	34 08	RCL 6	34 06
g R↓	35 08	EEX	43	RCL 8	34 08
STO 5	33 05	2	02	x	71
R/S	84	÷	81	RTN	24
LBL	23	+	61	LBL	23
D	14	CHS	42	4	04
0	00	R/S	84	RCL 3	34 03
STO 7	33 07	LBL	23	RCL 8	34 08
LBL	23	3	03	g x≠y	35 21
1	01	RCL 1	34 01	GTO	22
0	00	E	15	2	02
STO 8	33 08	+	61	RCL 4	34 04
1	01	g	35	RCL 7	34 07
STO	33	ABS	06	g x≠y	35 21
+	61	g x>y	35 24	GTO	22
7	07	GTO	22	1	01
LBL	23	4	04	0	00
2	02	RCL 2	34 02	÷	81
1	01	g x>y	35 24		
STO	33	GTO	22		
+	61	4	04		
8	08	RCL 7	34 07		
RCL 1	34 01	RCL 8	34 08		

R ₁ f _{max}	R ₄ M _{max}	R ₇ M
R ₂ f _{min}	R ₅ f ₁	R ₈ N
R ₃ N _{max}	R ₆ f ₂	R ₉ Used

FM SIDEBAND LEVELS

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 2	33 02	5	05	STO	33
g x≥y	35 07	+	61	+	61
STO 3	33 03	f	31	4	04
E	15	INT	83	g	35
LBL	23	STO 8	33 08	DSZ	83
2	02	1	01	GTO	22
f	31	+	61	1	01
LOG	08	STO 7	33 07	RCL 4	34 04
2	02	RCL 3	34 03	g	35
0	00	2	02	ABS	06
x	71	÷	81	RTN	24
RTN	24	↑	41	g NOP	35 01
LBL	23	f ⁻¹	32	g NOP	35 01
B	12	√x	09	g NOP	35 01
STO 2	33 02	CHS	42	g NOP	35 01
g x≥y	35 07	g x≥y	35 07	g NOP	35 01
STO 3	33 03	RCL 2	34 02	g NOP	35 01
E	15	g	35	g NOP	35 01
STO 6	33 06	y ^x	05	g NOP	35 01
0	00	RCL 2	34 02	g NOP	35 01
STO 2	33 02	g	35	g NOP	35 01
E	15	n!	03	g NOP	35 01
RCL 6	34 06	÷	81	g NOP	35 01
g x≥y	35 07	STO 4	33 04	g NOP	35 01
÷	81	LBL	23	g NOP	35 01
GTO	22	1	01	g NOP	35 01
2	02	RCL 7	34 07	g NOP	35 01
LBL	23	RCL 8	34 08	g NOP	35 01
E	15	—	51	g NOP	35 01
RCL 3	34 03	÷	81	g NOP	35 01
RCL 2	34 02	g LST X	35 00		
g x≤y	35 22	RCL 2	34 02		
g x≥y	35 07	+	61		
g NOP	35 01	÷	81		
1	01	x	71		

R ₁	R ₄ Sum	R ₇ k + 1
R ₂ n	R ₅	R ₈ k
R ₃ m	R ₆ J _n	R ₉

MODULATION INDEX FOR SPECIFIED CARRIER SUPPRESSION

KEYS	CODE	KEYS	CODE	KEYS	CODE
f	31	—	51	+	61
REG	43	g LST X	35 00	4	04
CHS	42	÷	81	g	35
2·	02	g	35	DSZ	83
0	00	ABS	06	GTO	22
÷	81	EEX	43	3	03
f ⁻¹	32	CHS	42	RCL 4	34 04
LOG	08	8	08	RCL 5	34 05
STO 5	33 05	g x>y	35 24	—	51
·	83	RCL 3	34 03	STO 4	33 04
1	01	R/S	84	RCL 7	34 07
+	61	9	09	x	71
CHS	42	STO 8	33 08	0	00
STO 7	33 07	RCL 3	34 03	g x≤y	35 22
1	01	2	02	GTO	22
RCL 5	34 05	÷	81	2	02
—	51	f ⁻¹	32	RCL 1	34 01
STO 6	33 06	√x	09	STO 2	33 02
4	04	CHS	42	RCL 7	34 07
STO 1	33 01	↑	41	STO 6	33 06
LBL	23	↑	41	LBL	23
1	01	1	01	2	02
RCL 1	34 01	STO 4	33 04	RCL 3	34 03
RCL 1	34 01	LBL	23	STO 1	33 01
RCL 2	34 02	3	03	RCL 4	34 04
—	51	RCL 8	34 08	STO 7	33 07
RCL 7	34 07	1	01	GTO	22
RCL 6	34 06	0	00	1	01
—	51	—	51	g NOP	35 01
÷	81	CHS	42	g NOP	35 01
RCL 7	34 07	↑	41		
x	71	x	71		
—	51	÷	81		
STO 3	33 03	x	71		
RCL 1	34 01	STO	33		

R ₁ x ₁	R ₄ f(x), f(x) - y	R ₇ f(x ₁)
R ₂ x ₀	R ₅ y	R ₈ # iter
R ₃ x	R ₆ f(x ₀)	R ₉

CONSTANT EXCESS NOISE MEASUREMENT

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 1	33 01	D	14	g NOP	35 01
RTN	24	1	01	g NOP	35 01
LBL	23	0	00	g NOP	35 01
B	12	÷	81	g NOP	35 01
STO 2	33 02	f ⁻¹	32	g NOP	35 01
RTN	24	LOG	08	g NOP	35 01
LBL	23	1	01	g NOP	35 01
C	13	—	51	g NOP	35 01
1	01	2	02	g NOP	35 01
0	00	9	09	g NOP	35 01
÷	81	0	00	g NOP	35 01
f ⁻¹	32	x	71	g NOP	35 01
LOG	08	RTN	24	g NOP	35 01
STO 3	33 03	LBL	23	g NOP	35 01
RCL 1	34 01	E	15	g NOP	35 01
x	71	2	02	g NOP	35 01
RCL 2	34 02	9	09	g NOP	35 01
—	51	0	00	g NOP	35 01
1	01	÷	81	g NOP	35 01
RCL 3	34 03	1	01	g NOP	35 01
—	51	+	61	g NOP	35 01
÷	81	f	31	g NOP	35 01
2	02	LOG	08	g NOP	35 01
9	09	1	01	g NOP	35 01
0	00	0	00	g NOP	35 01
÷	81	x	71	g NOP	35 01
1	01	RTN	24	g NOP	35 01
+	61	g NOP	35 01	g NOP	35 01
f	31	g NOP	35 01	g NOP	35 01
LOG	08	g NOP	35 01	g NOP	35 01
1	01	g NOP	35 01	g NOP	35 01
0	00	g NOP	35 01	g NOP	35 01
x	71	g NOP	35 01	g NOP	35 01
RTN	24	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01

R ₁ T _c	R ₄	R ₇
R ₂ T _h	R ₅	R ₈
R ₃ 10↑Y/10	R ₆	R ₉

NOISE FIGURE OF CASCADED NETWORKS

KEYS	CODE	KEYS	CODE	KEYS	CODE
1	01	LBL	23	g NOP	35 01
STO 1	33 01	0	00	g NOP	35 01
R/S	84	f	31	g NOP	35 01
LBL	23	LOG	08	g NOP	35 01
B	12	1	01	g NOP	35 01
g	35	0	00	g NOP	35 01
DSZ	83	x	71	g NOP	35 01
GTO	22	R/S	84	g NOP	35 01
1	01	LBL	23	g NOP	35 01
E	15	E	15	g NOP	35 01
STO 2	33 02	1	01	g NOP	35 01
g x ∇ y	35 07	0	00	g NOP	35 01
E	15	$\div$	81	g NOP	35 01
STO 3	33 03	f ⁻¹	32	g NOP	35 01
GTO	22	LOG	08	g NOP	35 01
0	00	RTN	24	g NOP	35 01
LBL	23	LBL	23	g NOP	35 01
1	01	C	13	g NOP	35 01
E	15	E	15	g NOP	35 01
g x ∇ y	35 07	1	01	g NOP	35 01
E	15	—	51	g NOP	35 01
1	01	2	02	g NOP	35 01
—	51	9	09	g NOP	35 01
g x ∇ y	35 07	0	00	g NOP	35 01
RCL 2	34 02	x	71	g NOP	35 01
RCL 1	34 01	R/S	84	g NOP	35 01
x	71	g NOP	35 01	g NOP	35 01
STO 1	33 01	g NOP	35 01	g NOP	35 01
g x ∇ y	35 07	g NOP	35 01	g NOP	35 01
STO 2	33 02	g NOP	35 01	g NOP	35 01
g R $\downarrow$	35 08	g NOP	35 01	g NOP	35 01
$\div$	81	g NOP	35 01	g NOP	35 01
RCL 3	34 03	g NOP	35 01	g NOP	35 01
+	61	g NOP	35 01	g NOP	35 01
STO 3	33 03	g NOP	35 01	g NOP	35 01

R ₁ Π G _i	R ₄	R ₇
R ₂ G _i	R ₅	R ₈
R ₃ NF	R ₆	R ₉

IMPEDANCE MATCHING

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 1	33 01	g R $\downarrow$	35 08	R/S	84
g R $\downarrow$	35 08	+	61	E	15
STO 2	33 02	f	31	R/S	84
R/S	84	$\sqrt{x}$	09	LBL	23
LBL	23	g R $\uparrow$	35 09	D	14
B	12	g x ∇ y	35 07	RCL 5	34 05
STO 3	33 03	—	51	R/S	84
g R $\downarrow$	35 08	STO 5	33 05	LBL	23
STO 4	33 04	g LST X	35 00	E	15
R/S	84	$\uparrow$	41	STO 7	33 07
LBL	23	+	61	RCL 2	34 02
C	13	+	61	+	61
RCL 2	34 02	STO 6	33 06	RCL 3	34 03
f ⁻¹	32	RTN	24	x	71
$\sqrt{x}$	09	E	15	RCL 7	34 07
RCL 1	34 01	R/S	84	RCL 4	34 04
f ⁻¹	32	LBL	23	+	61
$\sqrt{x}$	09	C	13	RCL 1	34 01
+	61	RCL 5	34 05	x	71
RCL 3	34 03	R/S	84	—	51
x	71	E	15	RCL 1	34 01
RCL 1	34 01	R/S	84	$\div$	81
RCL 3	34 03	LBL	23	RTN	24
—	51	D	14	g NOP	35 01
$\div$	81	RCL 1	34 01	g NOP	35 01
g LST X	35 00	RCL 3	34 03	g NOP	35 01
g	35	STO 1	33 01	g NOP	35 01
1/x	04	g R $\downarrow$	35 08	g NOP	35 01
RCL 3	34 03	STO 3	33 03	g NOP	35 01
x	71	RCL 2	34 02	g NOP	35 01
RCL 2	34 02	RCL 4	34 04	g NOP	35 01
x	71	STO 2	33 02	g NOP	35 01
f ⁻¹	32	g R $\downarrow$	35 08	g NOP	35 01
$\sqrt{x}$	09	STO 4	33 04	g NOP	35 01
g LST X	35 00	C	13	g NOP	35 01

R ₁ R _L	R ₄ X _S	R ₇ Used
R ₂ X _L	R ₅ Used	R ₈
R ₃ R _S	R ₆ Used	R ₉

FIGURE OF MERIT, MAXIMUM UNILATERAL GAIN

KEYS	CODE	KEYS	CODE	KEYS	CODE
↑	41	STO 3	33 03	f	31
↑	41	RTN	24	LOG	08
1	01	LBL	23	1	01
1	01	B	12	0	00
g x=y	35 23	RCL 1	34 01	x	71
GTO	22	RCL 2	34 02	RTN	24
1	01	x	71	LBL	23
CLX	44	RCL 3	34 03	D	14
1	01	x	71	RCL 7	34 07
2	02	RCL 4	34 04	LBL	23
g x=y	35 23	x	71	4	04
GTO	22	1	01	1	01
2	02	RCL 1	34 01	+	61
CLX	44	f ⁻¹	32	f ⁻¹	32
2	02	√x	09	√x	09
1	01	—	51	g	35
g x=y	35 23	1	01	1/x	04
GTO	22	RCL 4	34 04	E	15
3	03	f ⁻¹	32	C	13
g R↑	35 09	√x	09	+	61
STO 4	33 04	—	51	R/S	84
RTN	24	x	71	RCL 7	34 07
LBL	23	STO 6	33 06	CHS	42
1	01	÷	81	GTO	22
g R↑	35 09	STO 7	33 07	4	04
STO 1	33 01	RTN	24	g NOP	35 01
RTN	24	LBL	23	g NOP	35 01
LBL	23	C	13	g NOP	35 01
2	02	RCL 3	34 03	g NOP	35 01
g R↑	35 09	f ⁻¹	32	g NOP	35 01
STO 2	33 02	√x	09		
RTN	24	RCL 6	34 06		
LBL	23	÷	81		
3	03	LBL	23		
g R↑	35 09	E	15		

R ₁ s ₁₁	R ₄ s ₂₂	R ₇ u
R ₂ s ₁₂	R ₅	R ₈
R ₃ s ₂₁	R ₆ s ₂₁ ² /G _u	R ₉

UNILATERAL DESIGN: GAIN CIRCLES

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	STO 7	33 07	C	13
A	11	RCL 1	34 01	1	01
RCL 3	34 03	LBL	23	0	00
f ⁻¹	32	2	02	÷	81
√x	09	STO	33	f ⁻¹	32
E	15	9	09	LOG	08
R/S	84	x	71	STO 7	33 07
1	01	1	01	RCL 4	34 04
RCL 1	34 01	RCL 7	34 07	GTO	22
f ⁻¹	32	RCL	34	2	02
√x	09	9	09	LBL	23
—	51	f ⁻¹	32	E	15
g	35	√x	09	f	31
1/x	04	x	71	LOG	08
E	15	+	61	1	01
R/S	84	STO 6	33 06	0	00
+	61	÷	81	x	71
1	01	R/S	84	RTN	24
RCL 4	34 04			g NOP	35 01
f ⁻¹	32	RCL	34	g NOP	35 01
√x	09	9	09	g NOP	35 01
—	51	f ⁻¹	32	g NOP	35 01
g	35	√x	09	g NOP	35 01
1/x	04	1	01	g NOP	35 01
E	15	—	51	g NOP	35 01
R/S	84	RCL 7	34 07	g NOP	35 01
+	61	x	71	g NOP	35 01
R/S	84	1	01	g NOP	35 01
LBL	23	+	61	g NOP	35 01
B	12	f	31	g NOP	35 01
1	01	√x	09		
0	00	RCL 6	34 06		
÷	81	÷	81		
f ⁻¹	32	R/S	84		
LOG	08	LBL	23		

R ₁ s ₁₁	R ₄ s ₂₂	R ₇ G _i
R ₂ s ₁₂	R ₅	R ₈
R ₃ s ₂₁	R ₆ denominator	R ₉ s _{ij}

UNILATERAL DESIGN: NOISE FIGURE CIRCLES

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	RCL 4	34 04	$g x \rightleftharpoons y$	35 07
A	11	f^{-1}	32	$\div$	81
STO 1	33 01	R $\rightarrow$ P	01	R/S	84
$g R \downarrow$	35 08	RCL 2	34 02	1	01
STO 2	33 02	RCL 1	34 01	RCL 1	34 01
$g R \downarrow$	35 08	f^{-1}	32	f^{-1}	32
1	01	R $\rightarrow$ P	01	$\sqrt{x}$	09
0	00	$g x \rightleftharpoons y$	35 07	—	51
$\div$	81	$g R \downarrow$	35 08	RCL 8	34 08
f^{-1}	32	—	51	+	61
LOG	08	$g R \downarrow$	35 08	$g LST X$	35 00
STO 3	33 03	—	51	x	71
R/S	84	$g R \uparrow$	35 09	f	31
LBL	23	f	31	$\sqrt{x}$	09
B	12	R $\rightarrow$ P	01	1	01
STO 4	33 04	f^{-1}	32	RCL 8	34 08
$g R \downarrow$	35 08	$\sqrt{x}$	09	+	61
STO 5	33 05	1	01	$\div$	81
$g R \downarrow$	35 08	RCL 4	34 04	R/S	84
1	01	f^{-1}	32	$g NOP$	35 01
0	00	$\sqrt{x}$	09	$g NOP$	35 01
$\div$	81	—	51	$g NOP$	35 01
f^{-1}	32	$\div$	81	$g NOP$	35 01
LOG	08	RCL 7	34 07	$g NOP$	35 01
STO 6	33 06	RCL 3	34 03	$g NOP$	35 01
R/S	84	—	51	$g NOP$	35 01
LBL	23	x	71	$g NOP$	35 01
C	13	RCL 6	34 06	$g NOP$	35 01
1	01	RCL 3	34 03	$g NOP$	35 01
0	00	—	51	$g NOP$	35 01
$\div$	81	$\div$	81	$g NOP$	35 01
f^{-1}	32	STO 8	33 08		
LOG	08	1	01		
STO 7	33 07	+	61		
RCL 5	34 05	RCL 1	34 01		

R_1 $ \Gamma_0 $	R_4 $ \Gamma_s $	R_7 NF_i
R_2 $\angle \Gamma_0$	R_5 $\angle \Gamma_s$	R_8 N
R_3 NF_0	R_6 NF_s	R_9

INPUT S-PARAMETERS AND COMPUTE DELTA

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	$g R \uparrow$	35 09	9	09
A	11	STO 2	33 02	STO 7	33 07
1	01	R/S	84	CLX	44
1	01	LBL	23	1	01
$g x=y$	35 23	3	03	f^{-1}	32
GTO	22	$g R \uparrow$	35 09	R $\rightarrow$ P	01
1	01	STO 7	33 07	STO 6	33 06
CLX	44	$g R \uparrow$	35 09	$g R \downarrow$	35 08
1	01	STO 3	33 03	RCL 7	34 07
2	02	R/S	84	x	71
$g x=y$	35 23	LBL	23	$g LST X$	35 00
GTO	22	B	12	STO	33
2	02	RCL 5	34 05	x	71
CLX	44	RCL 8	34 08	6	06
2	02	+	61	CLX	44
1	01	1	01	RCL 6	34 06
$g x=y$	35 23	f^{-1}	32	$g R \downarrow$	35 08
GTO	22	R $\rightarrow$ P	01	—	51
3	03	RCL 1	34 01	$g R \downarrow$	35 08
$g R \uparrow$	35 09	RCL 4	34 04	—	51
STO 8	33 08	x	71	CHS	42
$g R \uparrow$	35 09	x	71	$g R \uparrow$	35 09
STO 4	33 04	$g x \rightleftharpoons y$	35 07	$g x \rightleftharpoons y$	35 07
R/S	84	$g LST X$	35 00	f	31
LBL	23	x	71	R $\rightarrow$ P	01
1	01	RCL 2	34 02	STO 6	33 06
$g R \uparrow$	35 09	RCL 3	34 03	$g x \rightleftharpoons y$	35 07
STO 5	33 05	x	71	STO 7	33 07
$g R \uparrow$	35 09	STO	33	R/S	84
STO 1	33 01	9	09	$g NOP$	35 01
R/S	84	CLX	44		
LBL	23	RCL 6	34 06		
2	02	RCL 7	34 07		
$g R \uparrow$	35 09	+	61		
STO 6	33 06	RCL	34		

R_1 s_{11}	R_4 s_{22}	R_7 $\theta_{21}, \angle \Delta$
R_2 s_{12}	R_5 θ_{11}	R_8 θ_{22}
R_3 s_{21}	R_6 $\theta_{12}, \Delta $	R_9 Used

BILATERAL DESIGN: K GMAX

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 3	34 03	ABS	06	$\sqrt{x}$	09
f^{-1}	32	g LST X	35 00	$g x \rightleftharpoons y$	35 07
$\sqrt{x}$	09	$\div$	81	$g R \downarrow$	35 08
f	31	$g R \uparrow$	35 09	x	71
LOG	08	1	01	CHS	42
1	01	+	61	$g R \uparrow$	35 09
0	00	RCL 1	34 01	+	61
x	71	f^{-1}	32	RCL 3	34 03
-	51	$\sqrt{x}$	09	x	71
RTN	24	-	51	RCL 2	34 02
LBL	23	RCL 4	34 04	$\div$	81
A	11	f^{-1}	32	g	35
RCL 6	34 06	$\sqrt{x}$	09	ABS	06
f^{-1}	32	-	51	f	31
$\sqrt{x}$	09	2	02	LOG	08
$\uparrow$	41	$\div$	81	1	01
$\uparrow$	41	RCL 2	34 02	0	00
1	01	RCL 3	34 03	x	71
-	51	x	71	RTN	24
RCL 1	34 01	g	35	g NOP	35 01
f^{-1}	32	ABS	06	g NOP	35 01
$\sqrt{x}$	09	$\div$	81	g NOP	35 01
-	51	STO	33	g NOP	35 01
RCL 4	34 04	9	09	g NOP	35 01
f^{-1}	32	RTN	24	g NOP	35 01
$\sqrt{x}$	09	LBL	23	g NOP	35 01
+	61	B	12	g NOP	35 01
CHS	42	A	11	g NOP	35 01
$\uparrow$	41	$\uparrow$	41	g NOP	35 01
CLX	44	x	71	g NOP	35 01
$g x = y$	35 23	g LST X	35 00	g NOP	35 01
1	01	$g x \rightleftharpoons y$	35 07		
g NOP	35 01	1	01		
+	61	-	51		
g	35	f	31		

$R_1 \ s_{11}$	$R_4 \ s_{22}$	$R_7 \ \angle \Delta$
$R_2 \ s_{12}$	$R_5 \ \theta_{11}$	$R_8 \ \theta_{22}$
$R_3 \ s_{21}$	$R_6 \ \Delta $	$R_9 \ K$

BILATERAL DESIGN: OPTIMUM MATCHING

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 6	34 06	RCL 5	34 05	$g x \rightleftharpoons y$	35 07
RCL 7	34 07	RCL 1	34 01	$g x \leq y$	35 22
RCL 5	34 05	D	14	0	00
RCL 1	34 01	RCL 1	34 01	+	61
C	13	f^{-1}	32	g LST X	35 00
RCL 8	34 08	$\sqrt{x}$	09	+	61
RCL 4	34 04	1	01	g LST X	35 00
D	14	+	61	+	61
RCL 4	34 04	RCL 4	34 04	R/S	84
f^{-1}	32	LBL	23	$g R \uparrow$	35 09
$\sqrt{x}$	09	1	01	R/S	84
1	01	f^{-1}	32	LBL	23
+	61	$\sqrt{x}$	09	D	14
RCL 1	34 01	-	51	f^{-1}	32
GTO	22	RCL 6	34 06	$R \rightarrow P$	01
1	01	f^{-1}	32	$g R \downarrow$	35 08
LBL	23	$\sqrt{x}$	09	-	51
C	13	-	51	$g R \downarrow$	35 08
$g R \downarrow$	35 08	$\div$	81	-	51
-	51	2	02	$g R \uparrow$	35 09
$g R \downarrow$	35 08	x	71	$g x \rightleftharpoons y$	35 07
x	71	g	35	f	31
$g R \uparrow$	35 09	$1/x$	04	$R \rightarrow P$	01
$g x \rightleftharpoons y$	35 07	$\uparrow$	41	$g x \rightleftharpoons y$	35 07
f^{-1}	32	$\uparrow$	41	STO	33
$R \rightarrow P$	01	x	71	9	09
$g x \rightleftharpoons y$	35 07	1	01	$g R \downarrow$	35 08
RTN	24	-	51	RTN	24
LBL	23	f	31	g NOP	35 01
A	11	$\sqrt{x}$	09	g NOP	35 01
RCL 6	34 06	-	51		
RCL 7	34 07	RCL	34		
RCL 8	34 08	9	09		
RCL 4	34 04	$g x \rightleftharpoons y$	35 07		
C	13	1	01		

$R_1 \ s_{11}$	$R_4 \ s_{22}$	$R_7 \ \angle \Delta$
$R_2 \ s_{12}$	$R_5 \ \theta_{11}$	$R_8 \ \theta_{22}$
$R_3 \ s_{21}$	$R_6 \ \Delta $	$R_9 \ \angle C^*$

BILATERAL DESIGN: GAIN CIRCLES

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 6	34 06	÷	81	RCL 1	34 01
RCL 7	34 07	STO	33	f^{-1}	32
RCL 5	34 05	0	09	$\sqrt{x}$	09
CHS	42	g	35	—	51
RCL 1	34 01	$1/x$	04	RCL 4	34 04
g R↓	35 08	LBL	23	f^{-1}	32
+	61	1	01	$\sqrt{x}$	09
g R↓	35 08	RCL 6	34 06	—	51
x	71	f^{-1}	32	1	01
g R↑	35 09	$\sqrt{x}$	09	+	61
$g x \rightleftharpoons y$	35 07	—	51	RCL 2	34 02
f^{-1}	32	RCL 4	34 04	÷	81
R→P	01	f^{-1}	32	RCL 3	34 03
$g x \rightleftharpoons y$	35 07	$\sqrt{x}$	09	÷	81
RCL 8	34 08	+	61	—	51
RCL 4	34 04	÷	81	x	71
f^{-1}	32	LBL	23	1	01
R→P	01	2	02	+	61
g R↓	35 08	R/S	84	f	31
—	51	$g x \rightleftharpoons y$	35 07	$\sqrt{x}$	09
g R↓	35 08	GTO	22	RCL	34
—	51	2	02	9	09
g R↑	35 09	LBL	23	÷	81
$g x \rightleftharpoons y$	35 07	B	12	g LST X	35 00
f	31	RCL	34	g	35
R→P	01	9	09	$1/x$	04
R/S	84	RCL 2	34 02	GTO	22
1	01	x	71	1	01
0	00	RCL 3	34 03	g NOP	35 01
÷	81	x	71	g NOP	35 01
f^{-1}	32	↑	41		
LOG	08	↑	41		
RCL 3	34 03	RCL 6	34 06		
f^{-1}	32	f^{-1}	32		
$\sqrt{x}$	09	$\sqrt{x}$	09		

R_1 s_{11}	R_4 s_{22}	R_7 Δ
R_2 s_{12}	R_5 θ_{11}	R_8 θ_{22}
R_3 s_{21}	R_6 $ \Delta $	R_9 G

BILATERAL DESIGN: STABILITY CIRCLES

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	RCL 6	34 06	B	12
B	12	f^{-1}	32	RCL 4	34 04
f^{-1}	32	$\sqrt{x}$	09	GTO	22
R→P	01	—	51	1	01
g R↓	35 08	÷	81	LBL	23
—	51	LBL	23	B	12
g R↓	35 08	2	02	RCL 2	34 02
—	51	R/S	84	RCL 3	34 03
g R↑	35 09	$g x \rightleftharpoons y$	35 07	x	71
$g x \rightleftharpoons y$	35 07	GTO	22	RCL 1	34 01
f	31	2	02	GTO	22
R→P	01	LBL	23	1	01
RTN	24	A	11	g NOP	35 01
LBL	23	RCL 6	34 06	g NOP	35 01
C	13	RCL 7	34 07	g NOP	35 01
g R↓	35 08	RCL 8	34 08	g NOP	35 01
+	61	CHS	42	g NOP	35 01
g R↓	35 08	RCL 4	34 04	g NOP	35 01
x	71	C	13	g NOP	35 01
g R↑	35 09	RCL 5	34 05	g NOP	35 01
$g x \rightleftharpoons y$	35 07	RCL 1	34 01	g NOP	35 01
f^{-1}	32	B	12	g NOP	35 01
R→P	01	RCL 1	34 01	g NOP	35 01
$g x \rightleftharpoons y$	35 07	GTO	22	g NOP	35 01
RTN	24	1	01	g NOP	35 01
LBL	23	LBL	23	g NOP	35 01
D	14	C	13	g NOP	35 01
RCL 2	34 02	RCL 6	34 06	g NOP	35 01
RCL 3	34 03	RCL 7	34 07	g NOP	35 01
x	71	RCL 5	34 05	g NOP	35 01
RCL 4	34 04	CHS	42	g NOP	35 01
LBL	23	RCL 1	34 01		
1	01	C	13		
f^{-1}	32	RCL 8	34 08		
$\sqrt{x}$	09	RCL 4	34 04		

R_1 s_{11}	R_4 s_{22}	R_7 Δ
R_2 s_{12}	R_5 θ_{11}	R_8 θ_{22}
R_3 s_{21}	R_6 $ \Delta $	R_9

LOAD AND SOURCE MAPPING

KEYS	CODE	KEYS	CODE	KEYS	CODE
E	15	g	35	g x ∇ y	35 07
RCL 5	34 05	1/x	04	f	31
RCL 1	34 01	C	13	R $\rightarrow$ P	01
D	14	CHS	42	g x ∇ y	35 07
RCL 3	34 03	g x ∇ y	35 07	RTN	24
RCL 8	34 08	f	31	LBL	23
+	61	R $\rightarrow$ P	01	E	15
RCL 4	34 04	LBL	23	STO 2	33 02
LBL	23	1	01	g x ∇ y	35 07
2	02	R/S	84	STO 3	33 03
STO	33	g x ∇ y	35 07	RCL 7	34 07
9	09	GTO	22	RCL 6	34 06
CLX	44	1	01	C	13
RCL 2	34 02	LBL	23	LBL	23
STO	33	C	13	B	12
x	71	g R $\downarrow$	35 08	E	15
9	09	+	61	RCL 8	34 08
CLX	44	g R $\downarrow$	35 08	RCL 4	34 04
RCL	34	x	71	D	14
9	09	g R $\uparrow$	35 09	RCL 3	34 03
f ⁻¹	32	g x ∇ y	35 07	RCL 5	34 05
R $\rightarrow$ P	01	f ⁻¹	32	+	61
STO	33	R $\rightarrow$ P	01	RCL 1	34 01
9	09	g x ∇ y	35 07	GTO	22
CLX	44	RTN	24	2	02
1	01	LBL	23	g NOP	35 01
STO	33	D	14	g NOP	35 01
-	51	f ⁻¹	32	g NOP	35 01
9	09	R $\rightarrow$ P	01	g NOP	35 01
CLX	44	g R $\downarrow$	35 08	g NOP	35 01
RCL	34	-	51		
9	09	CHS	42		
CHS	42	g R $\downarrow$	35 08		
f	31	-	51		
R $\rightarrow$ P	01	g R $\uparrow$	35 09		

R ₁ s ₁₁	R ₄ s ₂₂	R ₇ Δ
R ₂ s ₁₂ , $ \Gamma $	R ₅ $\angle s_{11}$	R ₈ $\angle s_{22}$
R ₃ s ₂₁ , $\angle \Gamma$	R ₆ $ \Delta $	R ₉

LINEAR AND LAGRANGIAN INTERPOLATION

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 4	33 04	g x ∇ y	35 07	RCL 2	34 02
g R $\downarrow$	35 08	-	51	-	51
STO 3	33 03	x	71	RCL 7	34 07
g R $\downarrow$	35 08	STO 6	33 06	RCL 3	34 03
STO 2	33 02	RTN	24	-	51
g R $\downarrow$	35 08	LBL	23	x	71
STO 1	33 01	D	14	RCL 4	34 04
R/S	84	$\uparrow$	41	x	71
LBL	23	RCL 6	34 06	RCL 7	34 07
B	12	$\div$	81	RCL 1	34 01
STO 5	33 05	STO 6	33 06	-	51
RCL 1	34 01	CLX	44	RCL 7	34 07
-	51	RCL 2	34 02	RCL 3	34 03
RCL 4	34 04	RCL 1	34 01	-	51
x	71	-	51	x	71
RCL 3	34 03	$\div$	81	RCL 5	34 05
RCL 5	34 05	RCL 2	34 02	x	71
-	51	RCL 3	34 03	+	61
RCL 2	34 02	-	51	RCL 7	34 07
x	71	$\div$	81	RCL 1	34 01
+	61	STO 5	33 05	-	51
RCL 3	34 03	CLX	44	RCL 7	34 07
RCL 1	34 01	RCL 1	34 01	RCL 2	34 02
-	51	RCL 2	34 02	-	51
$\div$	81	-	51	x	71
RTN	24	$\div$	81	RCL 6	34 06
LBL	23	RCL 1	34 01	x	71
C	13	RCL 3	34 03	+	61
STO 3	33 03	-	51	RTN	24
g x ∇ y	35 07	$\div$	81	g NOP	35 01
STO 2	33 02	STO 4	33 04		
-	51	RTN	24		
g x ∇ y	35 07	LBL	23		
STO 1	33 01	E	15		
RCL 3	34 03	STO 7	33 07		

R ₁ x ₁ , x ₀	R ₄ y ₂	R ₇ x
R ₂ y ₁ , x ₁	R ₅ x	R ₈
R ₃ x ₁ , x ₂	R ₆ (x ₂ -x ₁)(x ₂ -x ₀)	R ₉

INPUT S-PARAMETERS AND PRECONDITION

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	g R↑	35 09	1	01
A	11	STO 2	33 02	STO	33
1	01	R/S	34	x	71
1	01	LBL	23	2	02
g x=y	35 23	3	03	RTN	24
GTO	22	g R↑	35 09	g NOP	35 01
1	01	STO 7	33 07	g NOP	35 01
CLX	44	g R↑	35 09	g NOP	35 01
1	01	STO 3	33 03	g NOP	35 01
2	02	R/S	84	g NOP	35 01
g x=y	35 23	LBL	23	g NOP	35 01
GTO	22	B	12	g NOP	35 01
2	02	R/S	84	g NOP	35 01
CLX	44	LBL	23	g NOP	35 01
2	02	C	13	g NOP	35 01
1	01	D	14	g NOP	35 01
g x=y	35 23	E	15	g NOP	35 01
GTO	22	RTN	24	g NOP	35 01
3	03	LBL	23	g NOP	35 01
g R↑	35 09	D	14	g NOP	35 01
STO 8	33 08	1	01	g NOP	35 01
g R↑	35 09	CHS	42	g NOP	35 01
STO 4	33 04	STO	33	g NOP	35 01
R/S	84	x	71	g NOP	35 01
LBL	23	3	03	g NOP	35 01
1	01	STO	33	g NOP	35 01
g R↑	35 09	x	71	g NOP	35 01
STO 5	33 05	4	04	g NOP	35 01
g R↑	35 09	RTN	24	g NOP	35 01
STO 1	33 01	LBL	23	g NOP	35 01
R/S	84	E	15	g NOP	35 01
LBL	23	1	01	g NOP	35 01
2	02	CHS	42	g NOP	35 01
g R↑	35 09	STO	33	g NOP	35 01
STO 6	33 06	x	71	g NOP	35 01

$R_1 T_{11} $	$R_4 T_{22} $	$R_7 \angle T_{21}$
$R_2 T_{12} $	$R_5 \angle T_{11}$	$R_8 \angle T_{22}$
$R_3 T_{21} $	$R_6 \angle T_{12}$	R_9

Y-, Z-, G-, OR H-PARAMETERS AND PRECONDITION

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	g R↑	35 09	STO	33
A	11	STO 2	33 02	x	71
1	01	RTN	24	1	01
1	01	LBL	23	STO	33
g x=y	35 23	3	03	+	81
GTO	22	g R↑	35 09	4	04
1	01	STO 7	33 07	RTN	24
CLX	44	g R↑	35 09	g NOP	35 01
1	01	STO 3	33 03	g NOP	35 01
2	02	RTN	24	g NOP	35 01
g x=y	35 23	LBL	23	g NOP	35 01
GTO	22	C	13	g NOP	35 01
2	02	g	35	g NOP	35 01
CLX	44	$1/x$	04	g NOP	35 01
2	02	LBL	23	g NOP	35 01
1	01	B	12	g NOP	35 01
g x=y	35 23	STO	33	g NOP	35 01
GTO	22	x	71	g NOP	35 01
3	03	1	01	g NOP	35 01
g R↑	35 09	STO	33	g NOP	35 01
STO 8	33 08	x	71	g NOP	35 01
g R↑	35 09	2	02	g NOP	35 01
STO 4	33 04	STO	33	g NOP	35 01
RTN	24	x	71	g NOP	35 01
LBL	23	3	03	g NOP	35 01
1	01	STO	33	g NOP	35 01
g R↑	35 09	x	71	g NOP	35 01
STO 5	33 05	4	04	g NOP	35 01
g R↑	35 09	RTN	24	g NOP	35 01
STO 1	33 01	LBL	23	g NOP	35 01
RTN	24	E	15	g NOP	35 01
LBL	23	g	35	g NOP	35 01
2	02	$1/x$	04	g NOP	35 01
g R↑	35 09	LBL	23	g NOP	35 01
STO 6	33 06	D	14	g NOP	35 01

$R_1 T_{11} $	$R_4 T_{22} $	$R_7 \angle T_{21}$
$R_2 T_{12} $	$R_5 \angle T_{11}$	$R_8 \angle T_{22}$
$R_3 T_{21} $	$R_6 \angle T_{12}$	R_9

COMPUTE TPRIME – CARD 1

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 1	34 01	x	71	STO 1	33 01
RCL 5	34 05	RCL 1	34 01	g R↓	35 08
E	15	x	71	STO 4	33 04
RCL 4	34 04	RCL 1	34 01	CLX	44
RCL 8	34 08	RCL 5	34 05	RCL 5	34 05
E	15	E	15	RCL 8	34 08
x	71	RCL 8	34 08	STO 5	33 05
RCL 5	34 05	f	31	g R↓	35 08
f	31	SIN	04	STO 8	33 08
SIN	04	x	71	g R↓	35 08
RCL 8	34 08	RCL 4	34 04	RTN	24
f	31	x	71	LBL	23
SIN	04	+	61	E	15
x	71	RCL 6	34 06	f	31
RCL 1	34 01	RCL 7	34 07	COS	05
x	71	+	61	x	71
RCL 4	34 04	f	31	1	01
x	71	SIN	04	+	61
—	51	RCL 2	34 02	RTN	24
RCL 6	34 06	x	71	g NOP	35 01
RCL 7	34 07	RCL 3	34 03	g NOP	35 01
+	61	x	71	g NOP	35 01
f	31	—	51	g NOP	35 01
COS	05	g x↔y	35 07	g NOP	35 01
RCL 2	34 02	f	31	g NOP	35 01
x	71	R→P	01	g NOP	35 01
RCL 3	34 03	g	35	g NOP	35 01
x	71	1/x	04	g NOP	35 01
—	51	g x↔y	35 07	g NOP	35 01
RCL 4	34 04	CHS	42	g NOP	35 01
RCL 8	34 08	g x↔y	35 07	g NOP	35 01
E	15	2	02	g NOP	35 01
RCL 5	34 05	x	71	g NOP	35 01
f	31	RCL 1	34 01	g NOP	35 01
SIN	04	RCL 4	34 04	g NOP	35 01

$R_1 T_{11} , T_{12} $	$R_4 T_{22} , T_{11} $	$R_7 \angle T_{21}$
$R_2 T_{12} $	$R_5 \angle T_{11}, \angle T_{22}$	$R_8 \angle T_{22}, \angle T_{11}$
$R_3 T_{21} $	$R_6 \angle T_{12}$	R_9 Used

COMPUTE T' – CARD 2

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 5	34 05	f	31	1	01
RCL 1	34 01	R→P	01	STO	33
f ⁻¹	32	STO 1	33 01	—	51
R→P	01	g R↓	35 08	8	08
g x↔y	35 07	STO 5	33 05	CLX	44
STO 5	33 05	g R↓	35 08	RCL 8	34 08
CLX	44	RCL 8	34 08	f	31
1	01	RCL 4	34 04	R→P	01
+	61	f ⁻¹	32	STO 4	33 04
RCL 5	34 05	R→P	01	g R↓	35 08
g x↔y	35 07	g x↔y	35 07	STO 8	33 08
f	31	STO 8	33 08	g R↓	35 08
R→P	01	CLX	44	STO	33
g x↔y	35 07	1	01	x	71
g R↓	35 08	+	61	2	02
g x↔y	35 07	RCL 8	34 08	STO	33
x	71	g x↔y	35 07	x	71
g LST X	35 00	f	31	3	03
g x↔y	35 07	R→P	01	g x↔y	35 07
g R↑	35 09	g x↔y	35 07	1	01
g R↑	35 09	g R↓	35 08	8	08
+	61	g x↔y	35 07	0	00
g LST X	35 00	x	71	+	61
g R↓	35 08	g LST X	35 00	STO	33
g x↔y	35 07	g x↔y	35 07	+	61
f ⁻¹	32	g R↑	35 09	6	06
R→P	01	g R↑	35 09	STO	33
STO 5	33 05	+	61	+	61
CLX	44	g LST X	35 00	7	07
1	01	g R↓	35 08	RTN	24
STO	33	g x↔y	35 07		
—	51	f ⁻¹	32		
5	05	R→P	01		
CLX	44	STO 8	33 08		
RCL 5	34 05	CLX	44		

$R_1 T_{11}' $	$R_4 T_{22}' $	$R_7 \angle T_{21}'$
$R_2 T_{12}' $	$R_5 \angle T_{11}'$	$R_8 \angle T_{22}'$
$R_3 T_{21}' $	$R_6 \angle T_{12}'$	R_9

S — Y, Z, G, H POSTCONDITION

KEYS	CODE	KEYS	CODE	KEYS	CODE
g R↑	35 09	2	02	f ⁻¹	32
g	35	STO	33	R→P	01
1/x	04	÷	81	f	31
g R↓	35 08	3	03	R→P	01
LBL	23	STO	33	LBL	23
D	14	÷	81	6	06
g R↑	35 09	4	04	R/S	84
STO	33	LBL	23	g x ∇ y	35 07
÷	81	5	05	GTO	22
1	01	g x ∇ y	35 07	6	06
STO	33	1	01	LBL	23
x	71	1	01	1	01
4	04	g x=y	35 23	RCL 5	34 05
GTO	22	GTO	22	RCL 1	34 01
5	05	1	01	GTO	22
LBL	23	CLX	44	7	07
A	11	1	01	LBL	23
↑	41	2	02	2	02
↑	41	g x=y	35 23	RCL 6	34 06
↑	41	GTO	22	RCL 2	34 02
RTN	24	2	02	GTO	22
LBL	23	CLX	44	7	07
C	13	2	02	LBL	23
g R↑	35 09	1	01	3	03
g	35	g x=y	35 23	RCL 7	34 07
1/x	04	GTO	22	RCL 3	34 03
g R↓	35 08	3	03	GTO	22
LBL	23	RCL 8	34 08	7	07
B	12	RCL 4	34 04	g NOP	35 01
g R↑	35 09	LBL	23	g NOP	35 01
STO	33	7	07		
÷	81	1	01		
1	01	↑	41		
STO	33	g R↑	35 09		
÷	81	g R↑	35 09		

R ₁ T ₁₁ '	R ₄ T ₂₂ '	R ₇ T ₂₁ '
R ₂ T ₁₂ '	R ₅ T ₁₁ '	R ₈ T ₂₂ '
R ₃ T ₂₁ '	R ₆ T ₁₂ '	R ₉

Y, Z, G, OR H TO S
PARAMETERS POSTCONDITION

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	CLX	44	RCL 2	34 02
A	11	1	01	GTO	22
R/S	84	2	02	5	05
LBL	23	g x=y	35 23	LBL	23
B	12	GTO	22	3	03
D	14	2	02	RCL 7	34 07
LBL	23	CLX	44	RCL 3	34 03
C	13	2	02	GTO	22
1	01	1	01	5	05
CHS	42	g x=y	35 23	g NOP	35 01
STO	33	GTO	22	g NOP	35 01
x	71	3	03	g NOP	35 01
3	03	RCL 8	34 08	g NOP	35 01
STO	33	RCL 4	34 04	g NOP	35 01
x	71	LBL	23	g NOP	35 01
4	04	5	05	g NOP	35 01
RTN	24	f ⁻¹	32	g NOP	35 01
LBL	23	R→P	01	g NOP	35 01
D	14	f	31	g NOP	35 01
1	01	R→P	01	g NOP	35 01
CHS	42	LBL	23	g NOP	35 01
STO	33	6	06	g NOP	35 01
x	71	R/S	84	g NOP	35 01
1	01	g x ∇ y	35 07	g NOP	35 01
STO	33	GTO	22	g NOP	35 01
x	71	6	06	g NOP	35 01
2	02	LBL	23	g NOP	35 01
RTN	24	1	01	g NOP	35 01
LBL	23	RCL 5	34 05	g NOP	35 01
E	15	RCL 1	34 01	g NOP	35 01
1	01	GTO	22	g NOP	35 01
1	01	5	05	g NOP	35 01
g x=y	35 23	LBL	23		
GTO	22	2	02		
1	01	RCL 6	34 06		

R ₁ T ₁₁ '	R ₄ T ₂₂ '	R ₇ T ₂₁ '
R ₂ T ₁₂ '	R ₅ T ₁₁ '	R ₈ T ₂₂ '
R ₃ T ₂₁ '	R ₆ T ₁₂ '	R ₉

S TO T PARAMETER CONVERSION

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 7	34 07	RCL 7	34 07	g R↑	35 09
CHS	42	RCL 5	34 05	g x↔y	35 07
STO 7	33 07	RCL 1	34 01	f ⁻¹	32
RCL 3	34 03	E	15	R→P	01
g	35	g x↔y	35 07	g x↔y	35 07
1/x	04	f	31	RTN	24
STO 3	33 03	R→P	01	LBL	23
R/S	84	R/S	84	D	14
LBL	23	g x↔y	35 07	f ⁻¹	32
B	12	R/S	84	R→P	01
RCL 1	34 01	LBL	23	g R↓	35 08
RCL 5	34 05	C	13	—	51
RCL 8	34 08	RCL 4	34 04	g R↓	35 08
RCL 4	34 04	RCL 8	34 08	—	51
E	15	RCL 7	34 07	CHS	42
g x↔y	35 07	RCL 3	34 03	g R↑	35 09
f	31	E	15	g x↔y	35 07
R→P	01	CHS	42	f	31
g x↔y	35 07	g x↔y	35 07	R→P	01
RCL 7	34 07	CHS	42	g x↔y	35 07
RCL 3	34 03	f	31	RTN	24
E	15	R→P	01	g NOP	35 01
RCL 6	34 06	R/S	84	g NOP	35 01
RCL 2	34 02	g x↔y	35 07	g NOP	35 01
D	14	R/S	84	g NOP	35 01
g x↔y	35 07	RCL 3	34 03	g NOP	35 01
CHS	42	R/S	84	g NOP	35 01
f ⁻¹	32	RCL 7	34 07	g NOP	35 01
R→P	01	R/S	84	g NOP	35 01
f	31	LBL	23	g NOP	35 01
R→P	01	E	15	g NOP	35 01
R/S	84	g R↓	35 08		
g x↔y	35 07	+	61		
R/S	84	g R↓	35 08		
RCL 3	34 03	x	71		

R ₁ s ₁₁	R ₄ s ₂₂	R ₇ ∠s ₂₁
R ₂ s ₁₂	R ₅ ∠s ₁₁	R ₈ ∠s ₂₂
R ₃ s ₂₁	R ₆ ∠s ₁₂	R ₉

T TO S PARAMETER CONVERSION

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 8	34 08	D	14	g R↓	35 08
CHS	42	g x↔y	35 07	—	51
STO 8	33 08	CHS	42	CHS	42
RCL 4	34 04	f ⁻¹	32	g R↑	35 09
g	35	R→P	01	g x↔y	35 07
1/x	04	f	31	f	31
STO 4	33 04	R→P	01	R→P	01
R/S	84	R/S	84	g x↔y	35 07
LBL	23	g x↔y	35 07	RTN	24
B	12	R/S	84	LBL	23
RCL 4	34 04	LBL	23	E	15
RCL 8	34 08	C	13	g R↓	35 08
RCL 6	34 06	RCL 4	34 04	+	61
RCL 2	34 02	R/S	84	g R↓	35 08
E	15	RCL 8	34 08	x	71
g x↔y	35 07	R/S	84	g R↑	35 09
f	31	RCL 3	34 03	g x↔y	35 07
R→P	01	RCL 7	34 07	f ⁻¹	32
R/S	84	RCL 8	34 08	R→P	01
g x↔y	35 07	RCL 4	34 04	g x↔y	35 07
R/S	84	E	15	RTN	24
RCL 3	34 03	CHS	42	g NOP	35 01
RCL 7	34 07	g x↔y	35 07	g NOP	35 01
RCL 6	34 06	CHS	42	g NOP	35 01
RCL 2	34 02	f	31	g NOP	35 01
E	15	R→P	01	g NOP	35 01
g x↔y	35 07	R/S	84	g NOP	35 01
f	31	g x↔y	35 07	g NOP	35 01
R→P	01	R/S	84	g NOP	35 01
g x↔y	35 07	LBL	23	g NOP	35 01
RCL 8	34 08	D	14	g NOP	35 01
RCL 4	34 04	f ⁻¹	32		
E	15	R→P	01		
RCL 5	34 05	g R↓	35 08		
RCL 1	34 01	—	51		

R ₁ T ₁₁	R ₄ T ₂₂	R ₇ ∠T ₂₁
R ₂ T ₁₂	R ₅ ∠T ₁₁	R ₈ ∠T ₂₂
R ₃ T ₂₁	R ₆ ∠T ₁₂	R ₉

COMPLEX MATRIX OPERATIONS – CARD 1

KEYS	CODE	KEYS	CODE	KEYS	CODE
LBL	23	RCL 1	34 01	E	15
A	11	E	15	RCL 4	34 04
f^{-1}	32	D	14	E	15
$R \rightarrow P$	01	STO 6	33 06	D	14
f	31	RCL 8	34 08	STO 4	33 04
$R \rightarrow P$	01	E	15	R/S	84
EEX	43	RCL 3	34 03	LBL	23
4	04	E	15	D	14
x	71	D	14	$g x \rightarrow y$	35 07
$g x \rightarrow y$	35 07	STO 8	33 08	$g R \downarrow$	35 08
$g LST X$	35 00	R/S	84	+	61
$\div$	81	A	11	$g R \downarrow$	35 08
+	61	STO 3	33 03	x	71
$\cdot$	83	E	15	EEX	43
0	00	RCL 2	34 02	4	04
3	03	E	15	$\div$	81
6	06	D	14	f	31
+	61	STO 1	33 01	INT	83
RTN	24	RCL 3	34 03	$g R \uparrow$	35 09
STO 7	33 07	E	15	+	61
E	15	RCL 4	34 04	RTN	24
RCL 1	34 01	E	15	LBL	23
E	15	D	14	E	15
D	14	STO 3	33 03	f	31
STO 5	33 05	R/S	84	INT	83
RCL 7	34 07	A	11	$g LST X$	35 00
E	15	STO	33	f^{-1}	32
RCL 3	34 03	9	09	INT	83
E	15	E	15	RTN	24
D	14	RCL 2	34 02	$g NOP$	35 01
STO 7	33 07	E	15		
R/S	84	D	14		
A	11	STO 2	33 02		
STO 8	33 08	RCL	34		
E	15	9	09		

$R_1 \ a_{11}, a_{12} b_{21}$	$R_4 \ a_{21}, a_{22} b_{22}$	$R_7 \ a_{21} b_{11}$
$R_2 \ a_{12}, a_{12} b_{22}$	$R_5 \ a_{11} b_{11}$	$R_8 \ a_{21} b_{12}$
$R_3 \ a_{21}, a_{22} b_{21}$	$R_6 \ a_{11} b_{12}$	R_9

COMPLEX MATRIX OPERATIONS – CARD 2

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 5	34 05	E	15	E	15
E	15	RCL 7	34 07	f	31
STO 5	33 05	D	14	INT	83
CLX	44	STO 7	33 07	$g LST X$	35 00
RCL 1	34 01	$g x \rightarrow y$	35 07	f^{-1}	32
E	15	STO 3	33 03	INT	83
RCL 5	34 05	$g x \rightarrow y$	35 07	EEX	43
D	14	R/S	84	4	04
STO 5	33 05	$g x \rightarrow y$	35 07	x	71
$g x \rightarrow y$	35 07	R/S	84	$g x \rightarrow y$	35 07
STO 1	33 01	RCL 8	34 08	EEX	43
$g x \rightarrow y$	35 07	E	15	4	04
R/S	84	STO 8	33 08	$\div$	81
R/S	84	CLX	44	f^{-1}	32
RCL 6	34 06	RCL 4	34 04	$R \rightarrow P$	01
E	15	E	15	RTN	24
STO 6	33 06	RCL 8	34 08	$g NOP$	35 01
CLX	44	D	14	$g NOP$	35 01
RCL 2	34 02	STO 8	33 08	$g NOP$	35 01
E	15	$g x \rightarrow y$	35 07	$g NOP$	35 01
RCL 6	34 06	$g x \rightarrow y$	35 07	$g NOP$	35 01
D	14	R/S	84	$g NOP$	35 01
STO 6	33 06	$g x \rightarrow y$	35 07	$g NOP$	35 01
$g x \rightarrow y$	35 07	R/S	84	$g NOP$	35 01
STO 2	33 02	LBL	23	$g NOP$	35 01
$g x \rightarrow y$	35 07	D	14	$g NOP$	35 01
R/S	84	+	61	$g NOP$	35 01
$g x \rightarrow y$	35 07	$g R \downarrow$	35 08	$g NOP$	35 01
R/S	84	+	61	$g NOP$	35 01
RCL 7	34 07	$g R \uparrow$	35 09	$g NOP$	35 01
E	15	f	31		
STO 7	33 07	$R \rightarrow P$	01		
CLX	44	RTN	24		
RCL 3	34 03	LBL	23		

$R_1 \ C_{11}$	$R_4 \ C_{22}$	$R_7 \ c_{21} $
$R_2 \ C_{12}$	$R_5 \ c_{11} $	$R_8 \ c_{22} $
$R_3 \ C_{21}$	$R_6 \ c_{12} $	R_9



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