INTRODUCTION

This handbook is intended to be a collection of circuit diagrams and other relevant information about the locking servos of the 40 meter prototype Gravitational Wave Detector at Caltech.

The information contained in this handbook reflects the state of the servos as of July 1989. The handbook should be updated continuously; Otherwise it will be obsolete very soon.

In order to update a circuit diagram in the hand book; please make a copy of the old diagram and mark your changes on the copy. Then put the upgraded copy in front of the old diagram in the handbook. A short explanation of the changes on the diagram is also very desirable.

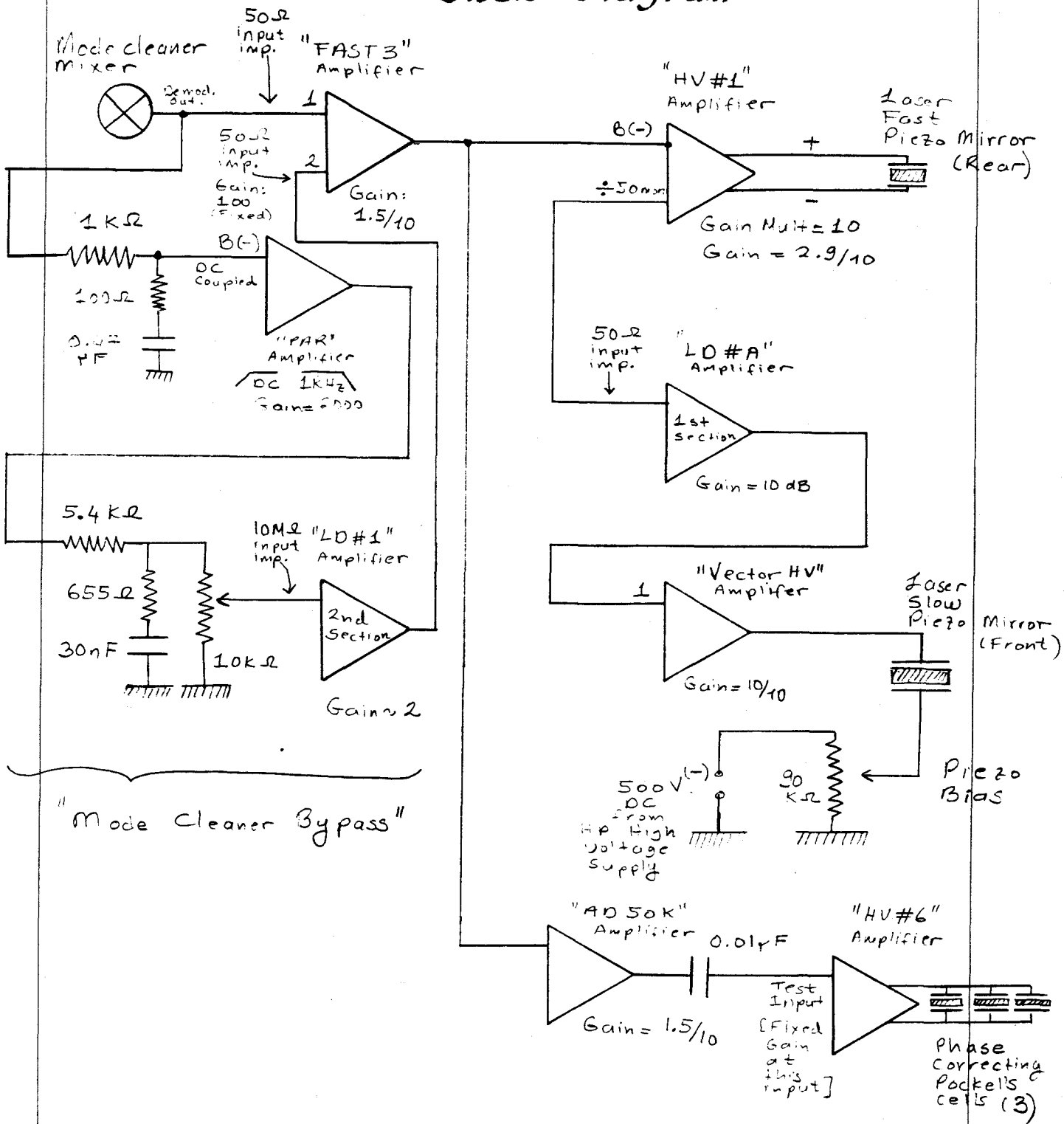
Thank you very much for your cooperation.

Yelda Ciürel
July 24, 1989

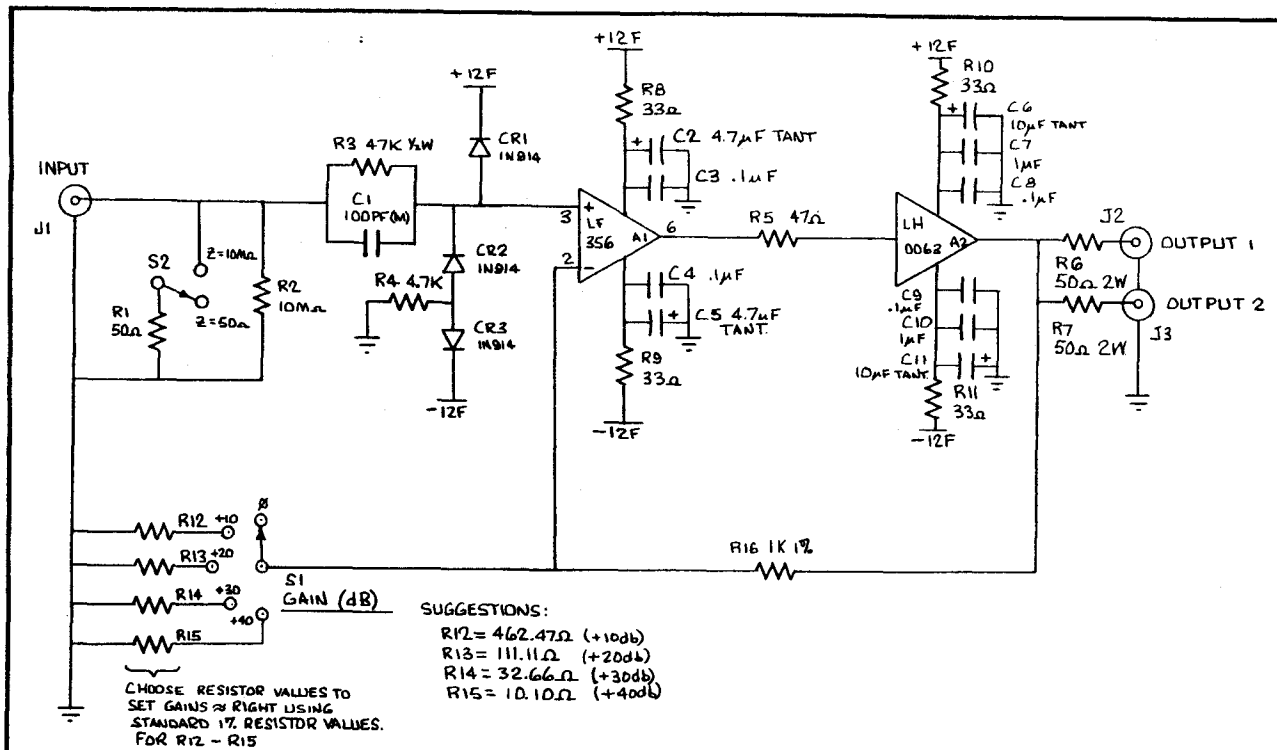
BATCH START

STAPLE
OR
DIVIDER

Mode Cleaner Servo Loop
Block Diagram



July 21, 1989
yk

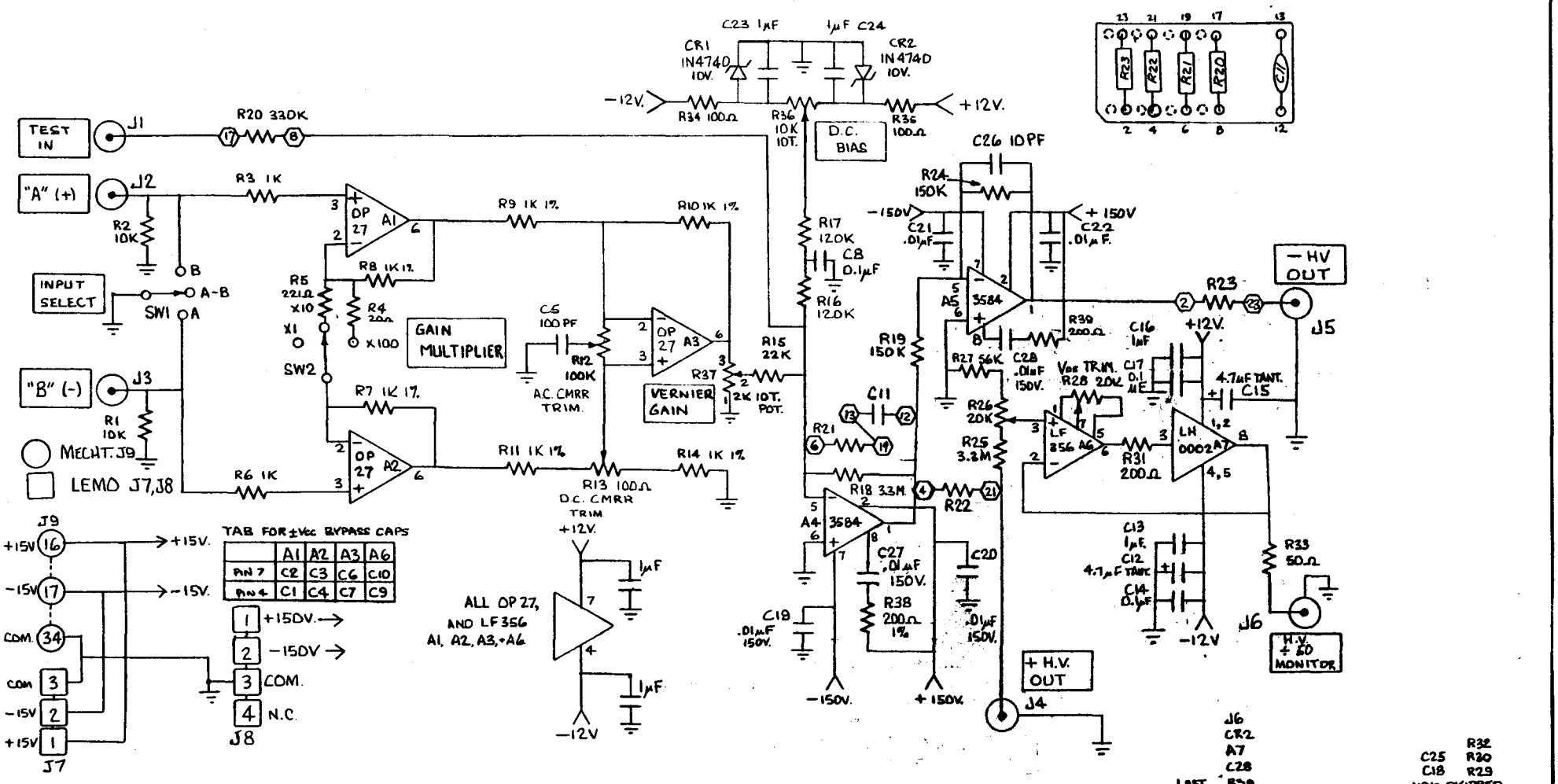


A 2
CR3
S2
J3
R16

LAST C

CALIFORNIA INSTITUTE OF TECHNOLOGY GRAVITATIONAL PHYSICS		
LINE DRIVER		
DRAWN BY B.T.	DATE 6-13-88	DRAWING NO.
CHECKED BY	SCALE	
APPROVED BY	W.O.	

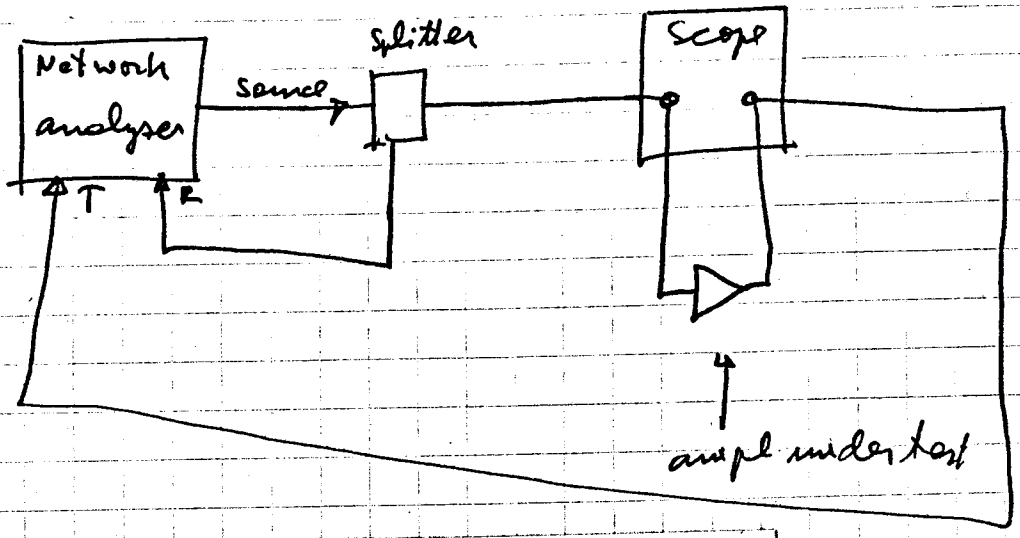
88-0613-1



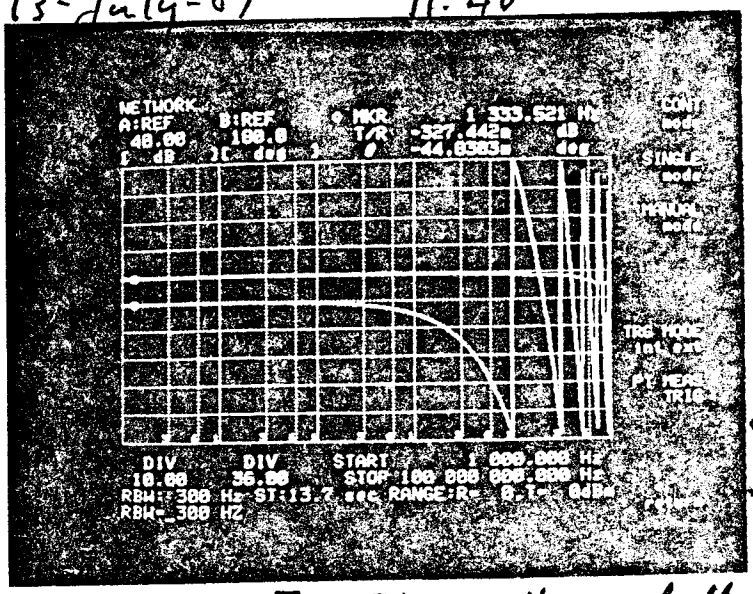
88-0304-1

13-July-89

Since ~30' of cables were used to connect the amplifier under test (see diagram below), we took the response of the cables themselves (trace at 11:40)



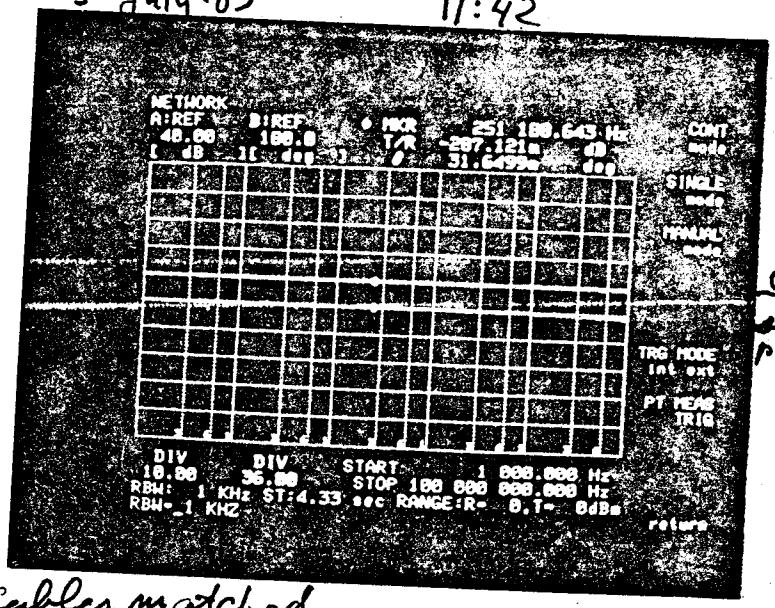
13-July-89 11:40



TR. FUNCTION OF CABLES - they are badly unbalanced

- It turns out that at 250 kHz the cables alone show a phase shift of 5°.
- Therefore, the ~3' cable from splitter to R input was replaced with a long cable, matched to the one in the test path. See traces overleaf

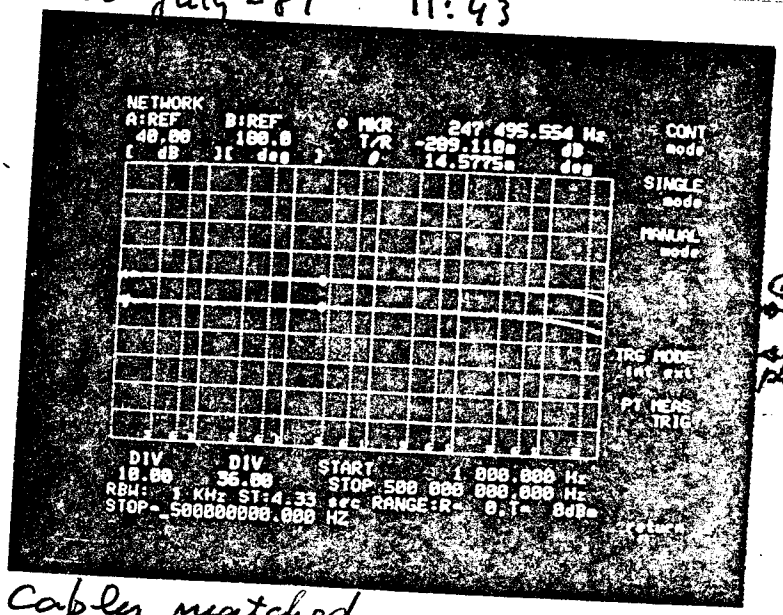
13-July-89 11:42



G
ph

Cables matched

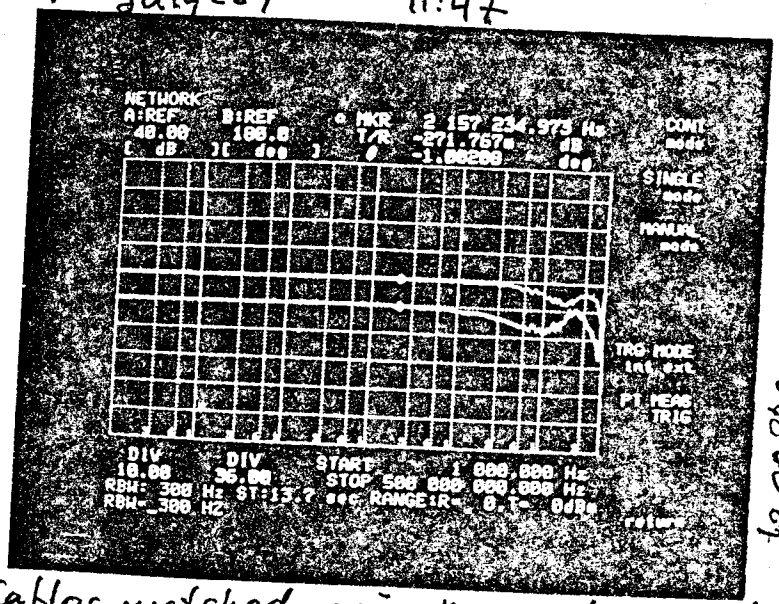
13-July-89 11:43



G
ph

Cables matched

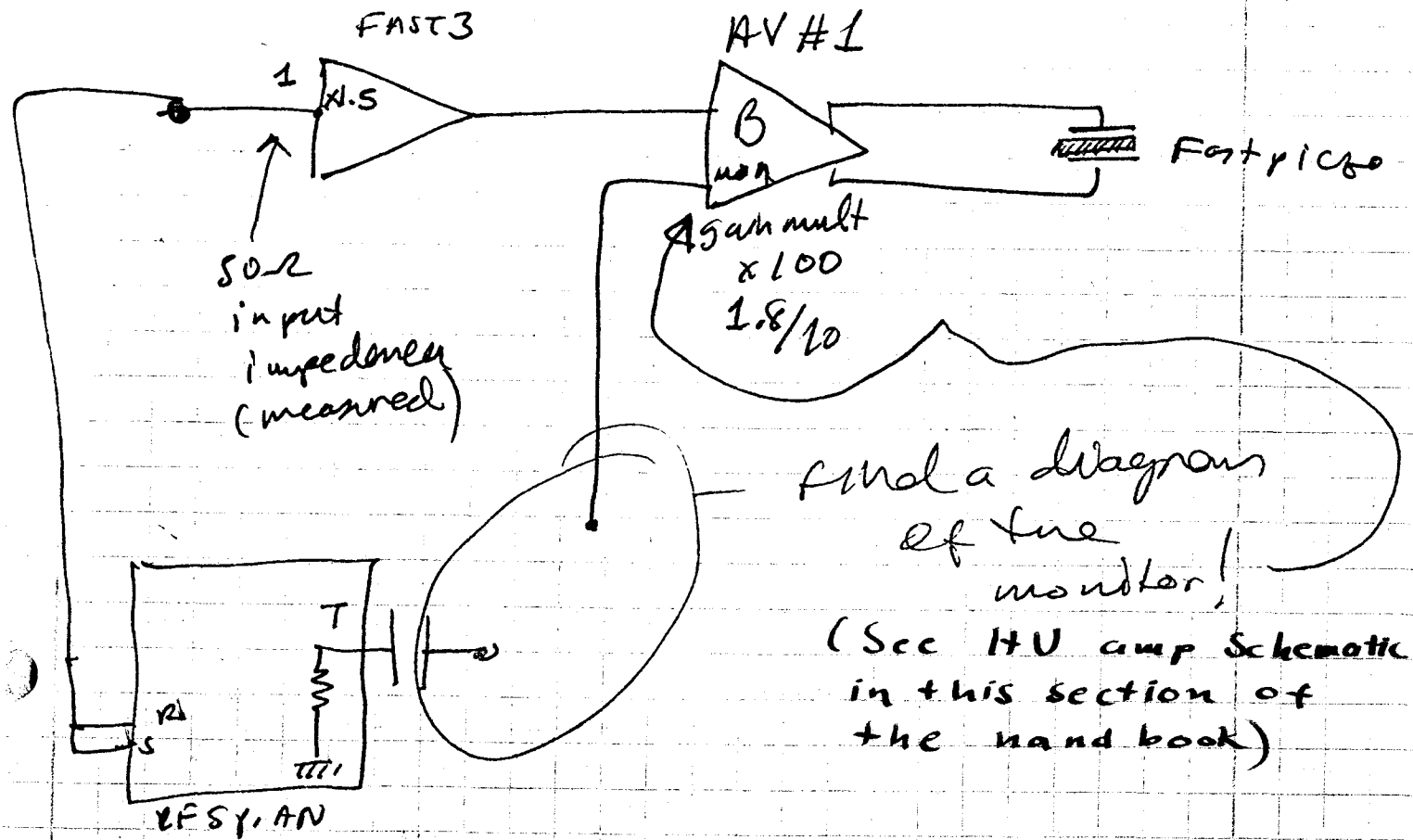
13-July-89 11:47

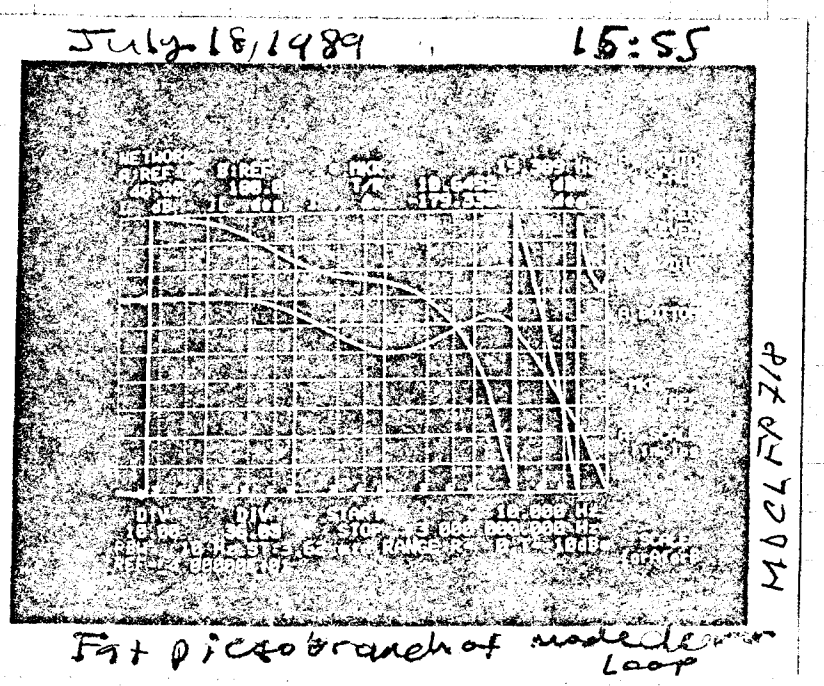


to amp

Cables matched, going thru a T's connected

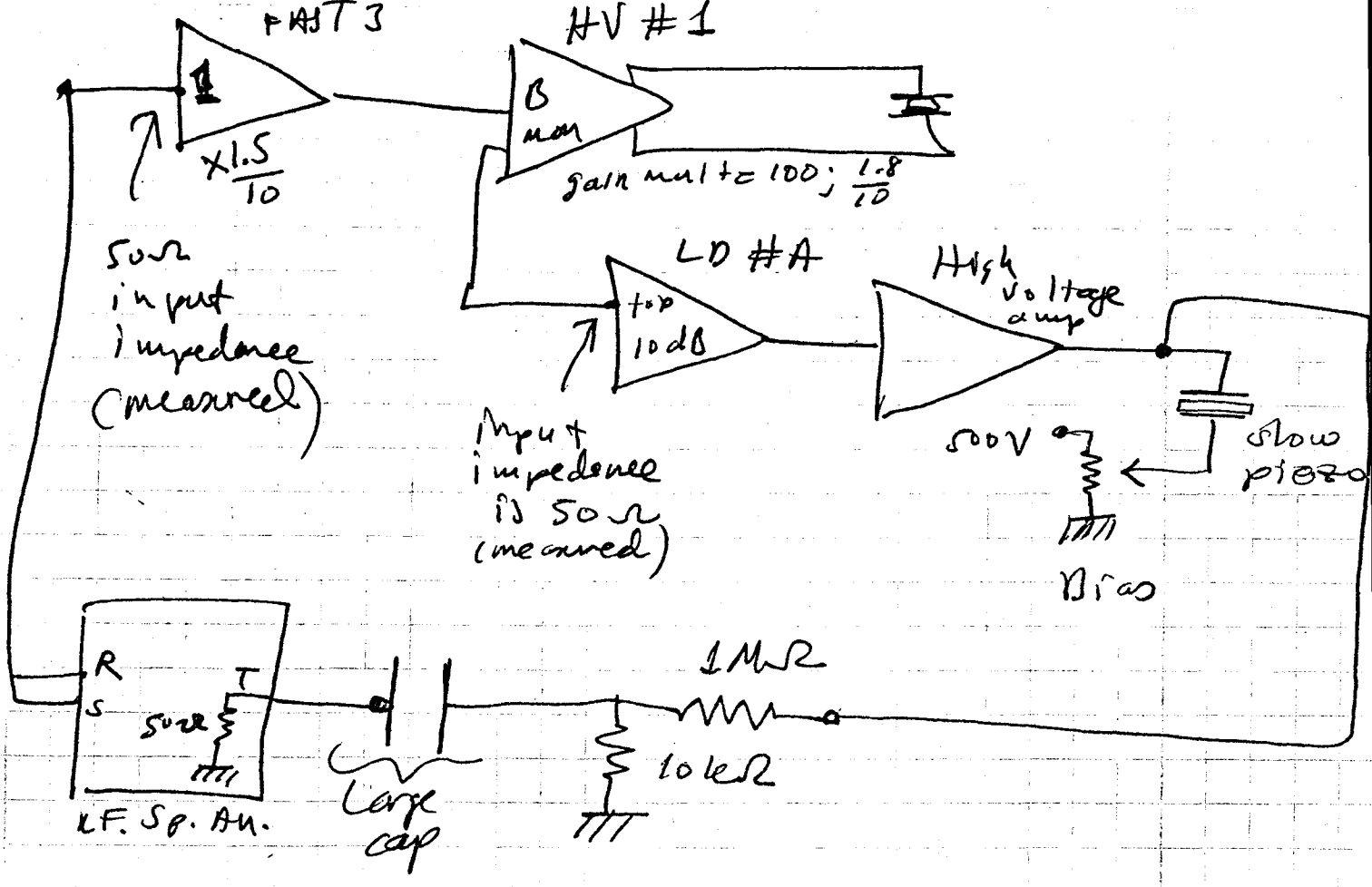
Fast Piezo branch of mode cleaner loop (Transfer Function)

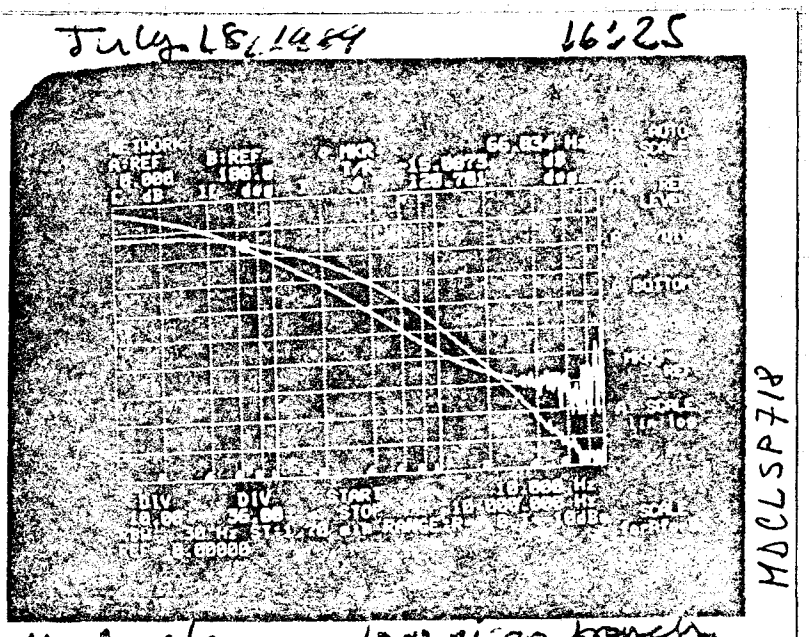




Fast piezo branch of mode cleaner loop

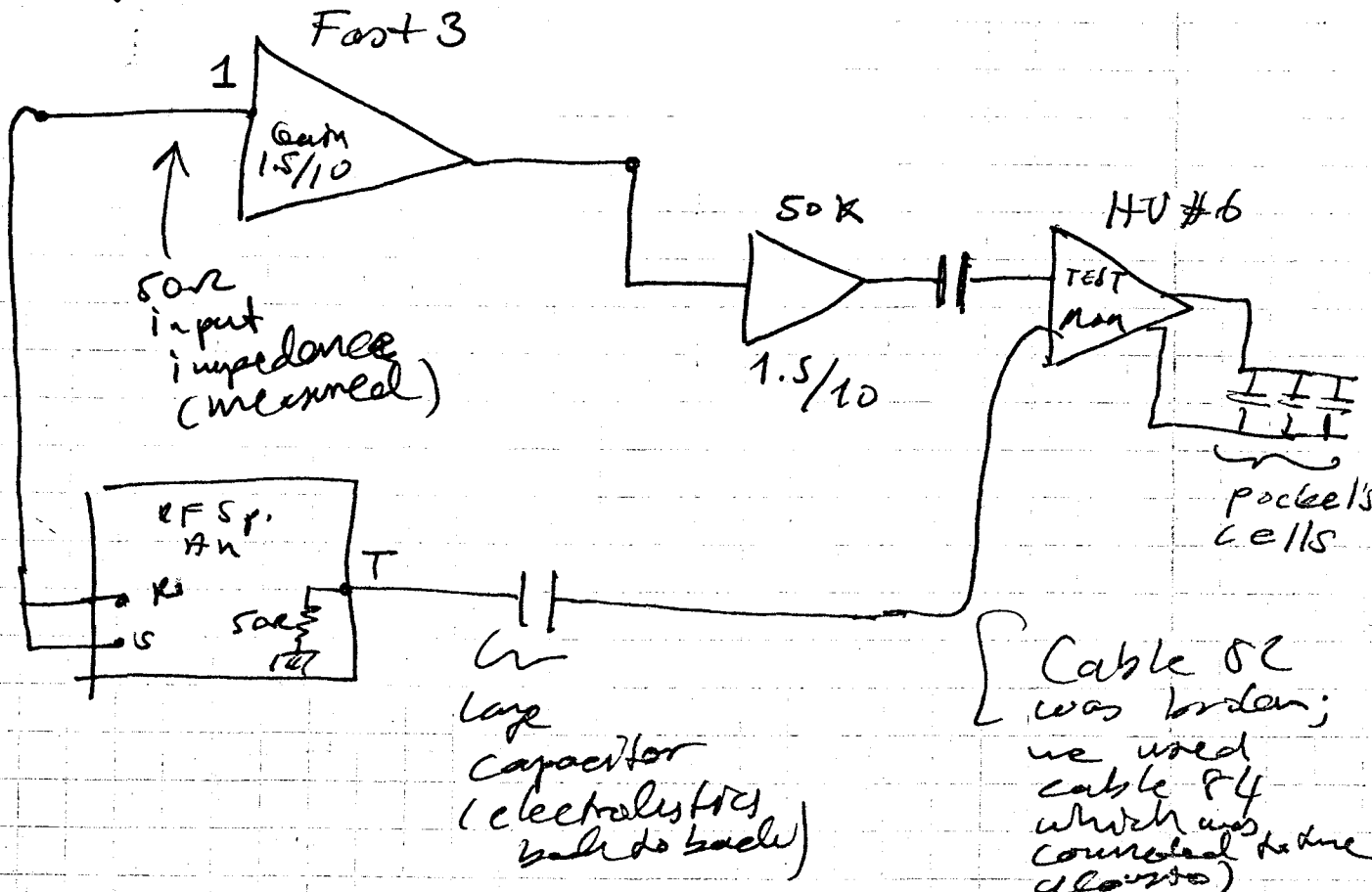
Mode cleaner slow piezo branch transfer function:

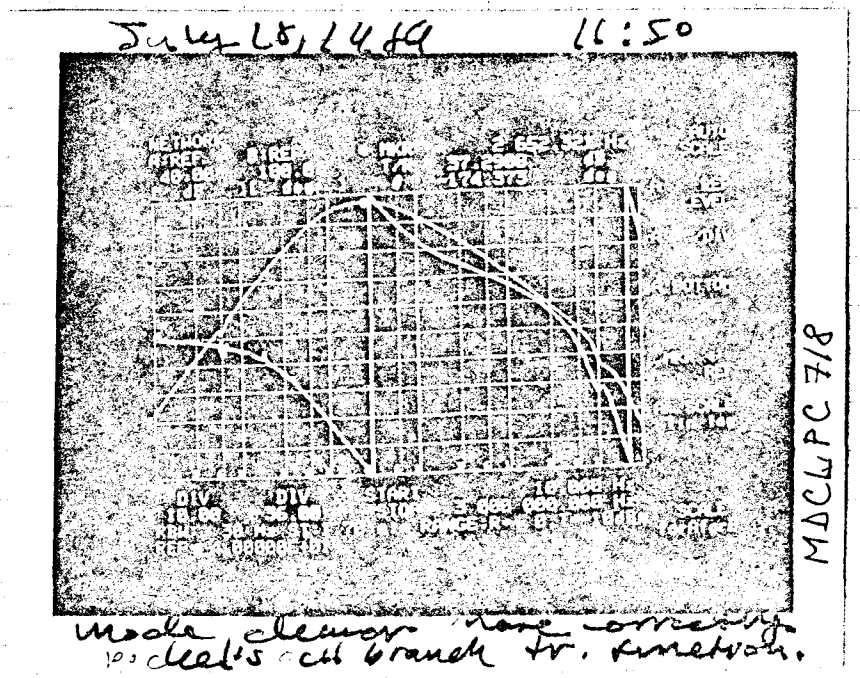




Mode cleaner slow piezo branch transfer function

Mode cleaner phase correctly
pockels cells branch transfer
function:

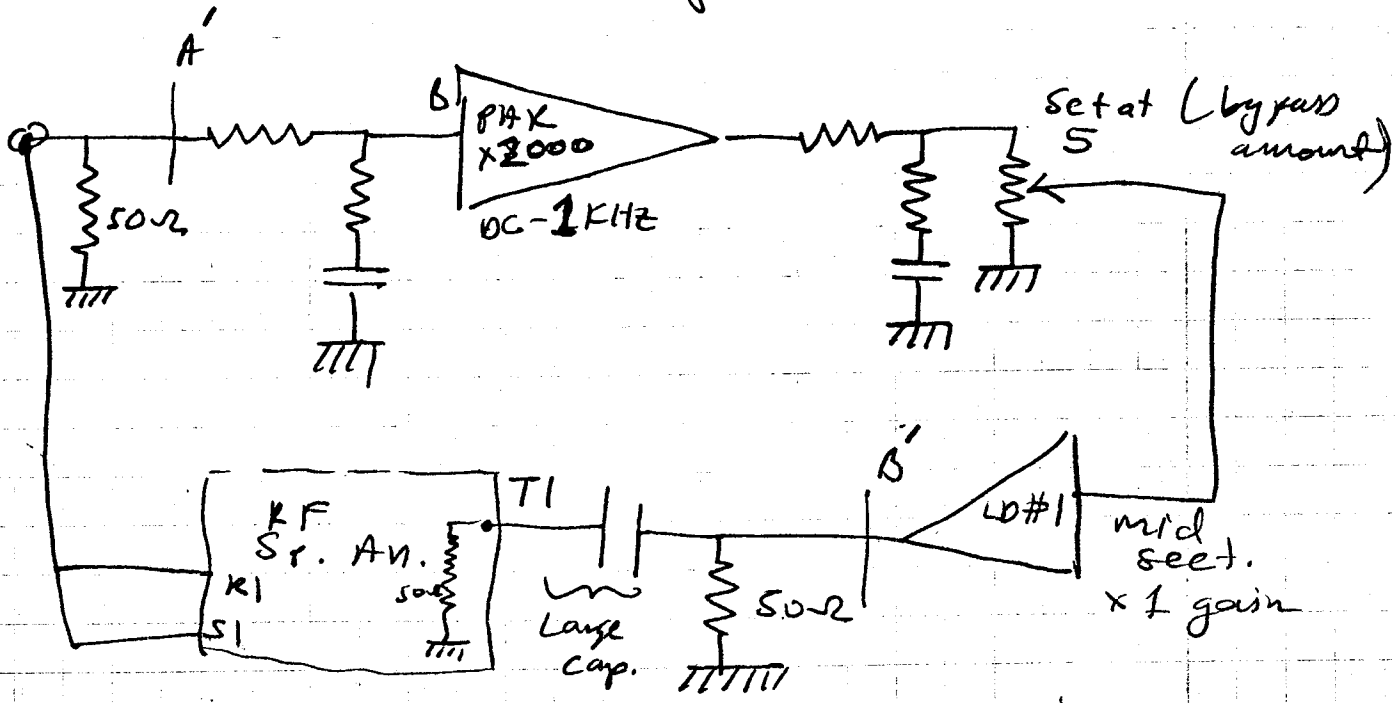




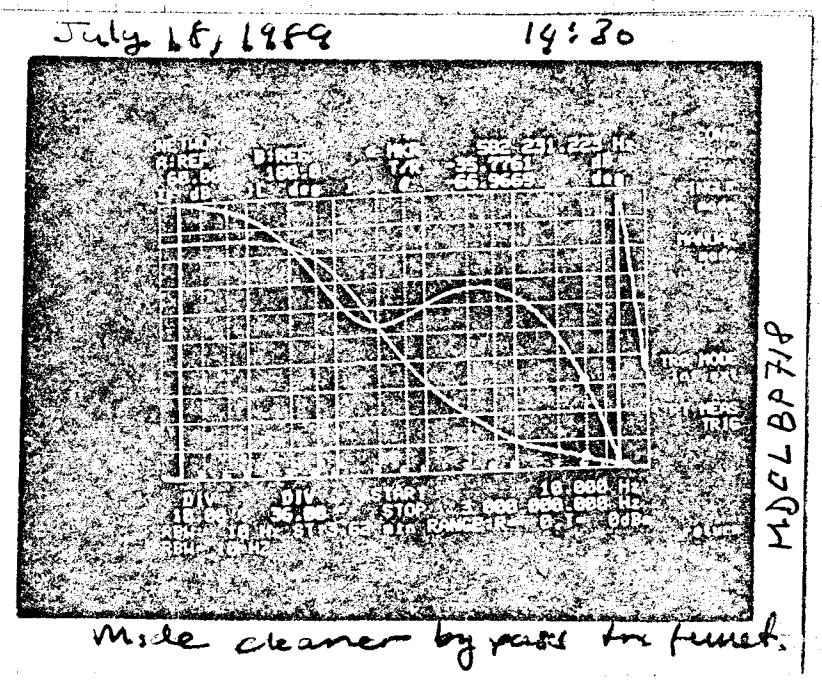
Mode cleaner phase correctly
pockels cells branch transfer function.

July 18, 1989
YB

Mode cleaner loop servo
branch transfer functions:

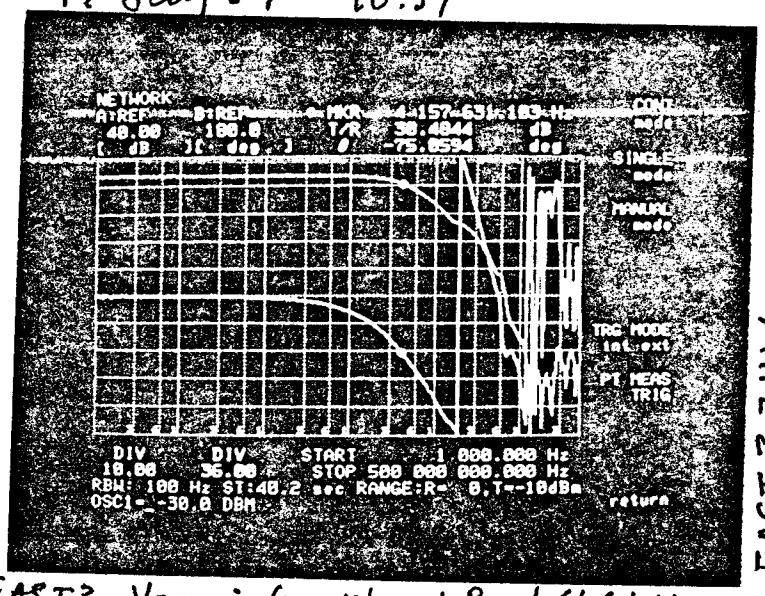


A' to B': Mode cleaner bypass circuit.



Mode cleaner bypass transfer.

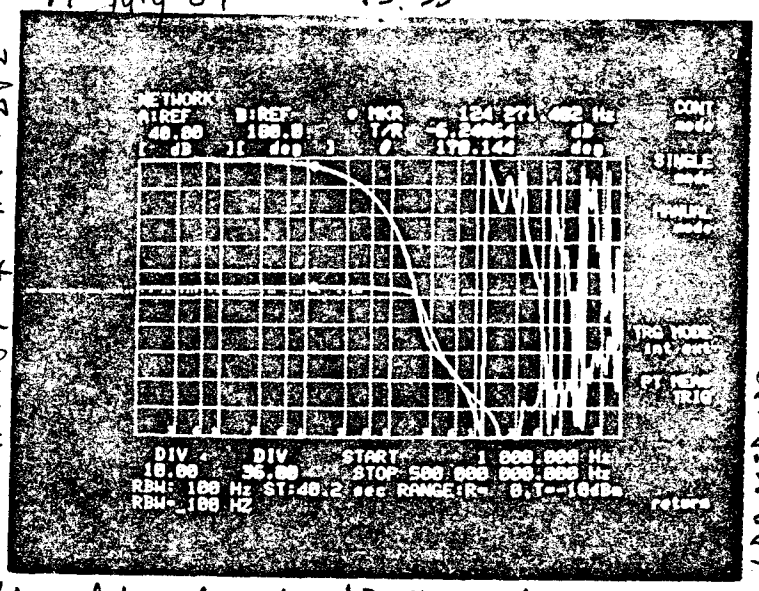
14-July 89 10:59



FAST 3711V

FAST3, Var. in (max) 10° : 461.6 kHz

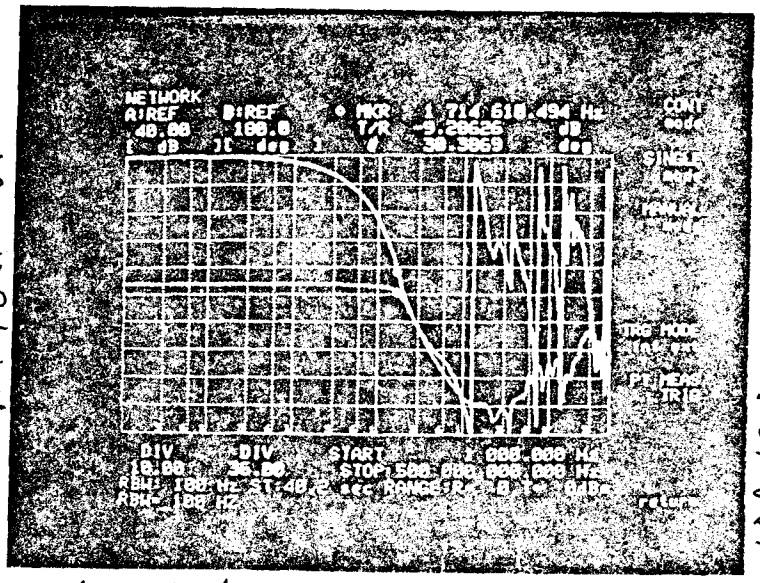
17 July 89 13:35



3dB point at: 1.955MHz

LDA MIDØDB

Line driver A, mid, 0dB, 50Ω out.

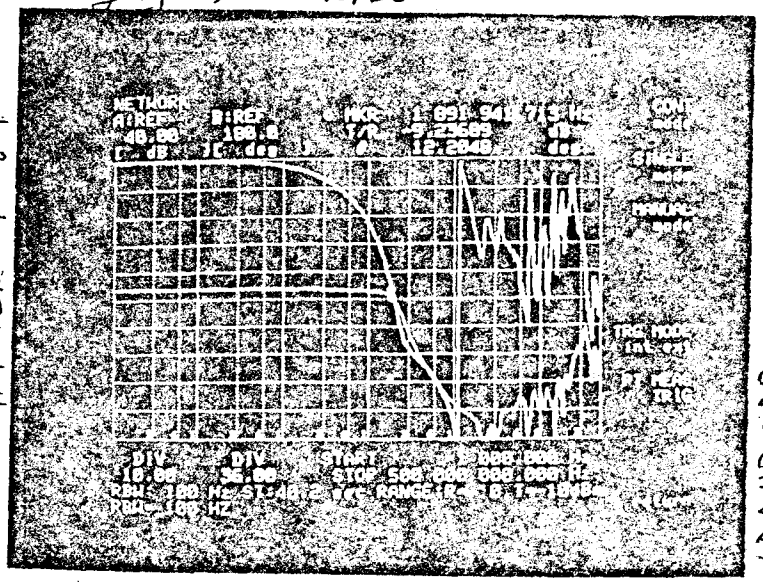


3dB at 4.821 : 00

LDA LOW

Line driver A lower, 50Ω out, 0dB

17 July-89 13:30



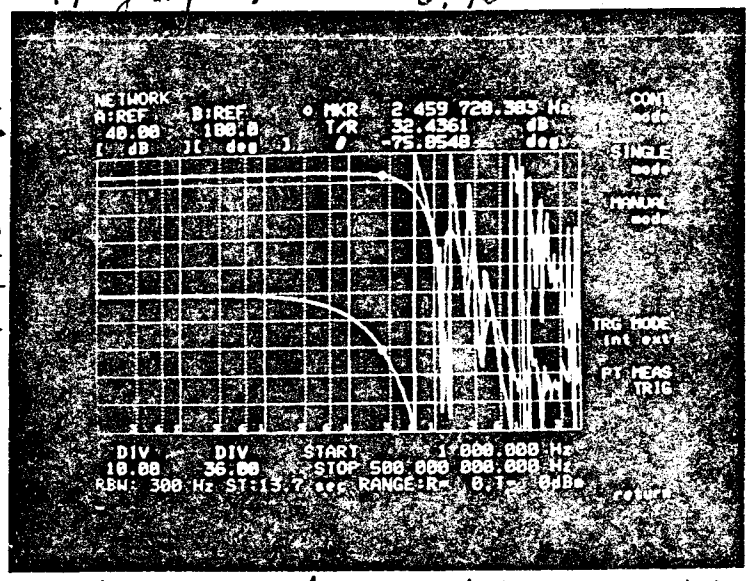
3dB at: 4.21 : 00

LDA UP 0DB

Line driver A, upper, 0 dB, 50Ω at outp.

17 July 1989

17 July 89 9:40

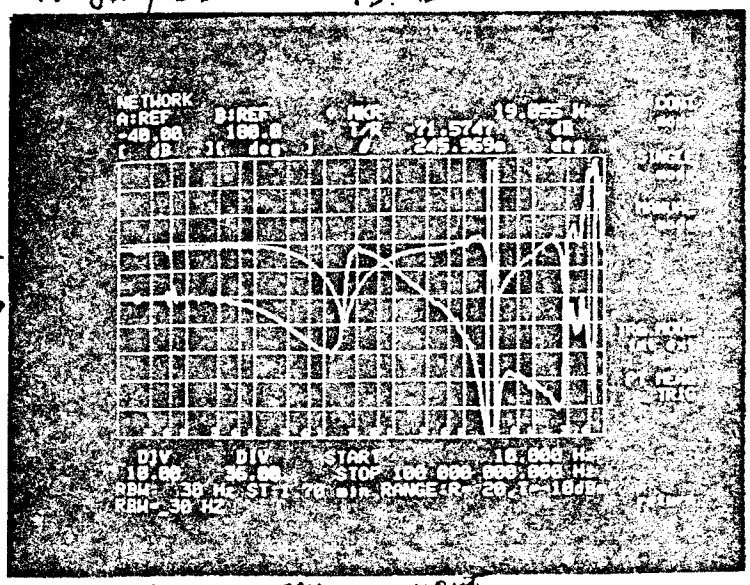


10° ; 321 kHz

FAST 1 V AXES: 100 MHz/div

FAST 1 50 Ω ant, V inp, full gain (~~33~~.5 dB)

17 July-89 13:43



e

Φ

CROST 1

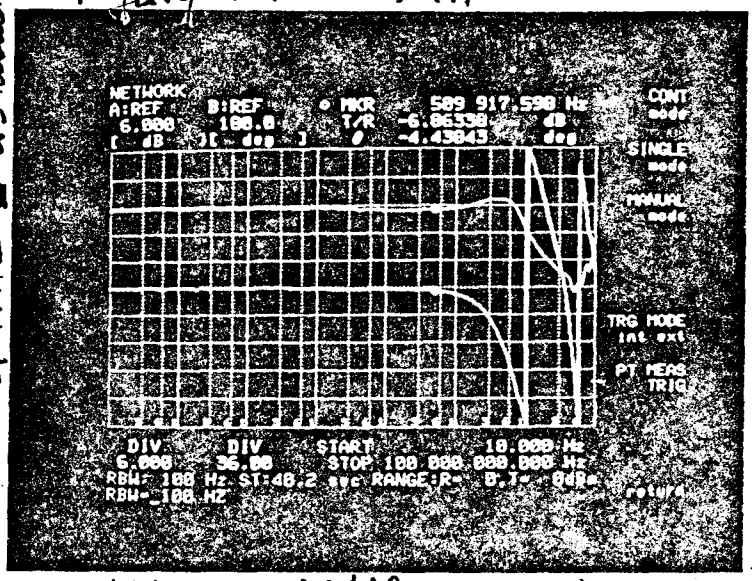
Crosstalk between Hi T. and Lower ant on LD#A

14-July-89

More transfer functions taken

14-July-89 10:17

GAIN = 0 dB nominal

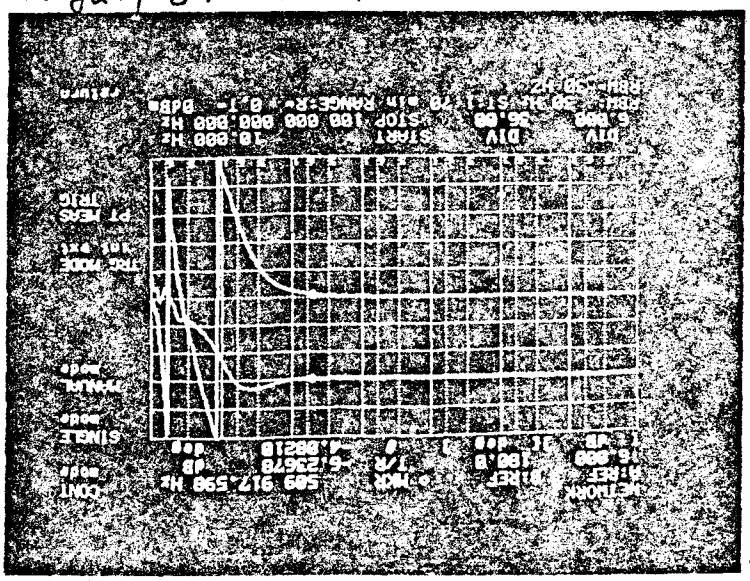


LD1 MID

LINE DRIVER 1, Middle, 50Ω in, out

14-July-89 10:25

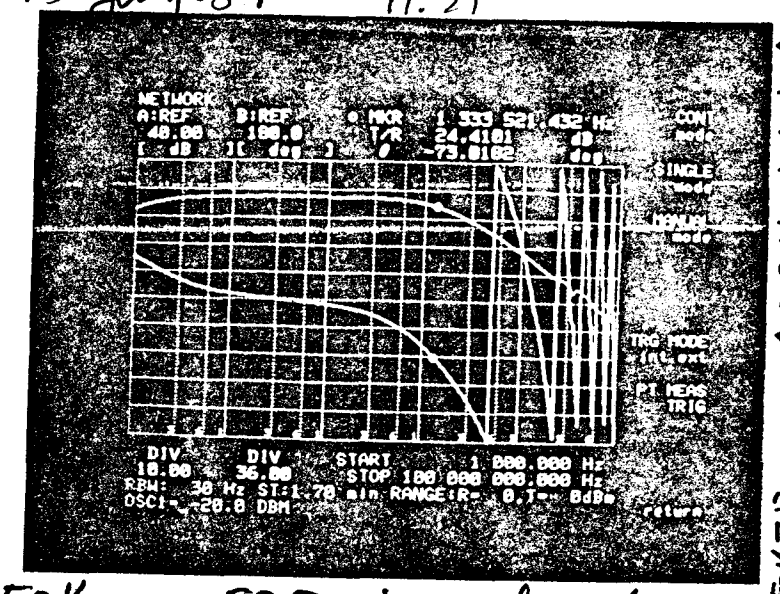
GAIN = 0 dB nominal



LD1 Low

Line driver 1, Lower, 50Ω in out

13-July-89 11:21



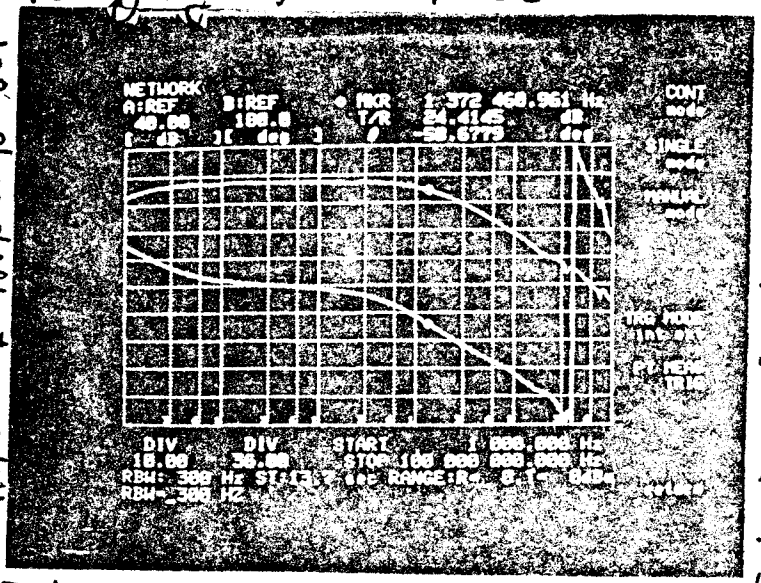
50K 50Ω in and out

AXES: 100 MHz 40dB

50KHz

← unmatched cables

13-July 89 12:02



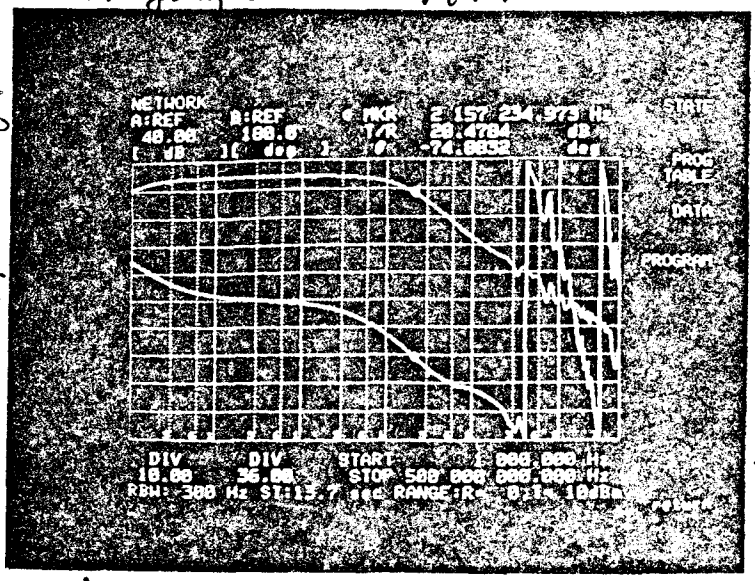
10° phase shift at 230 kHz

50K 50Ω in and out

50K in and out 50KHz

○ matched cables

14-July 89 17:40



160°, 203 kHz

50K 50Ω ~~and~~ out

50K 713

CALIFORNIA INSTITUTE OF TECHNOLOGY

GRAVITATIONAL PHYSICS 130-33

November 16, 1988

Jeff Livas
MIT Gravitational Physics Group

Howdy, Jeff—

I've finally come up with the much–promised description and evaluation of our current (reasonably successful) fast piezo laser stabilization servo. The numbers are very crude but give all the qualitative features we actually observe in their respective places. Some of the numbers I quoted to you on the phone weren't quite right; one that I remember misquoting is the responsivity of our "slow" pzt stack. It is really more like 40 Å /volt.

The procedure I use for working out the crossover points between the various parallel signal paths in these "bypass topology" loops is to break them apart into subunits at those points where they share a common input or output. In this example, I've taken the output of the "Fast # 3" video preamplifier as one common signal path, and the laser output frequency (after all the contributions from fast and slow piezos and the phase–correcting Pockels cells have been added together) as another. The various electronic transfer functions of the parallel subunits are computed, multiplied by the electro–optic transfer functions of their respective actuators, and added together. It's easiest to just do this graphically on a log–log plot, since your input data is rarely more accurate than your pencil and (for a good robust design) the major stability criteria should be extremely insensitive to small changes in gain.

You should be warned of a few glitches that we'd rather not have. Since our PA-85 amp blew up we've been using the "HV # 6" in its place for the pockels cells. It unfortunately is not fast enough

PASADENA, CALIFORNIA 91125 TELEPHONE (818) 356-4098

and has this weird wrinkle around 100 kHz where the inverting half poops out. With the PA-85 in place we got a unity–gain frequency of about 1 MHz rather than 350 kHz and no wrinkle. Also, you will note that the slow pzt/fast pzt crossover violates the canonical rule of "no crossovers at greater than 6 db/octave relative slope." We just barely get away with this one because this crossover is not far enough away from the "extra" pole to have the full effect of its phase shift. This is a marginal situation which we hope to correct in the next version.

In our conversation you asked about dealing with the resonance of the PZ80 piezo mirror at 5 kHz and I'm afraid I wasn't too clear about my recommendation. Just in case, let me state the problem more formally; one wants to attenuate the signal reaching the nasty element (the PZ80) by a large factor to prevent its resonant behavior from dominating over the righteous and properly–phased feedback going to, say, your fast piezo at that resonant frequency f_r. At the same time, the crossover rule prohibits you from adding too much phase shift at some lower frequency $f_{\text{crossover}}$. The optimization therefore is for maximum attenuation in the stop band with minimum phase shift in the passband, and the solution we tend to use is a Butterworth filter with the 3dB point chosen at the geometric mean $f_{3\text{dB}} = (f_r f_{\text{crossover}})^{1/2}$ with whatever number of poles it takes to control the resonance.

Give me a ring if you have a chance to look at this stuff and we can discuss it. Happy frequency stabilization !!

Closing the loop,

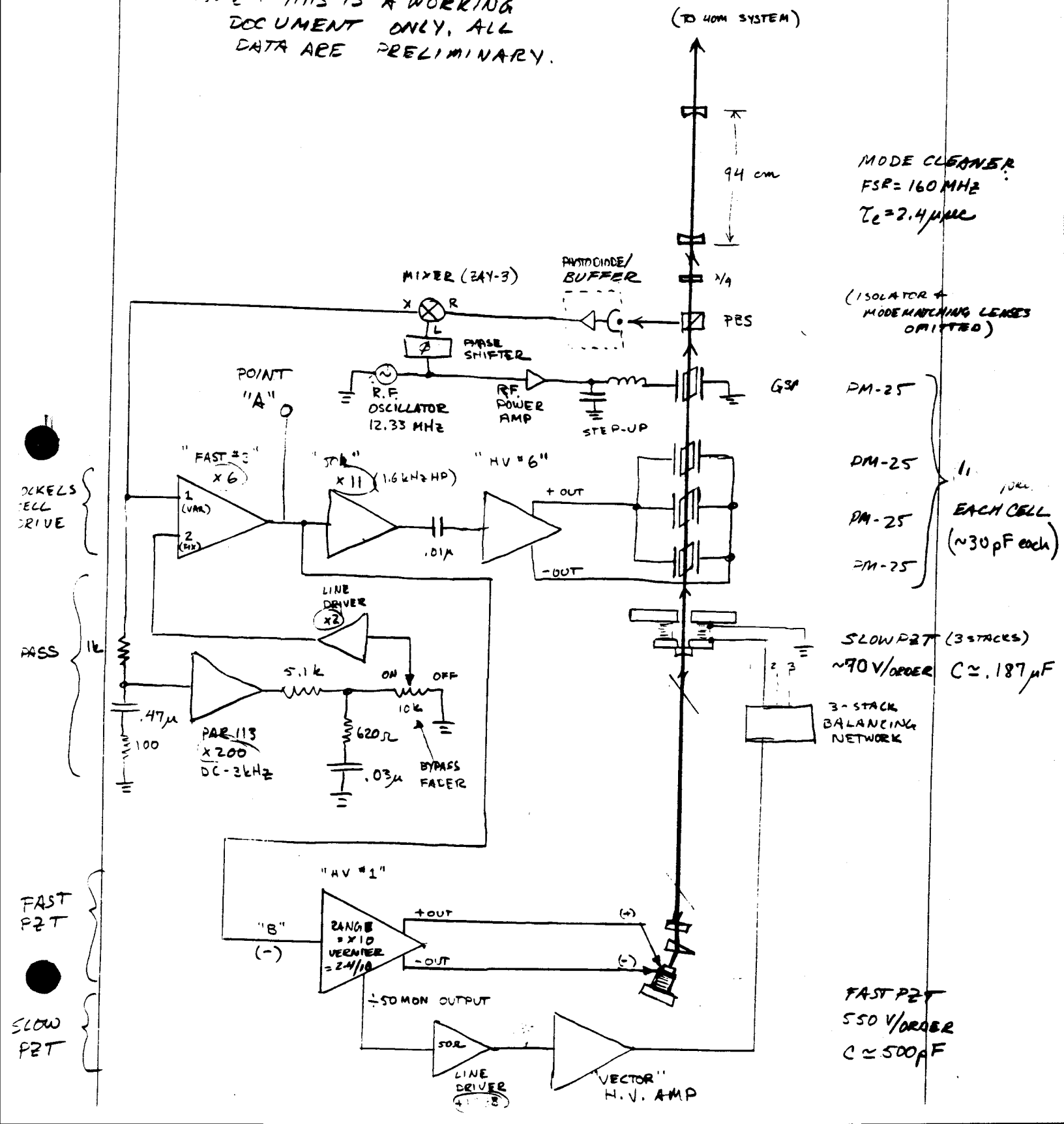
M. E. Zucker

cc: Alex Abramovici
Bob Spero
Jeff Harman

11/14/98 MEC

MODE CLEANER SERVO BLOCK DIAGRAM

NOTE: THIS IS A WORKING DOCUMENT ONLY. ALL DATA ARE PRELIMINARY.



11/14/68 MEG

MODE CLEANER SERVO TRANSDUCERS (IN TERMS OF EQUIVALENT LASER FREQUENCY)

1. POCKELS CELLS

$$2\pi\nu_{laser} = \frac{\partial \phi_{laser}}{\partial t} \; ; \quad \phi_{laser} = 2\pi\nu_0 t + \phi_{PC} \; ; \quad \phi_{PC} = \frac{2\pi n_{PC} l_{PC}}{\lambda} \; ;$$

$$n_{PC} l_{PC} = K + \alpha V_{PC} \qquad (\alpha \simeq .22 \text{ nm/V for FM-25})$$

$$\phi_{PC} = 2\pi (K + \alpha V_{PC})/\lambda$$

$$\Rightarrow \delta\nu_{laser} = \frac{2\pi\alpha}{\lambda} \frac{dV_{PC}}{dt}$$

i.e., for $V_{PC} = V_0 \sin(2\pi f t)$ (single Fourier component at f)

$$\frac{\partial(\delta\nu_{laser})}{\partial V_0} = 2.7 \times 10^{-3} \frac{f}{V_0} = 2.7 \text{ Hz} \left(\frac{f}{1\text{kHz}}\right)\left(\frac{1 \text{ volt}}{V_0}\right)$$

NOTE: We are using 2 phase-adjusting pockels cells in series, driven in parallel.

2. FAST PIEZO MIRROR

Since $\frac{dV_{FPZT}}{dl} = 550$ V/order and the laser is ~2.3 meters long

$$\Rightarrow c/2l = 65 \text{ MHz} = 1 \text{ order}$$

$$\Rightarrow \frac{\partial\nu}{\partial V_{FPZT}} = \frac{65 \text{ MHz}}{550 \text{ V}} \simeq \frac{120 \text{ kHz}}{\text{volt}}$$

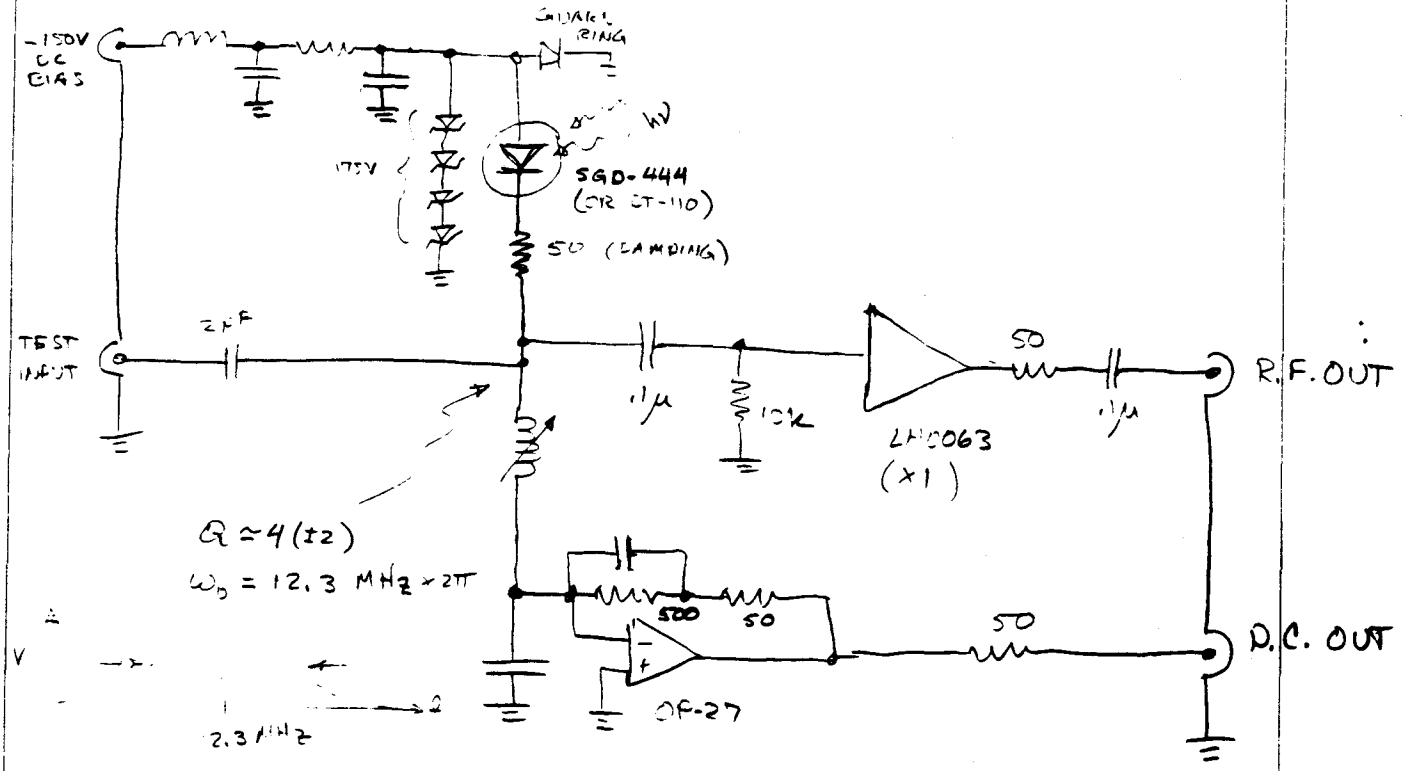
3. SLOW PIEZO MIRROR

Similarly, with $\frac{dV_{SPZT}}{dl} \simeq 70$ V/order, we get

$$\frac{\partial\nu}{\partial V_{SPZT}} = \frac{65 \text{ MHz}}{70 \text{ V}} \simeq \frac{930 \text{ kHz}}{\text{volt}}$$

11/14/88 MES

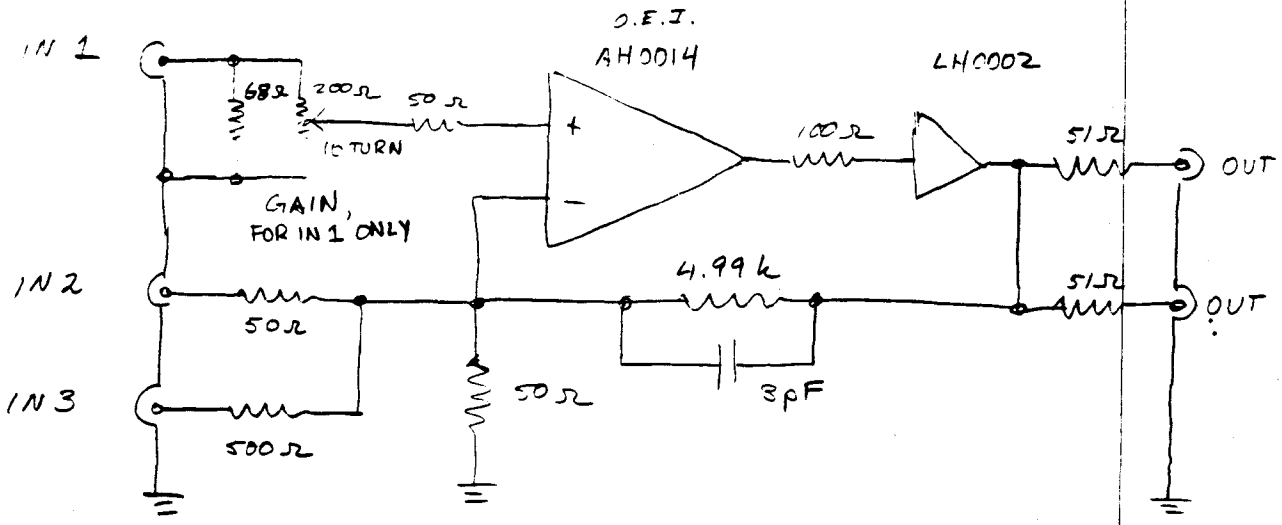
MODE CLEANER SERVO PHOTODIODE / BUFFER
(STANDARD CALTECH FRONT END)



R.F. DARK NOISE ≃ SHOT NOISE AT 1 mW, 5145 Å

11/14/88 MEC

MODE CLEANER SERVO "FAST #3" AMPLIFIER

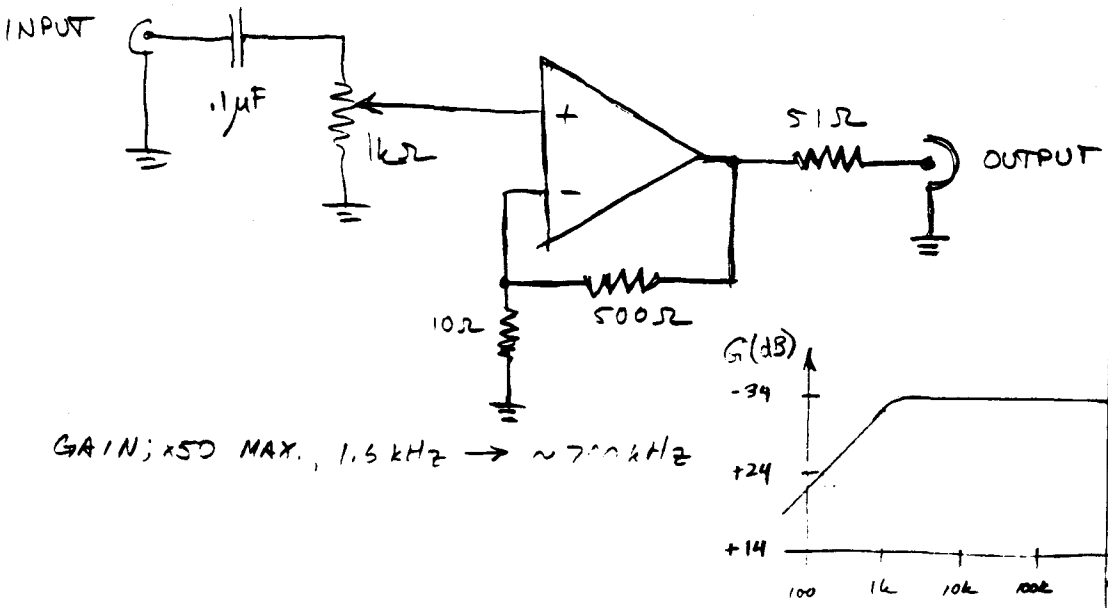


GAIN; IN1 ×0 → ×100, DC - 10 MHz

IN2 × -100

IN3 × 10

"50k" AMPLIFIER

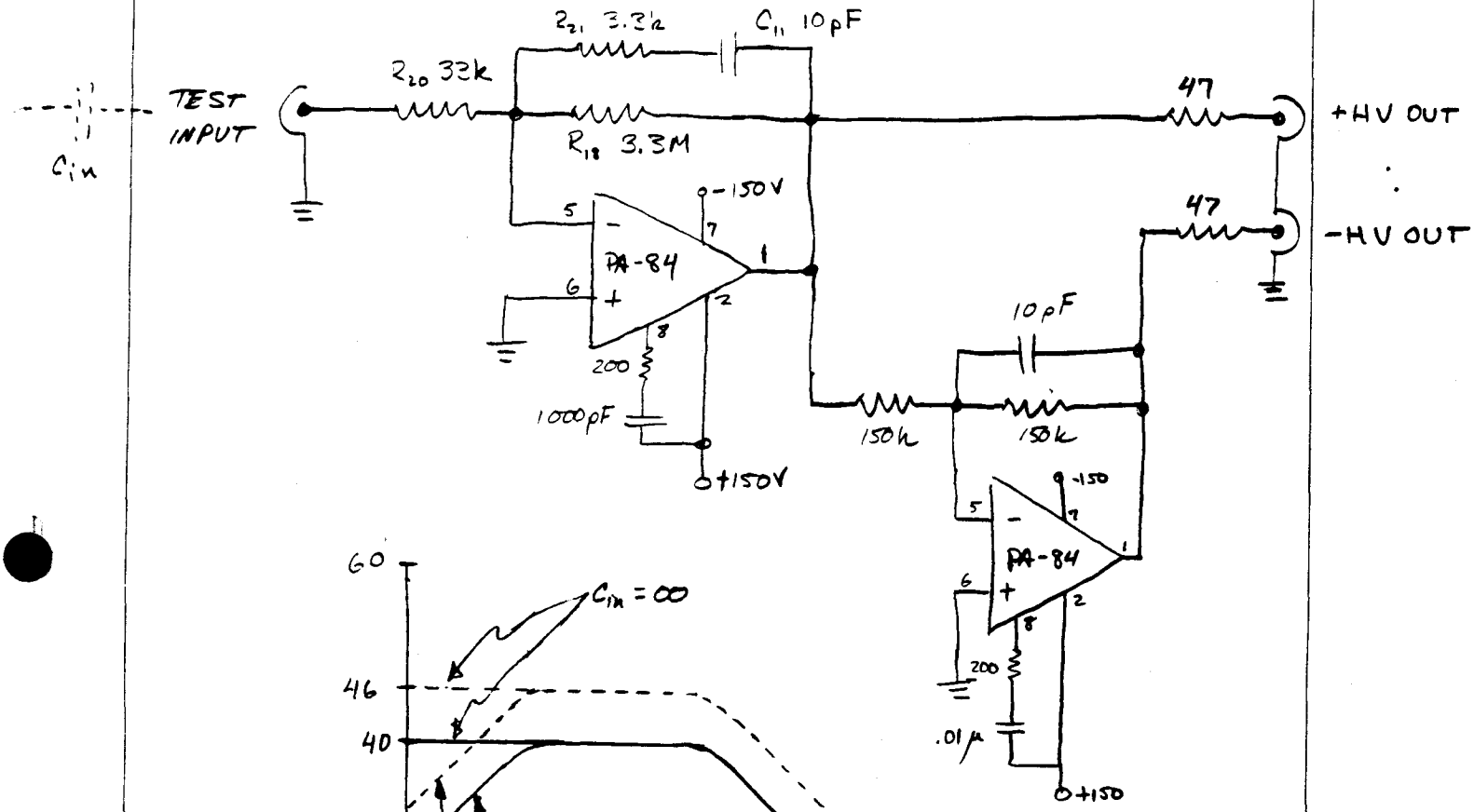


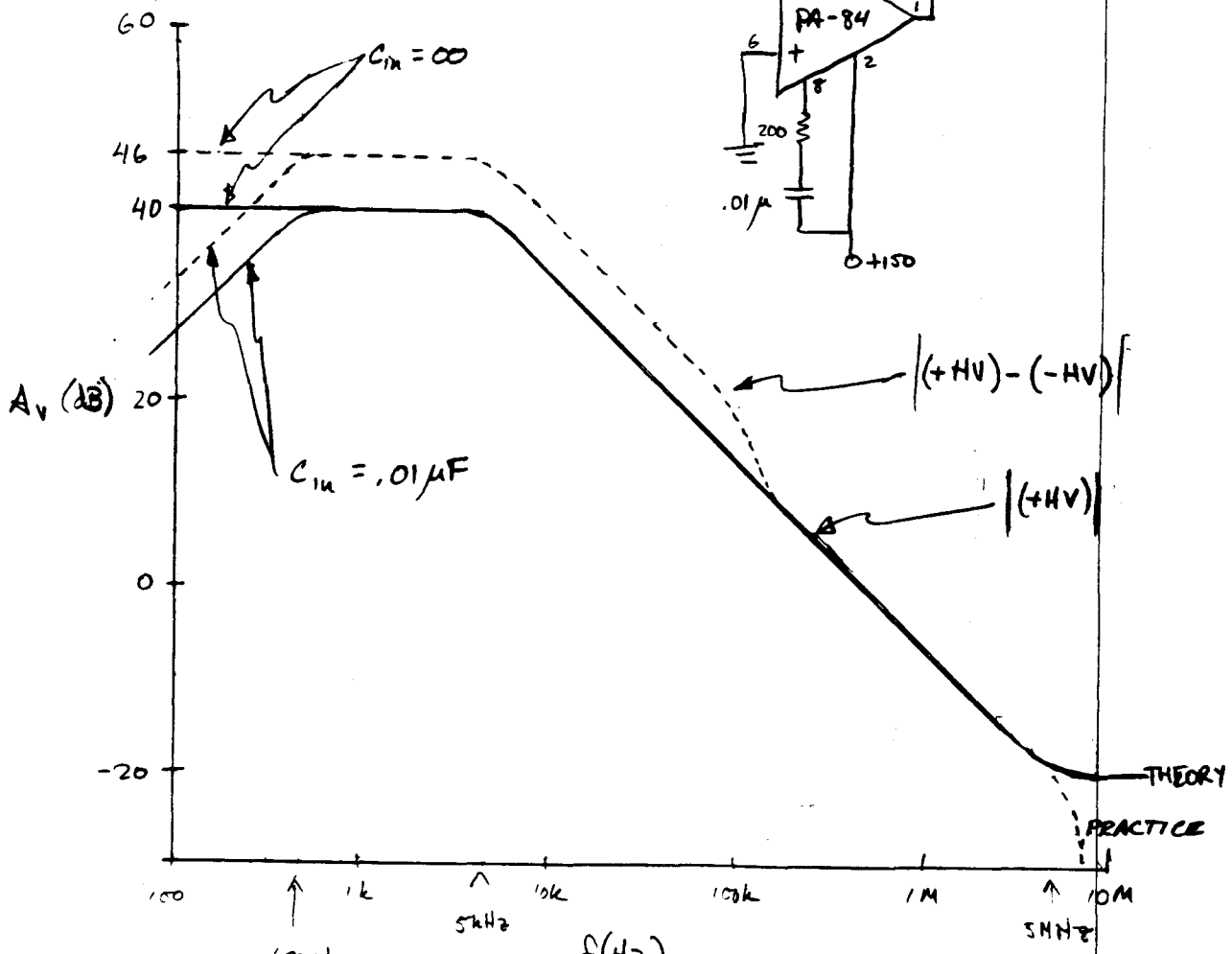
GAIN; ×50 MAX., 1.5 kHz → ~7[illegible] kHz

11/15/88 MES

MODE CLEANER SERVO LOOP "HV#6" AMP

(IMPORTANT CIRCUITRY SHOWN — SEE GENERAL "HV AMP" SCHEMATIC FOR FULL DETAILS)

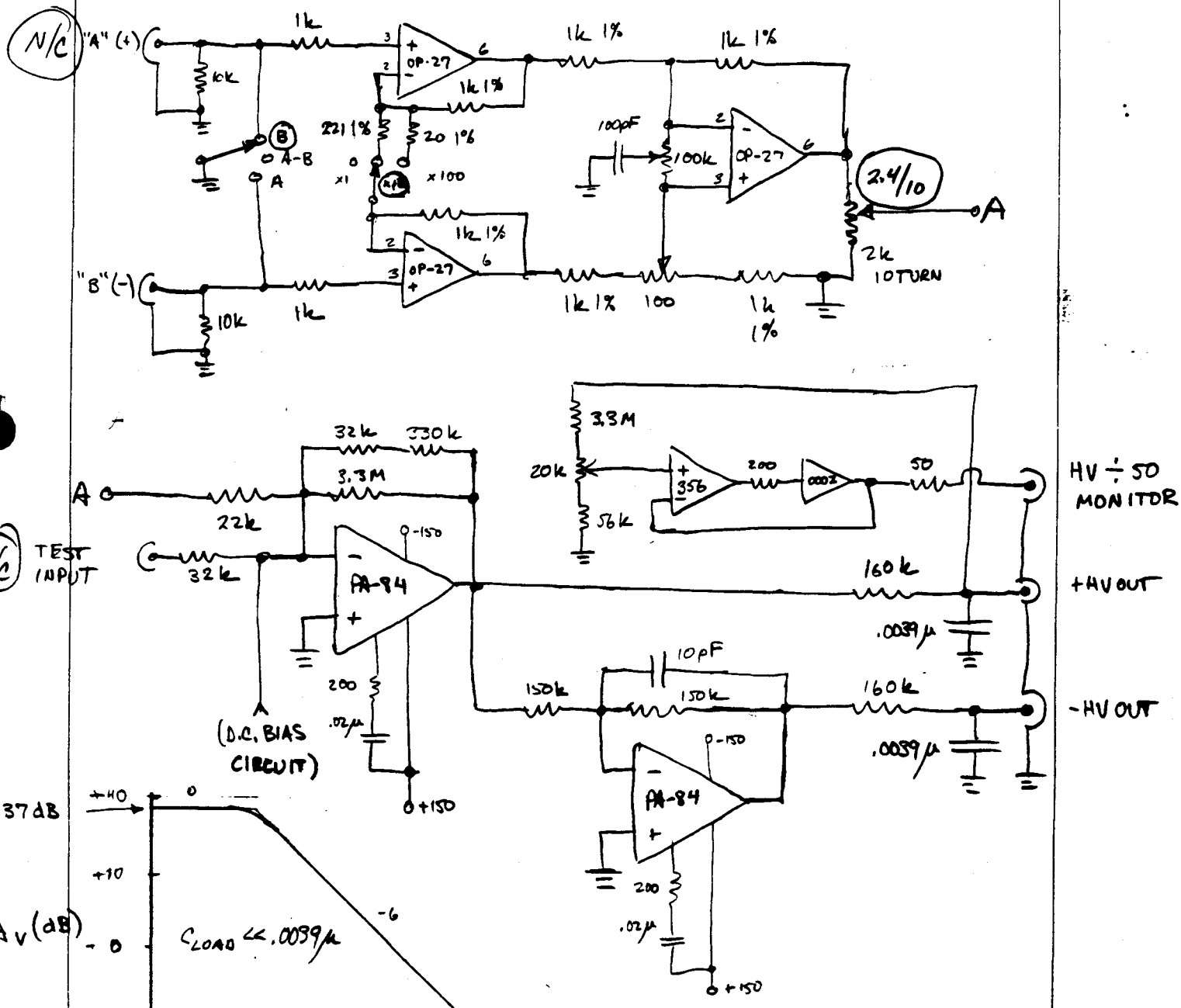




11/15/88 MES

MODE CLEANER SERVO LOOP "HV #1" AMP

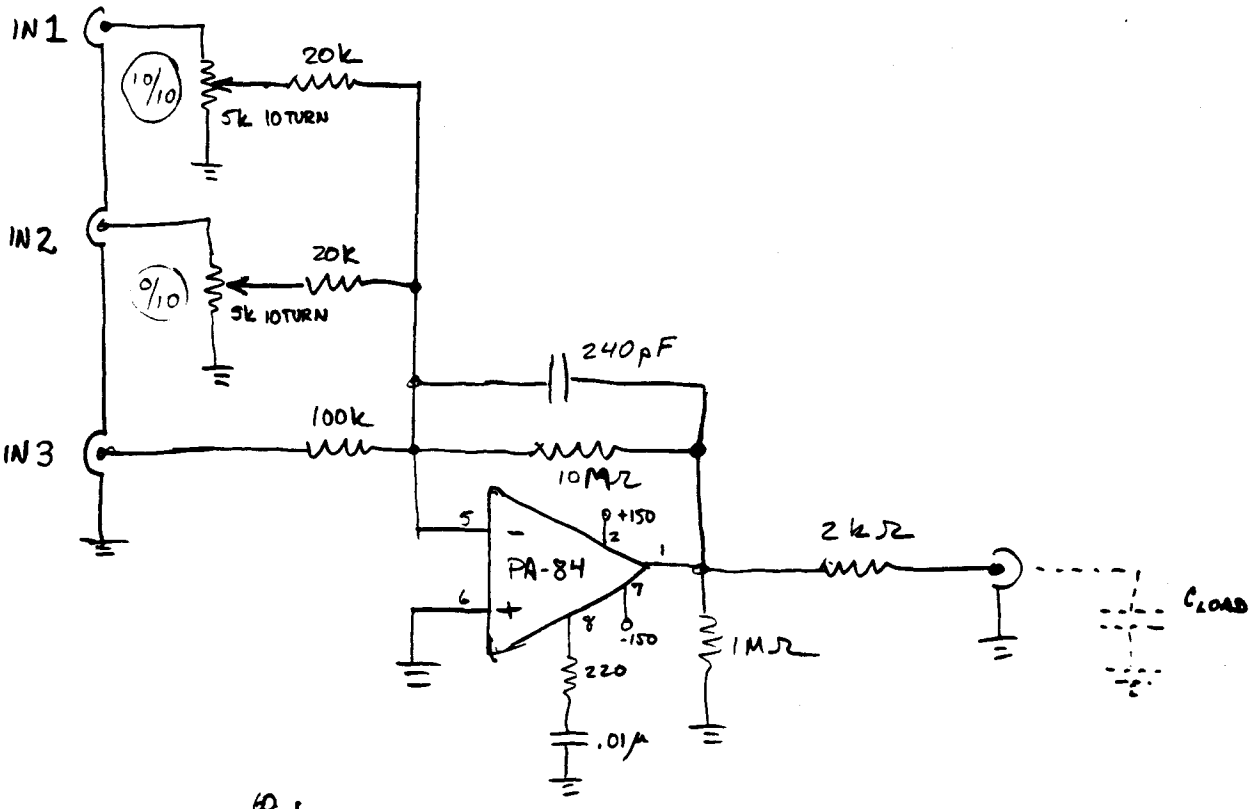
(IMPORTANT CIRCUITRY SHOWN - SEE GENERAL "HV AMP" SCHEMATIC FOR DETAILS).

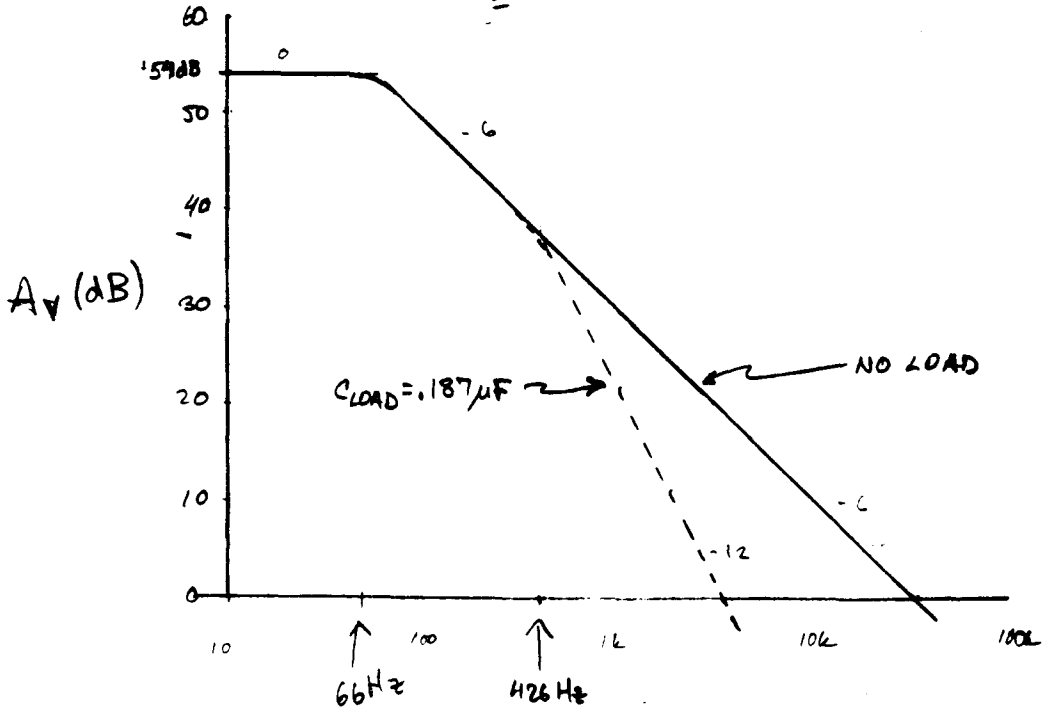


SINGLE-ENDED,
GAIN RANGE ×10, VERNIER $\frac{2.4}{10}$

11/15/88 MES

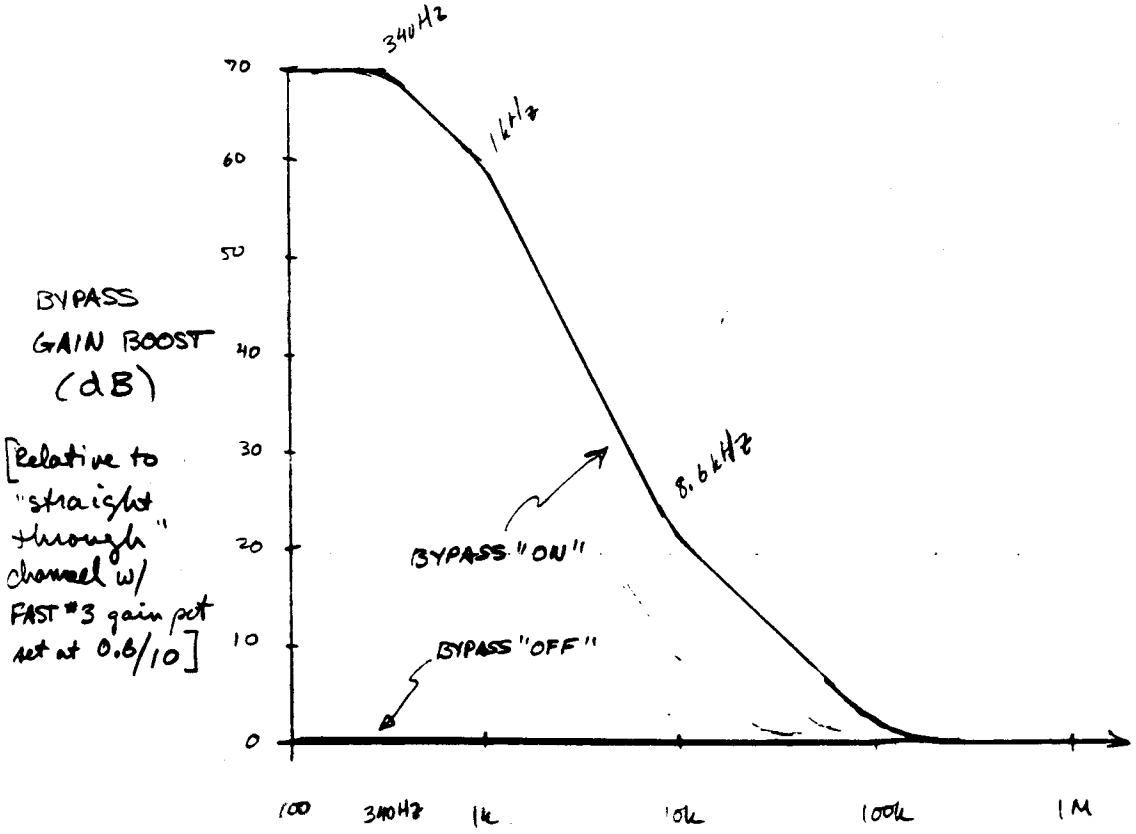
MODE CLEANER SERVO LOOP "VECTOR H.V. AMP"

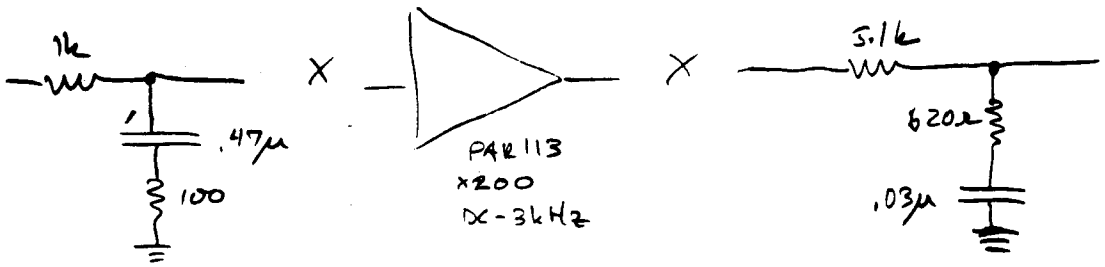


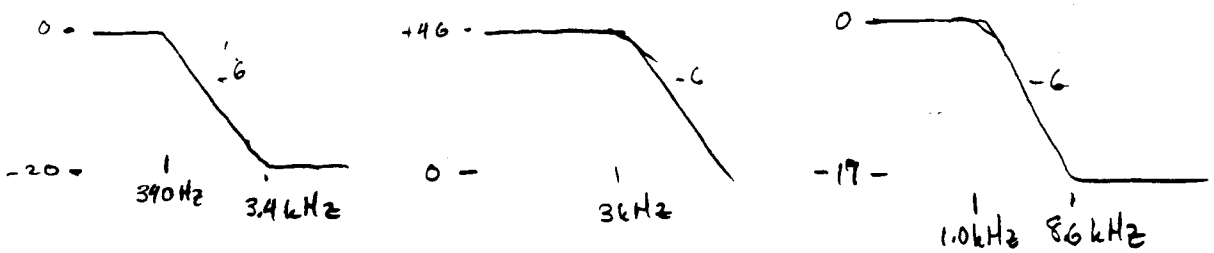


11/15/88 MES

MODE CLEANER SERVO BYPASS GAIN ENHANCEMENT



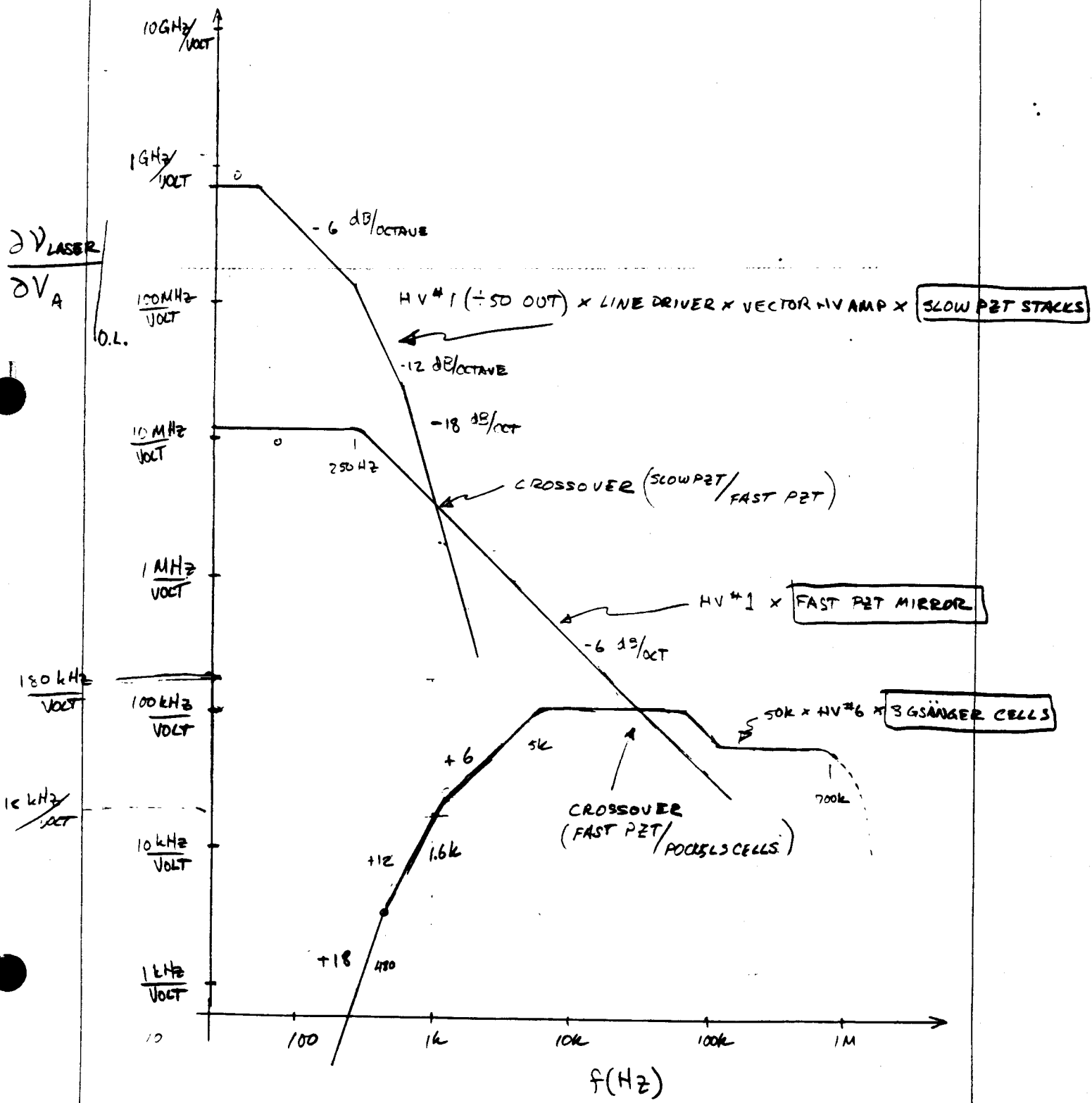




11/15/88 MEZ

MODE CLEANER SERVO ELECTRONIC AND TRANSDUCER OPEN-LOOP TRANSFER FUNCTION

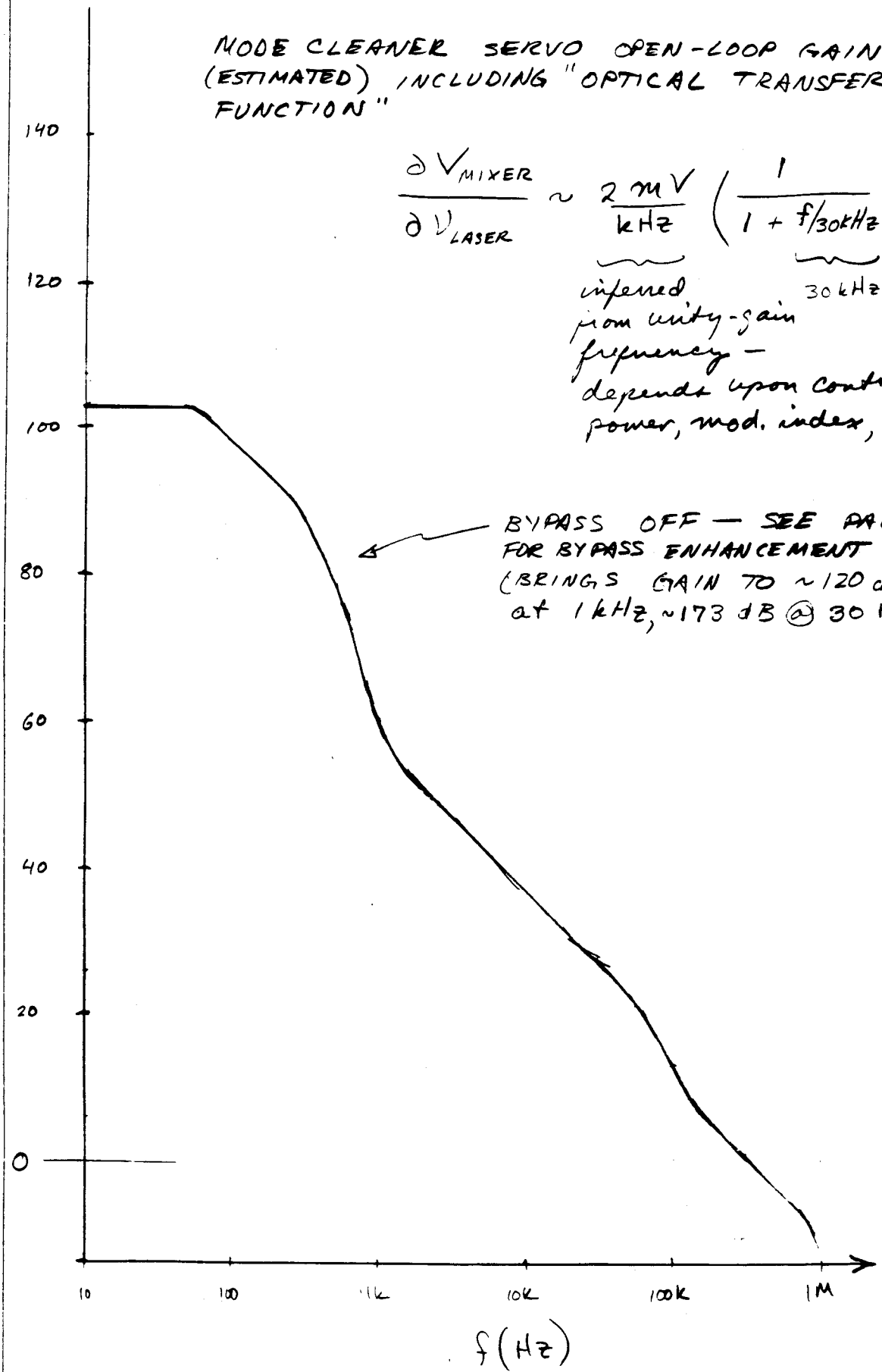
LASER FREQUENCY EXCURSION PER VOLT APPLIED AT POINT "A" (OPEN-LOOP)



11/15/88 mes

MODE CLEANER SERVO OPEN-LOOP GAIN (ESTIMATED) INCLUDING "OPTICAL TRANSFER FUNCTION"

$$\frac{\partial V_{MIXER}}{\partial V_{LASER}} \sim \underbrace{\frac{2\,mV}{kHz}}_{\text{inferred from unity-gain frequency — depends upon contrast, power, mod. index, ...}} \left(\frac{1}{1 + f/\underbrace{30kHz}_{= \frac{1}{4\pi\tau_c}}} \right)$$

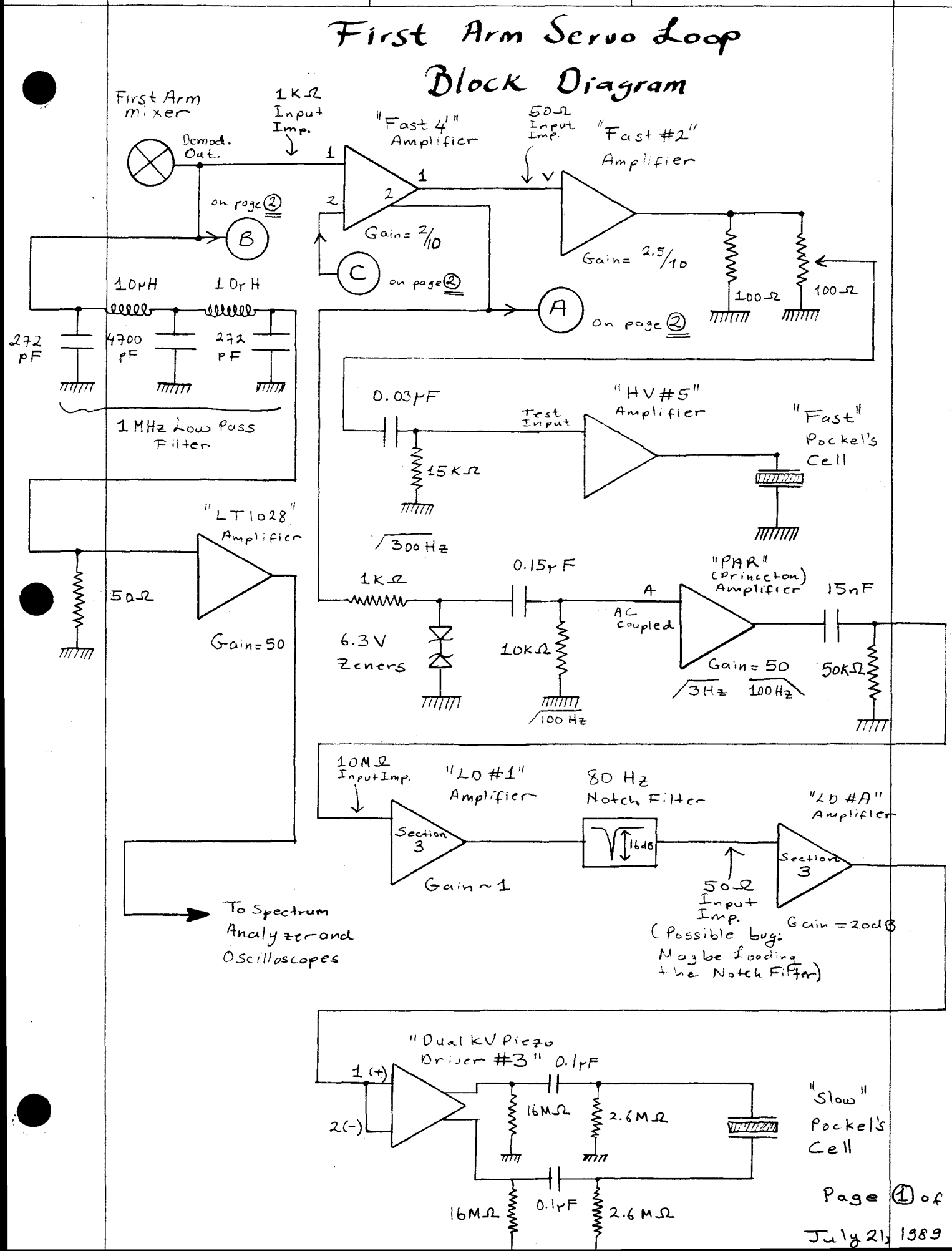


BYPASS OFF — SEE PAGE 8 FOR BYPASS ENHANCEMENT (BRINGS GAIN TO ~120 dB at 1 kHz, ~173 dB @ 30 Hz)

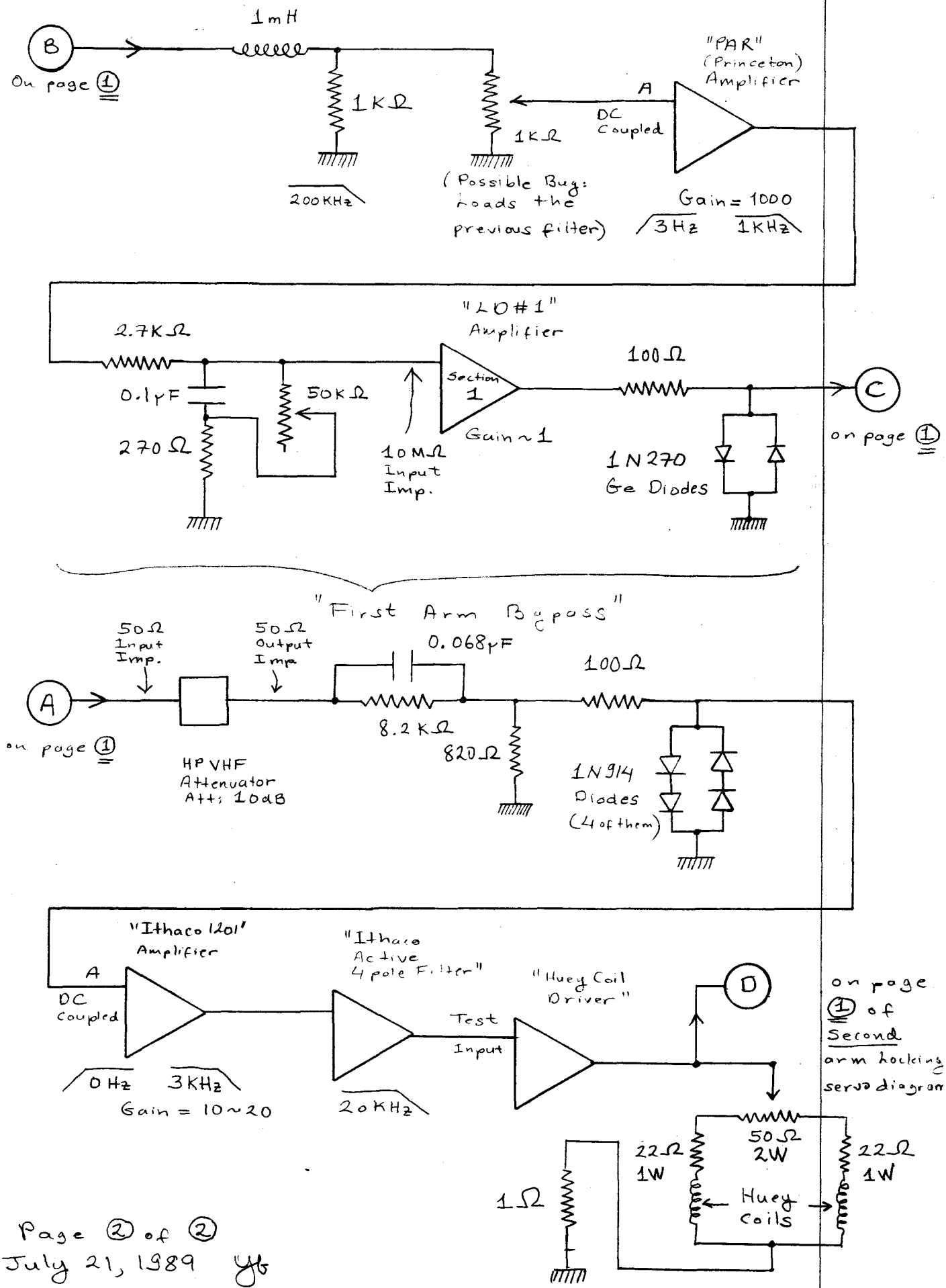
BATCH START

STAPLE
OR
DIVIDER

First Arm Servo Loop Block Diagram

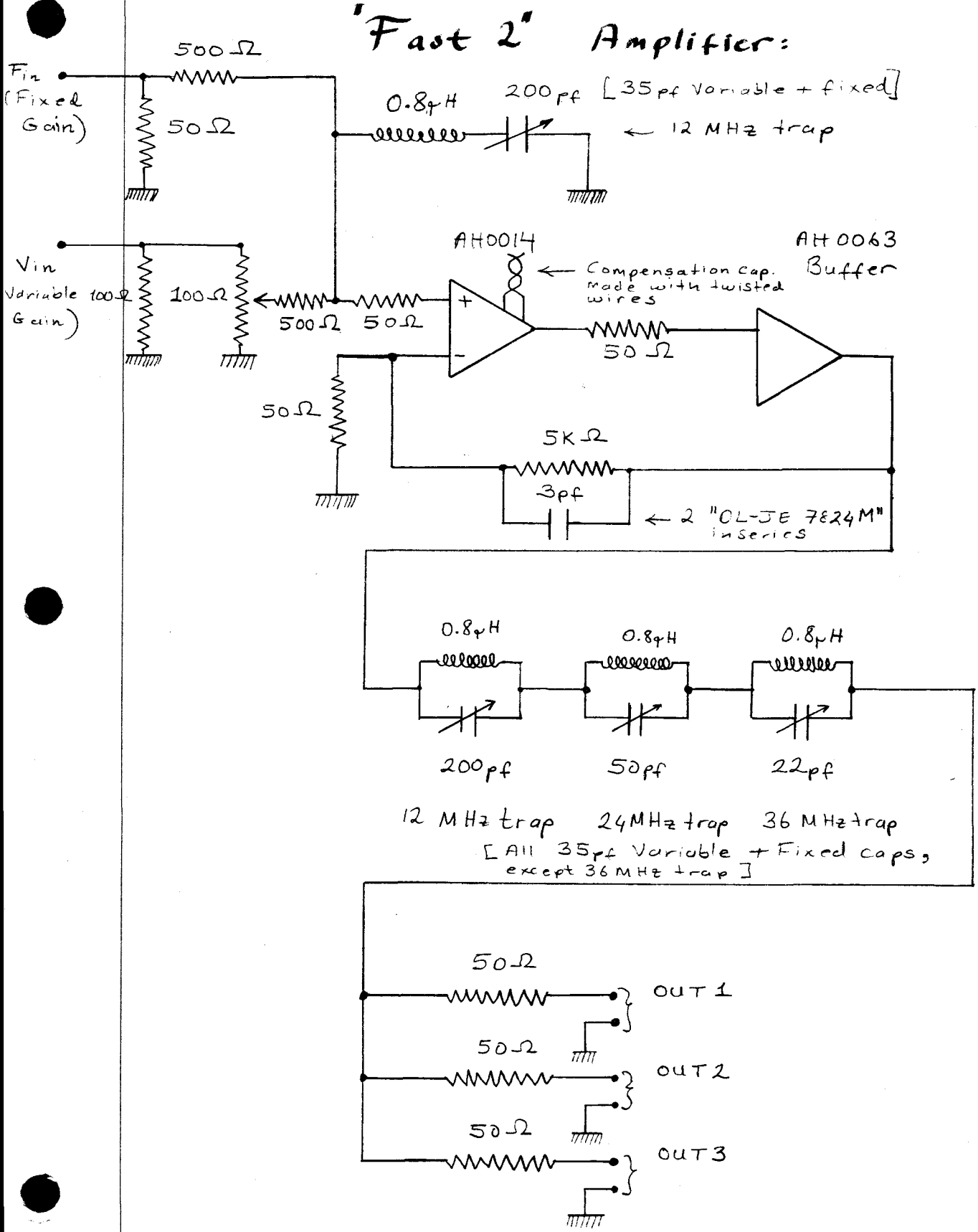


July 21, 1989 yb



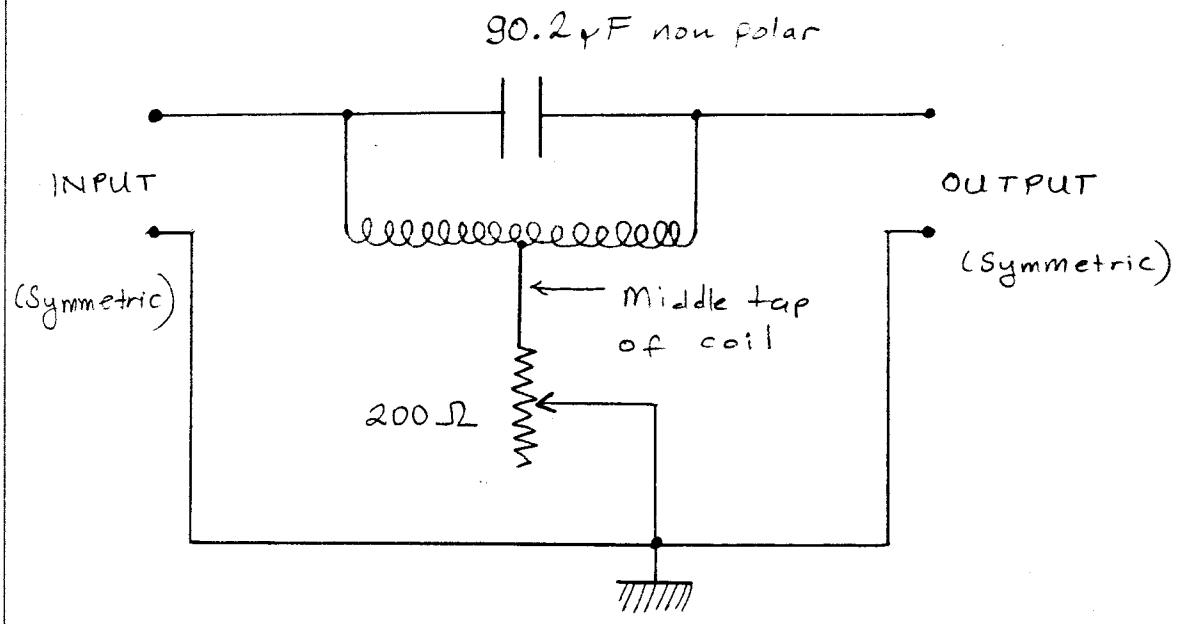
July 21, 1989 yb

'Fast 2' Amplifier:



July 24, 1989
ys

80 Hz Notch Filter:



The coil is chosen in such away that the resonance of the LC combination is 80 ± 1 Hz.

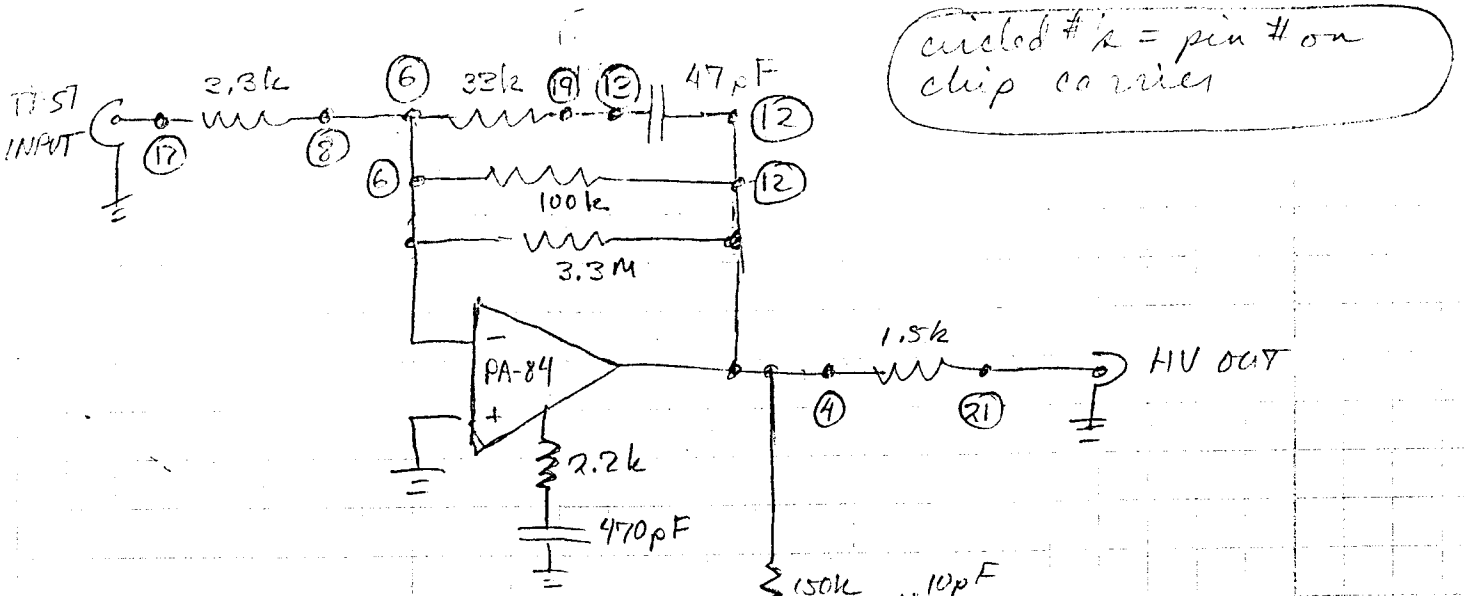
July 24, 1989 YB

8/24/89

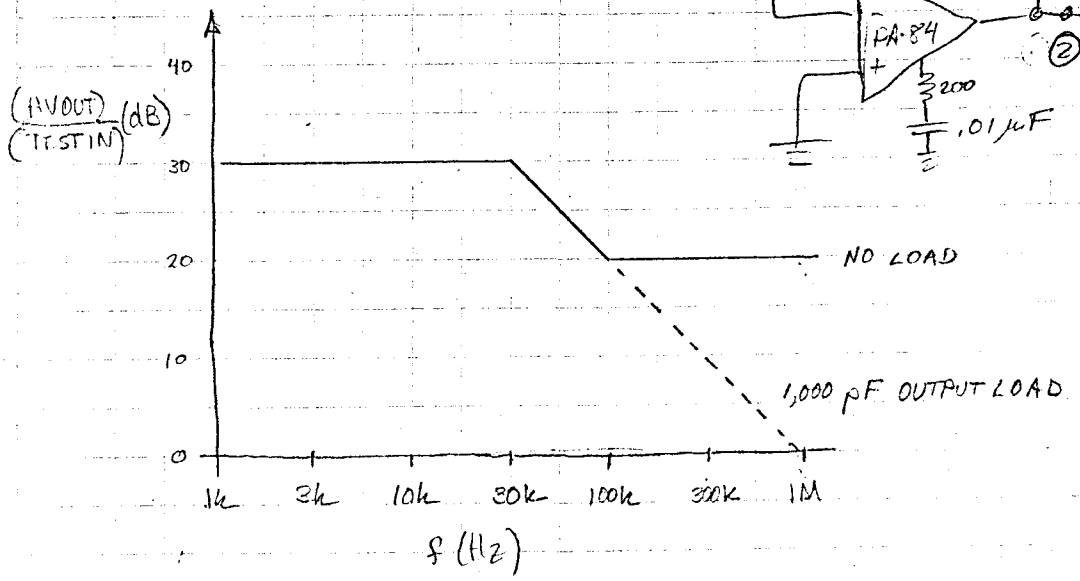
→ LABELED "Y"

Another H.V. amp has been modified for use in phase correcting loop (to replace/supplement "push" amplifier used for fast H.O. in previous setups).

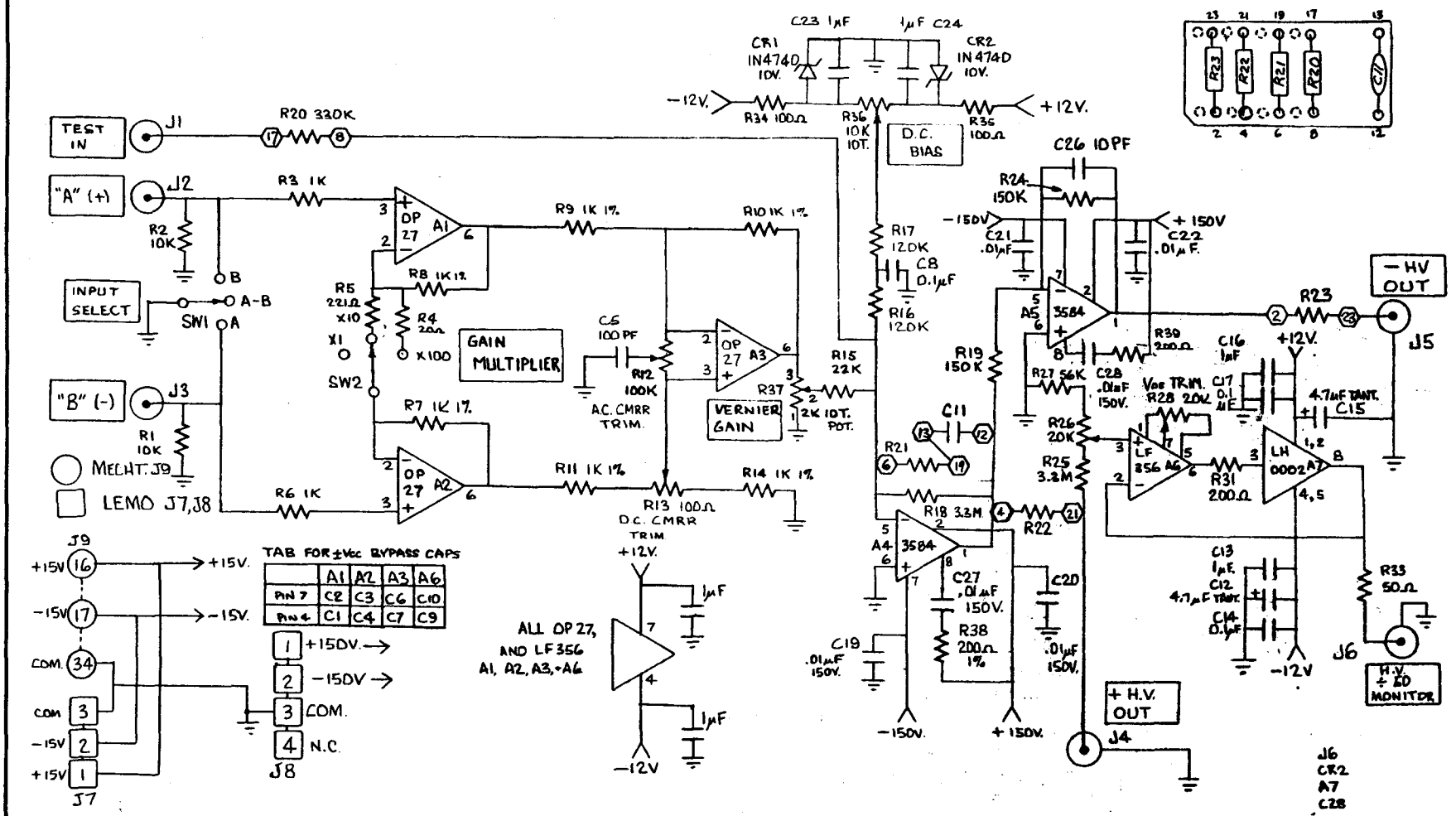
Relevant parts of circuit;



Transfer Function (theoretical);



Actual transfer function very close to theoretical, but peaky at ~2MHz



SMARTWRK FILE C:\SMARTWRK HVAMP.PCB
DRAWN FROM E. LINDELEF OF 9-1-87 PRO HVAMP.PL
ADDED COMP. CARRIED PIN NO's TO DWG.

REPLACES 87-0901-1

NOTES 1. [J] INDICATES JUMPER TO SHORT.

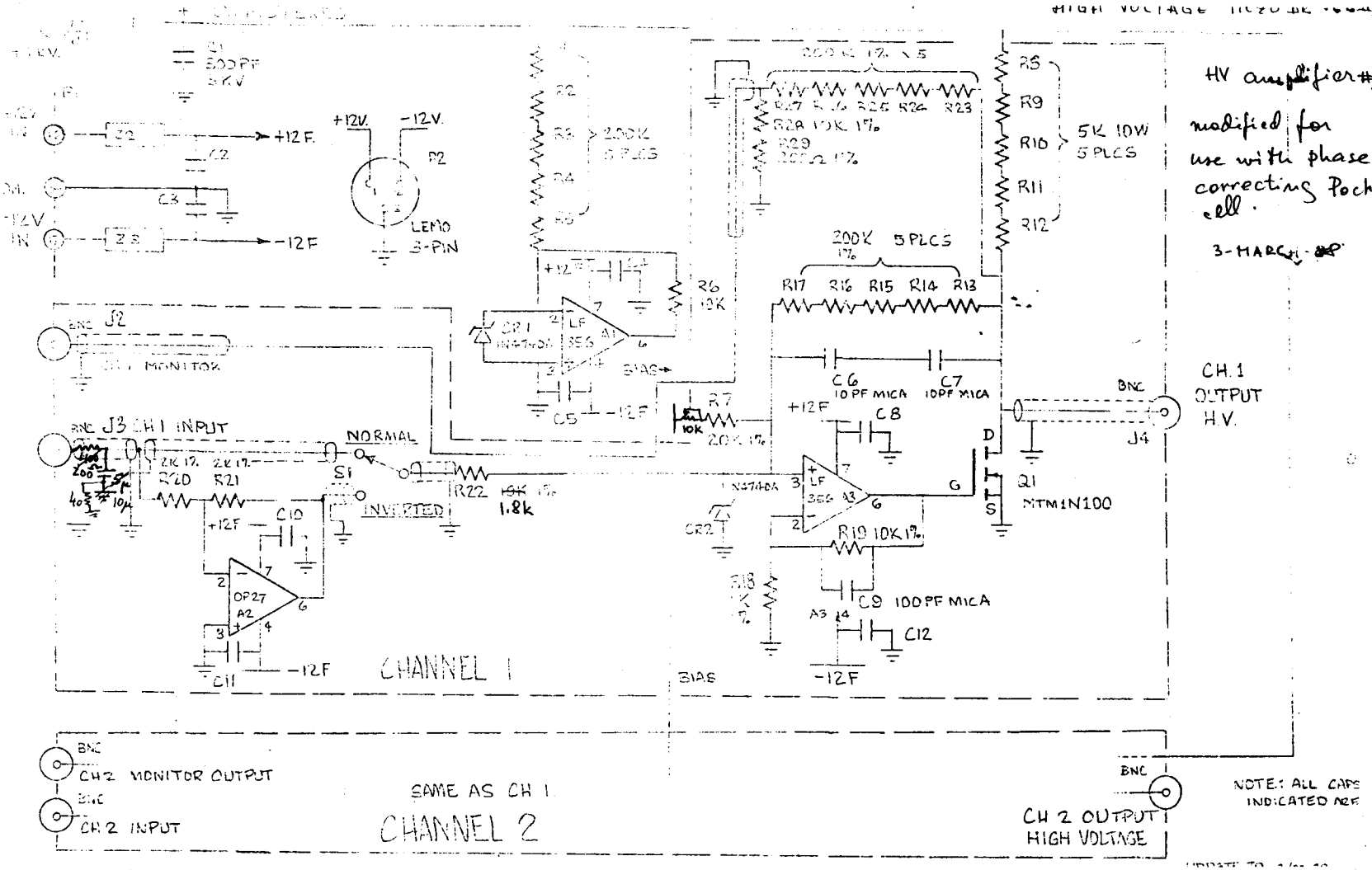
2. J7, J8, and J9 ARE ALL MOUNTED ON BACK PANEL.

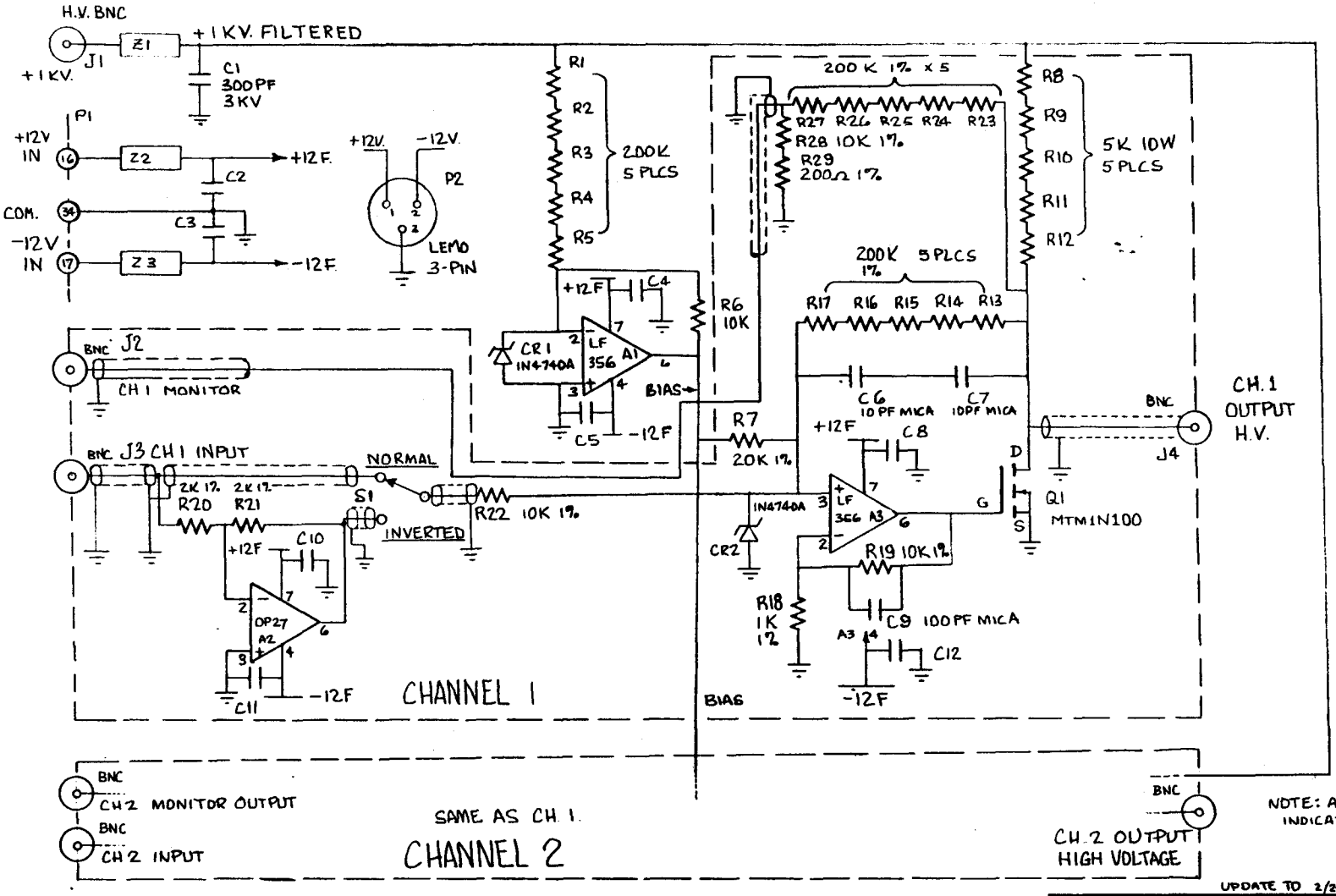
CALIFORNIA INSTITUTE OF TECHNOLOGY
GRAVITATIONAL PHYSICS

HV AMPLIFIER ± 150V.

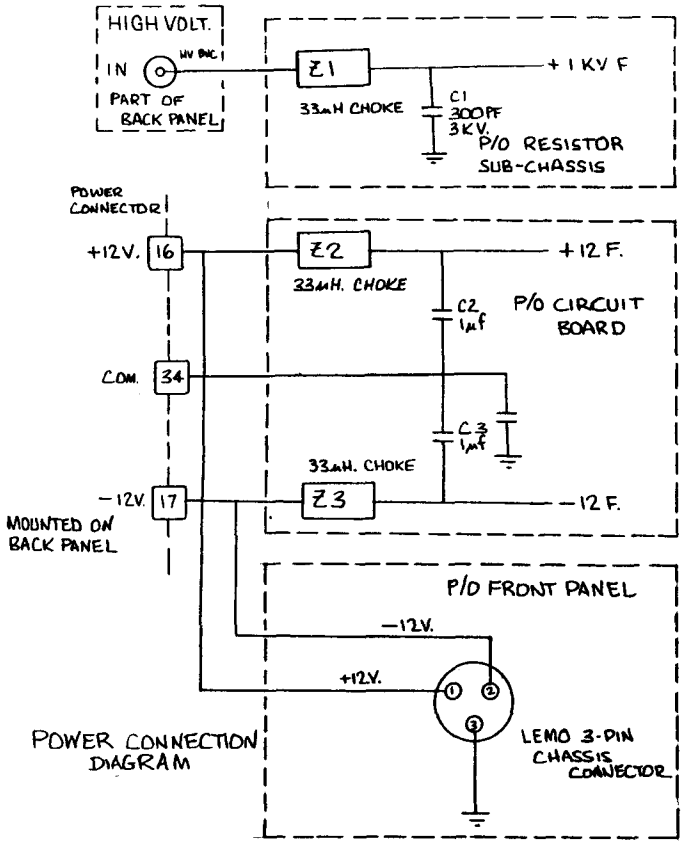
DRAWN BY B. TINKER	DATE 3-4-88	DRAWING NO.
CHECKED BY	SCALE	
APPROVED BY	W.O.	

88-0304-1


HV amplifier #
modified for
use with phase
correcting Pocke
cell.
3-MARCH
+12V.
-12V.
+12 F.
-12F
LEMO
3-PIN
C1
500PF
3KV
C2
C3
R2
R3
R4
R5
200K
5 PLCS
R6
10K
R7
10K
200K 1%
R17 R16 R15 R14 R13
200K 5 PLCS
1%
R5
R9
R10
R11
R12
5K 10W
5 PLCS
R27 R26 R25 R24 R23
R28 10K 1%
R29
CR1
LF
356
A1
C5
BIAS
C6
10 PF MICA
C7
10PF MICA
C8
BNC
J4
CH. 1
OUTPUT
H.V.
Q1
MTM1N100
BNC J2
MONITOR
BNC J3 CH 1 INPUT
NORMAL
INVERTED
S1
R20
R21
2K 1%
2K 1%
R22
1.8k
C10
OP27
A2
C11
CHANNEL 1
CR2
R19 10K 1%
R18
C9 100PF MICA
C12
A3
BIAS
BNC
CH 2 MONITOR OUTPUT
BNC
CH 2 INPUT
SAME AS CH 1
CHANNEL 2
BNC
CH 2 OUTPUT
HIGH VOLTAGE
NOTE: ALL CAPS
INDICATED ARE

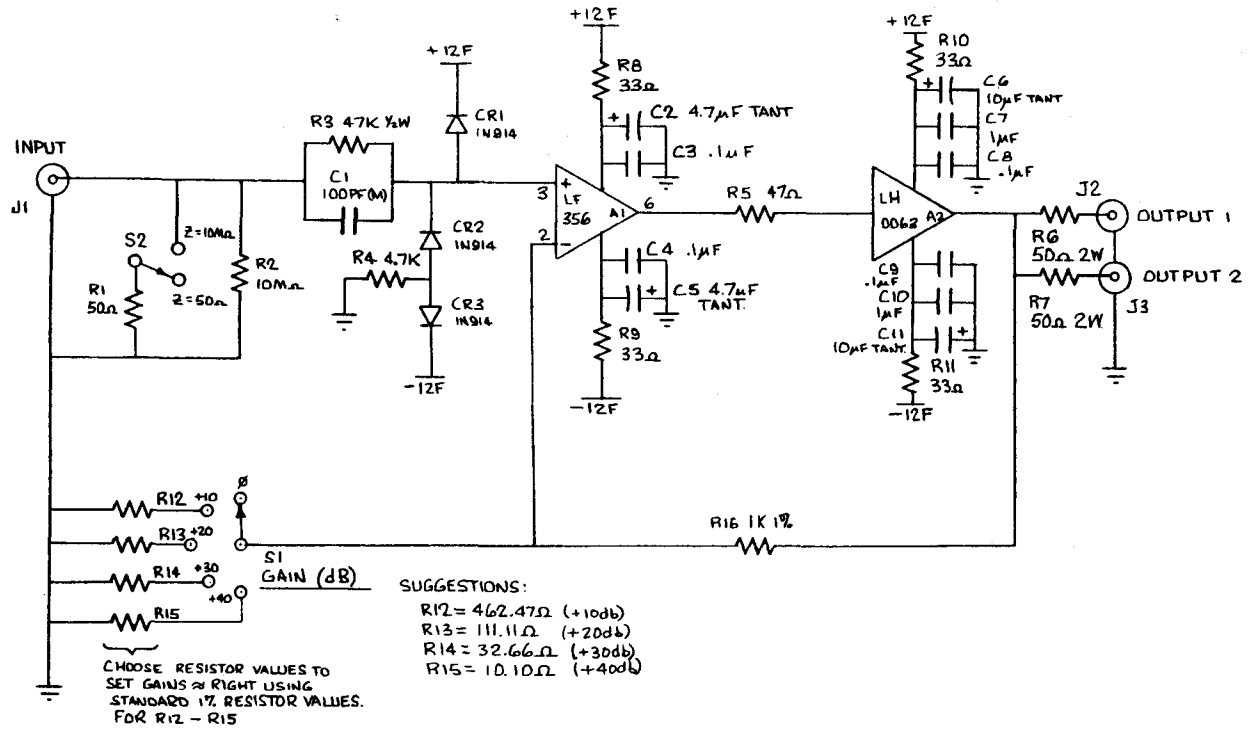


87-1124-1



CALIFORNIA INSTITUTE OF TECHNOLOGY GRAVITATIONAL PHYSICS		
DUAL KILOVOLT PIEZO DRIVER		
DRAWN BY B. TINKER	DATE 2-2-88	DRAWING NO.
CHECKED BY	SCALE	-2
APPROVED BY	W.O.	

87-1124-2



SUGGESTIONS:

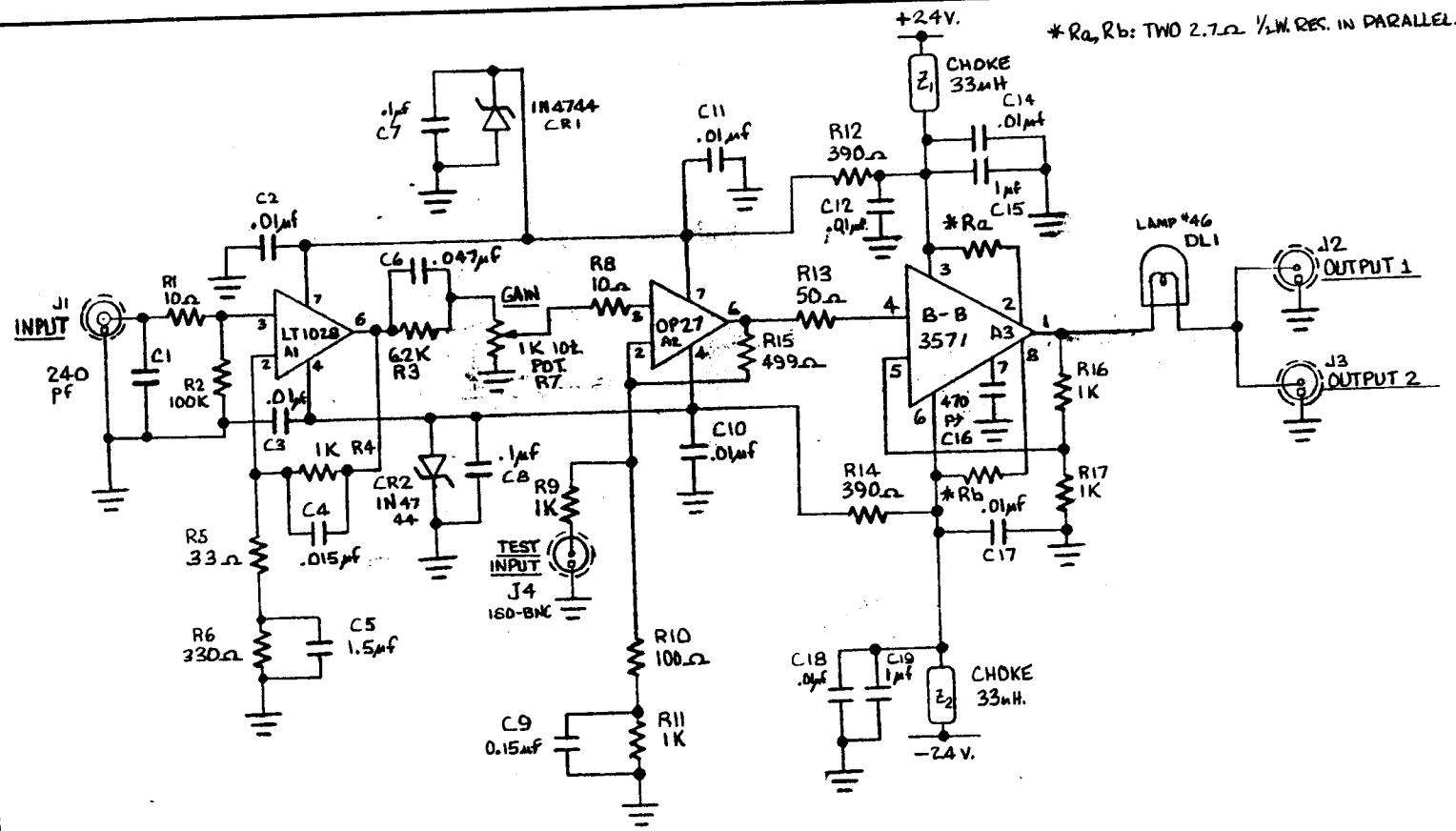
R12 = 462.47Ω (+10db)
R13 = 111.11Ω (+20db)
R14 = 32.66Ω (+30db)
R15 = 10.10Ω (+40db)

A 2
CR3
S2
J3
R16

LAST C

CALIFORNIA INSTITUTE OF TECHNOLOGY GRAVITATIONAL PHYSICS		
LINE DRIVER		
DRAWN BY B.T.	DATE 6-13-88	DRAWING NO.
CHECKED BY	SCALE	
APPROVED BY	W.O.	

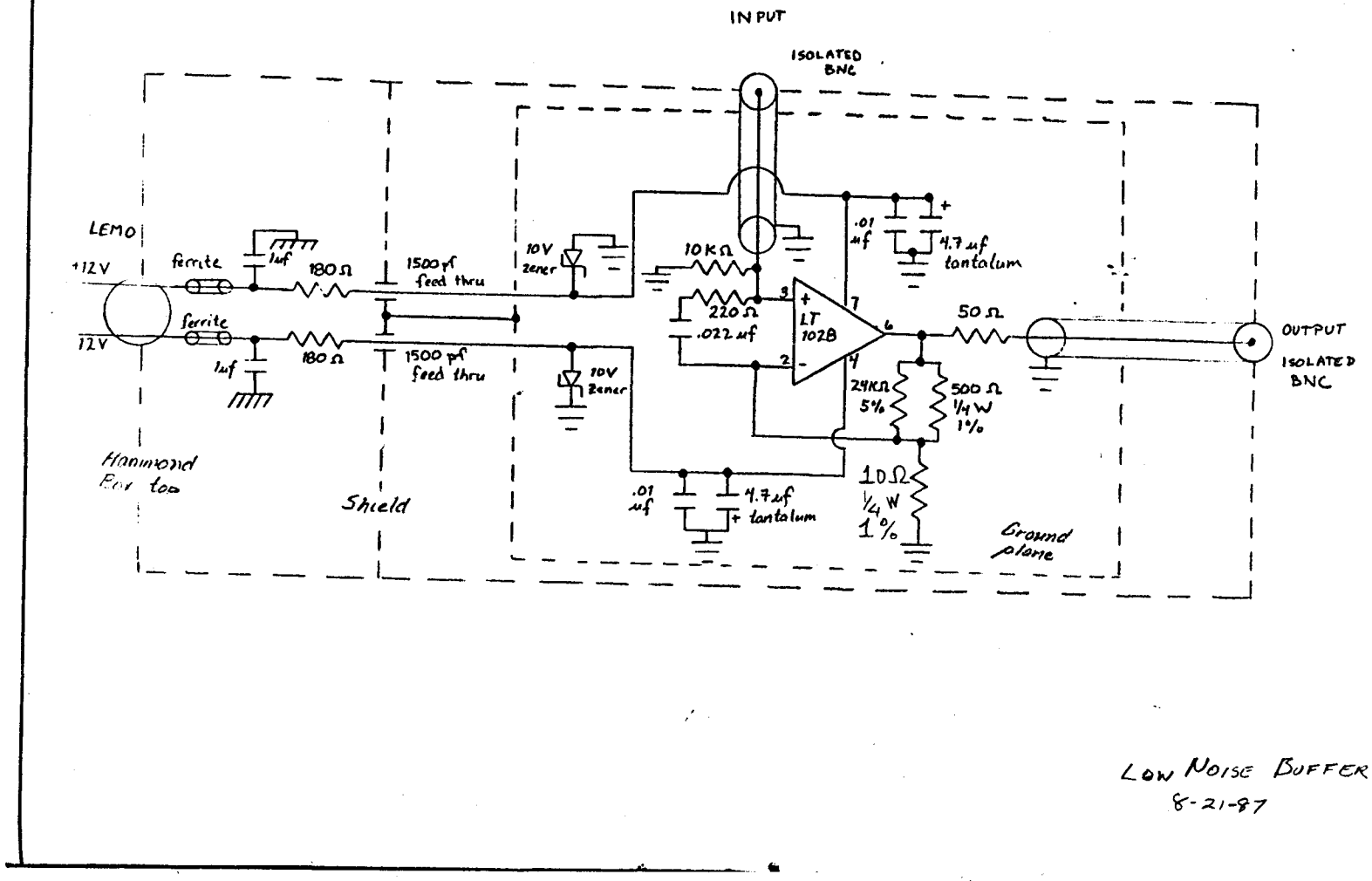
88-0613-1



3-1-88 R15 MOVED: 1K TO 500Ω
1-28-88 C16 FROM 220pf TO 470pf
UPDATE TO 9-8-78

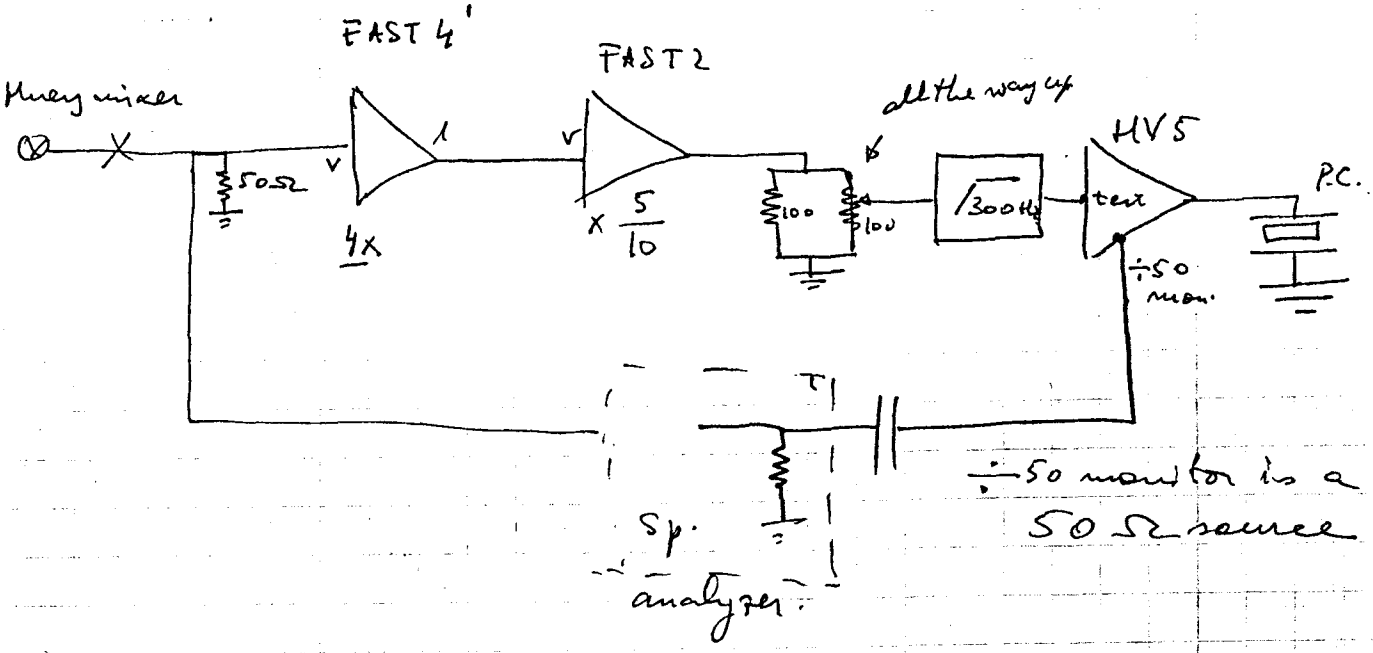
CALIFORNIA INSTITUTE OF TECHNOLOGY GRAVITATIONAL PHYSICS		
COIL DRIVER HIGH CURRENT		
DRAWN BY B.T.	DATE 9-2-87	DRAWING NO. -1
CHECKED BY	SCALE	
APPROVED BY	W.O.	

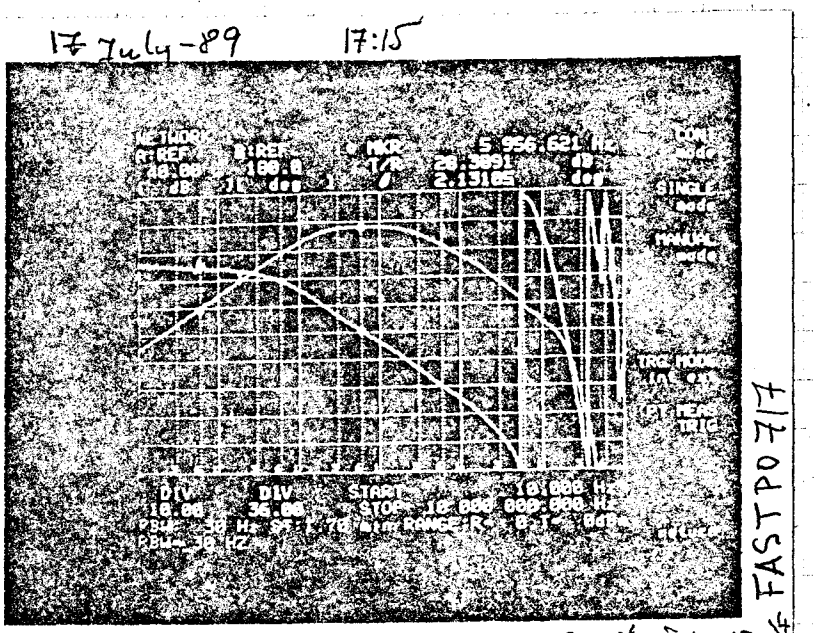
87-0902-1



LOW NOISE BUFFER
8-21-87

1st amn (phase correction) servo : fast Pockels cell leg



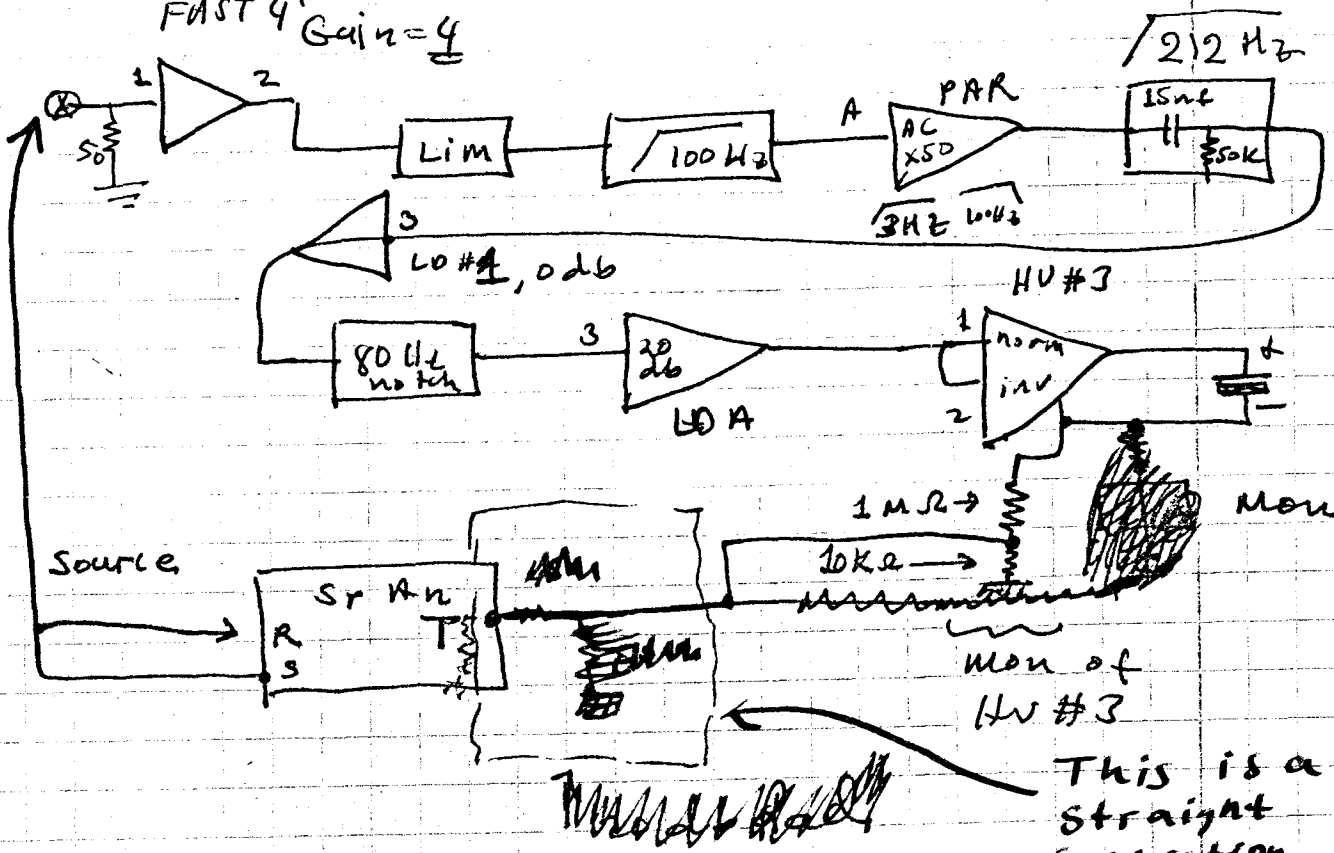


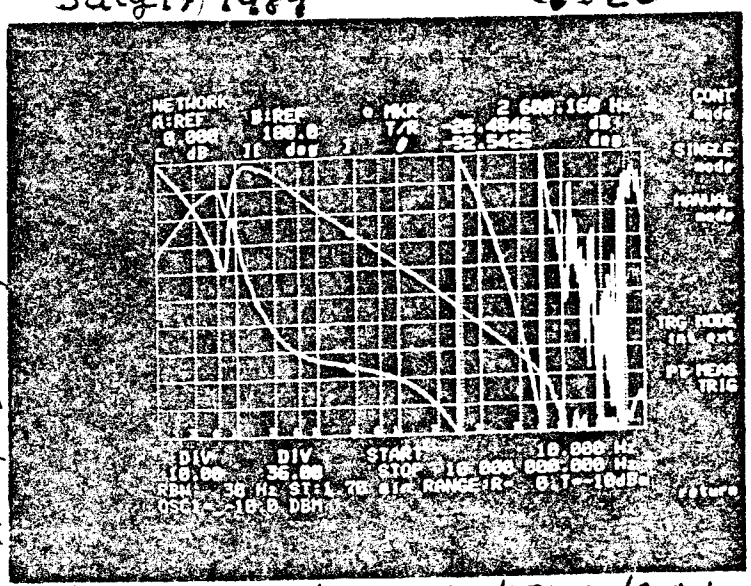
Fast PC. leg transf. function, 50Ω at input of Fast

July 17, 1989
YG, AA, SH

Servo block frequency and phase response:

1st arm: slow pockel's cell loop:





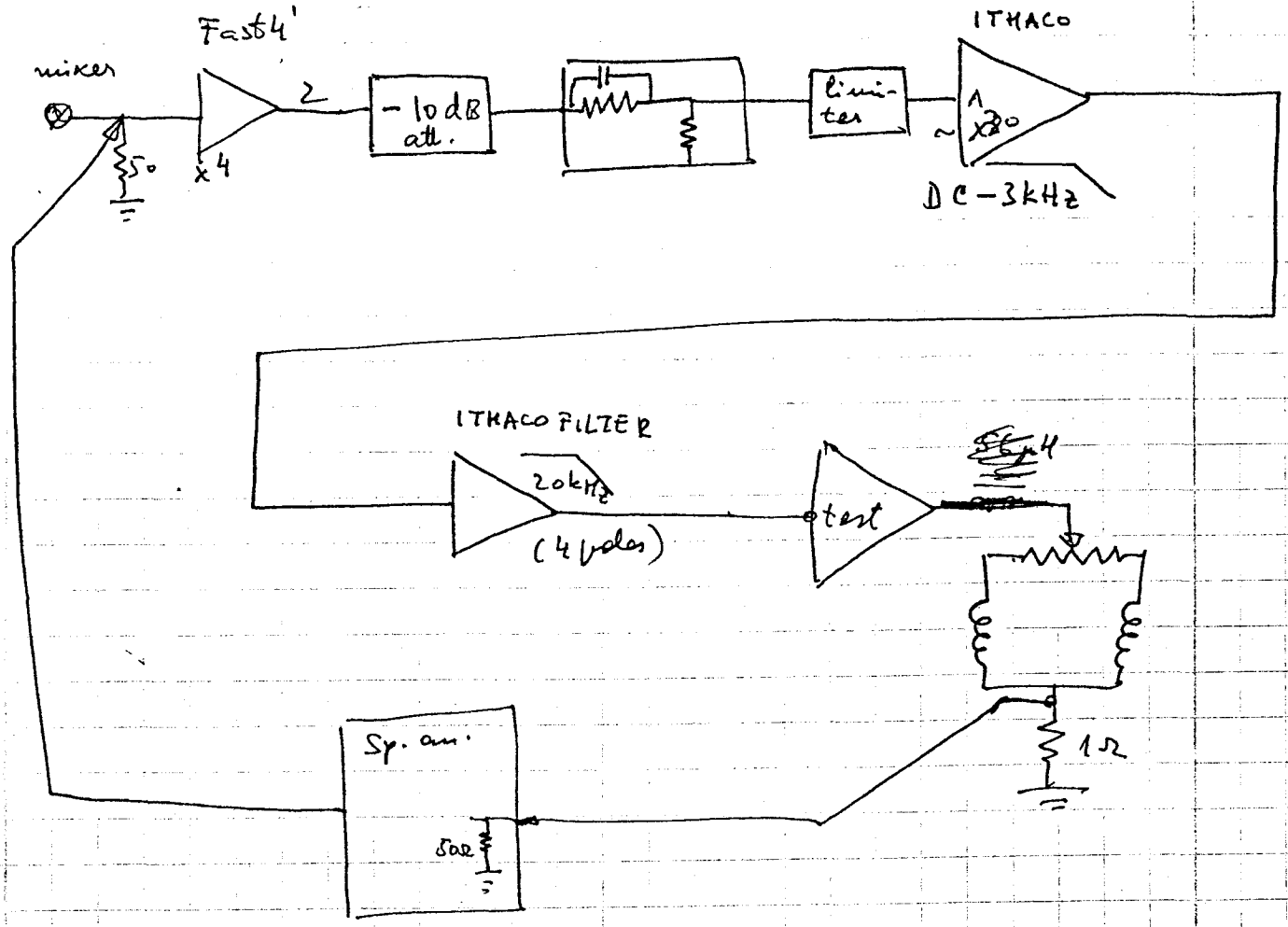
slow pockel's cell branch of 1st arm servo loop

← real gain: add 92dB (see dividers on sketch above)

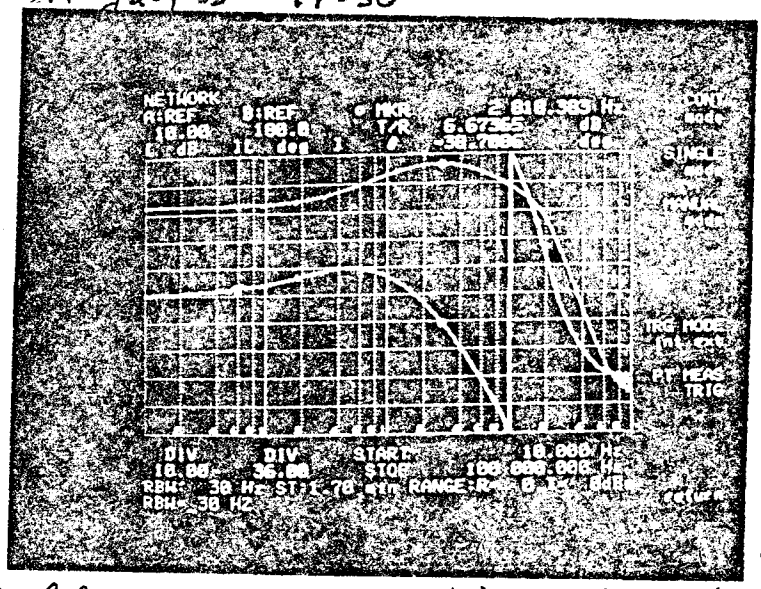
← 50Ω term at Fast 4 ampl.

AR

1st arm (phase correcting) servo; coil driver leg

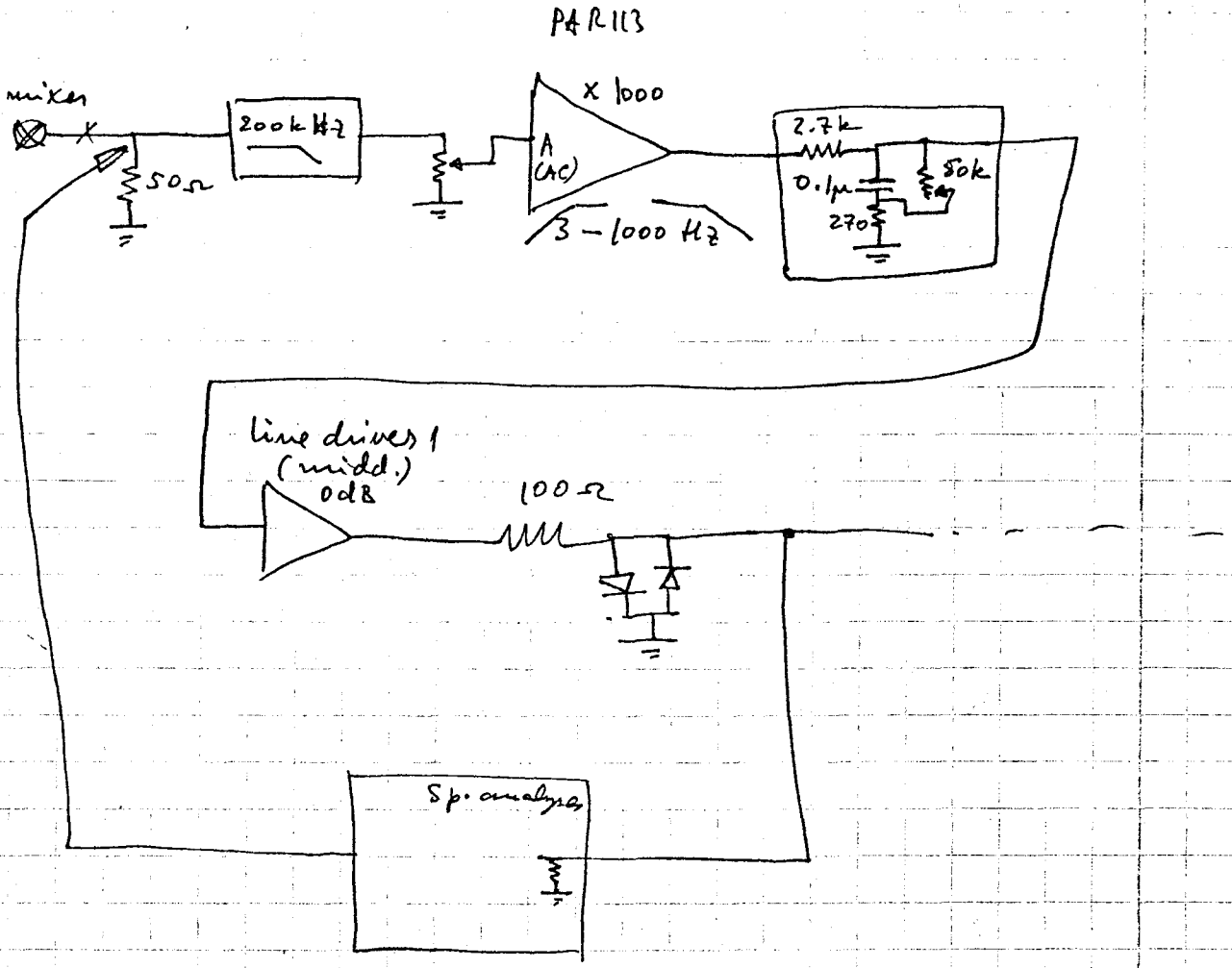


17 July 89 17:30

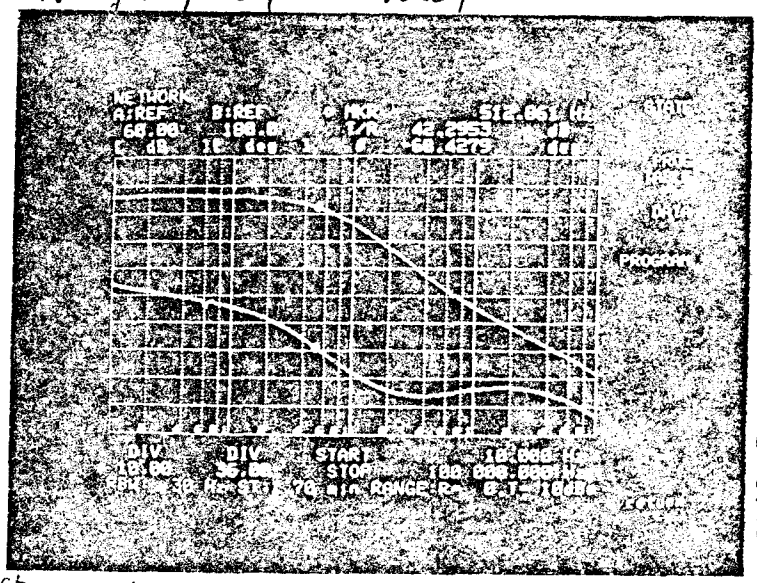


Coil leg response, 50Ω at inp of FAST4'

1st arm locking (phase correction) servo: bypass



17-July-89 18:09

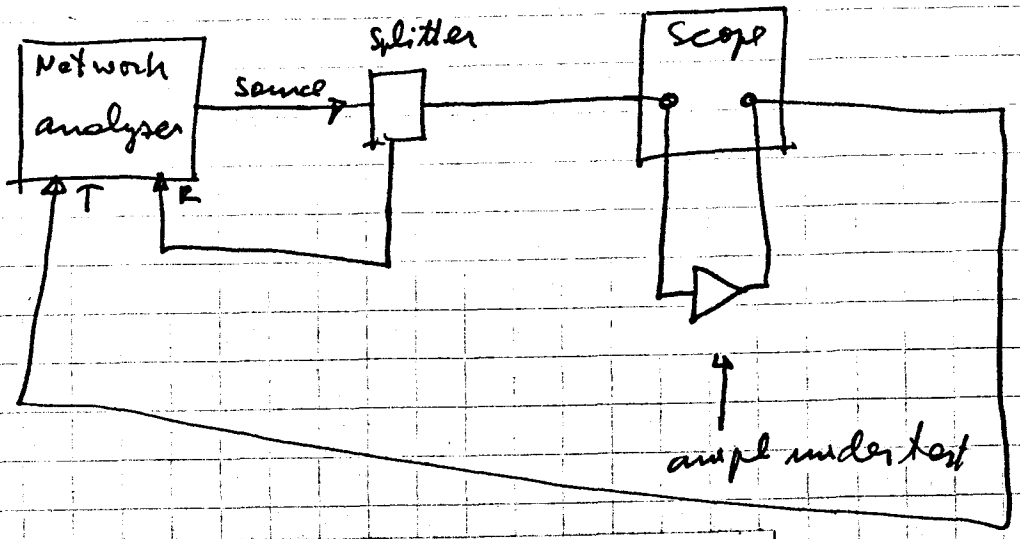


BYP 717

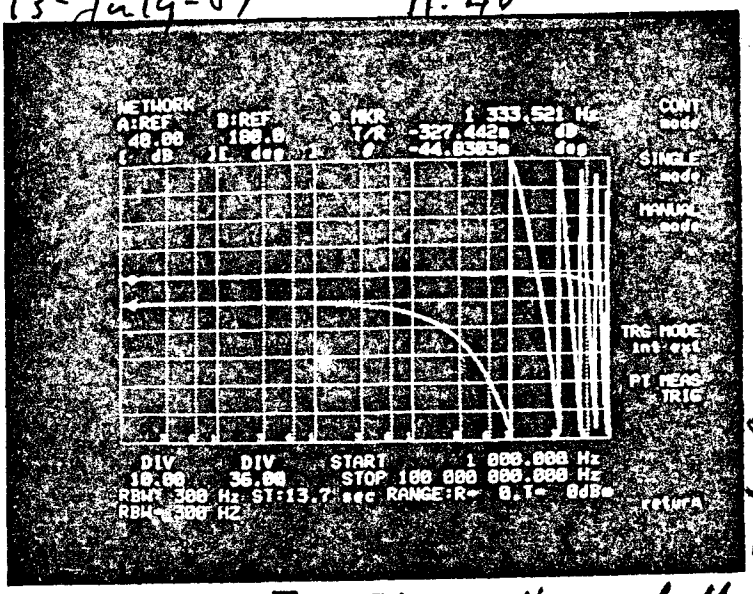
1st arm bypass response

13-July-89

Since ~30' of cables were used to connect the amplifier under test (see diagram below), we took the response of the cables themselves (trace at 11:40)



13-July-89 11:40

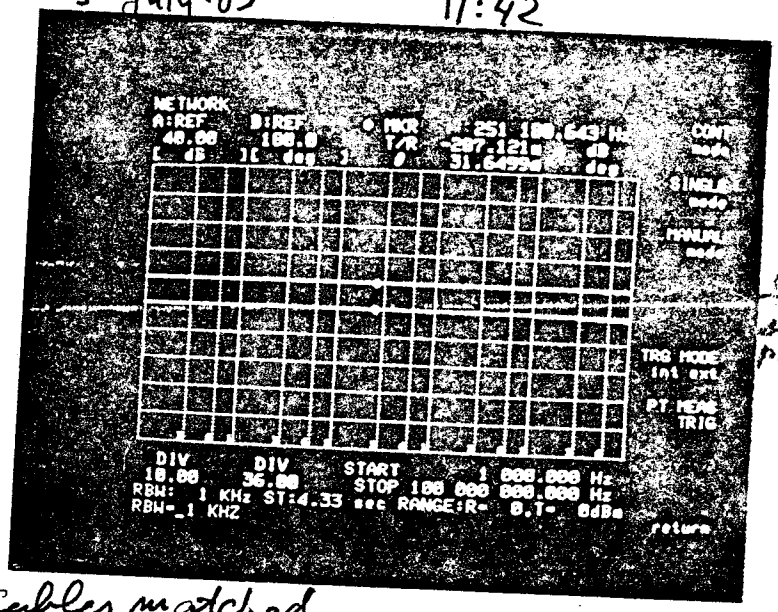


in balance

TR. FUNCTION OF CABLES - they are badly

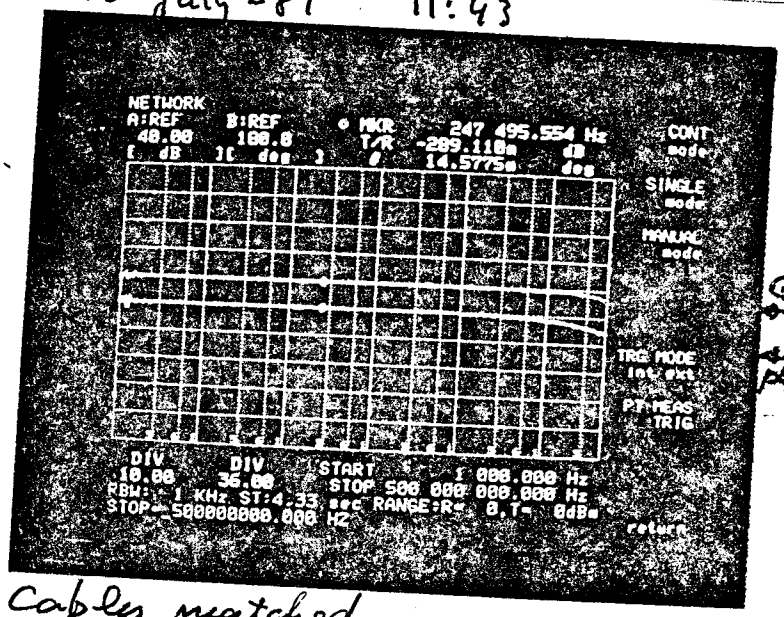
- It turns out that at 250 kHz the cables alone show a phase shift of 5°.
- Therefore, the ~3' cable from splitter to R input was replaced with a long cable, matched to the one in the test path. See traces overleaf

13-July-89 11:42



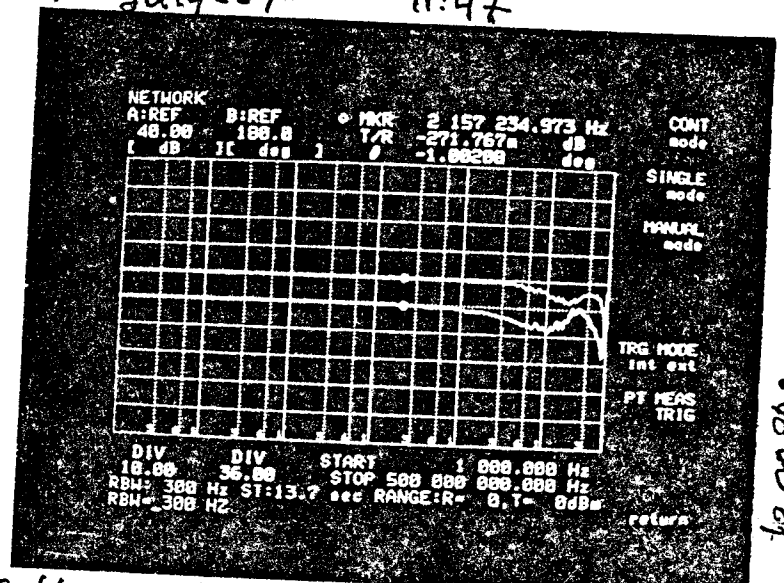
Cables matched

13-July-89 11:43



Cables matched

13-July-89 11:47

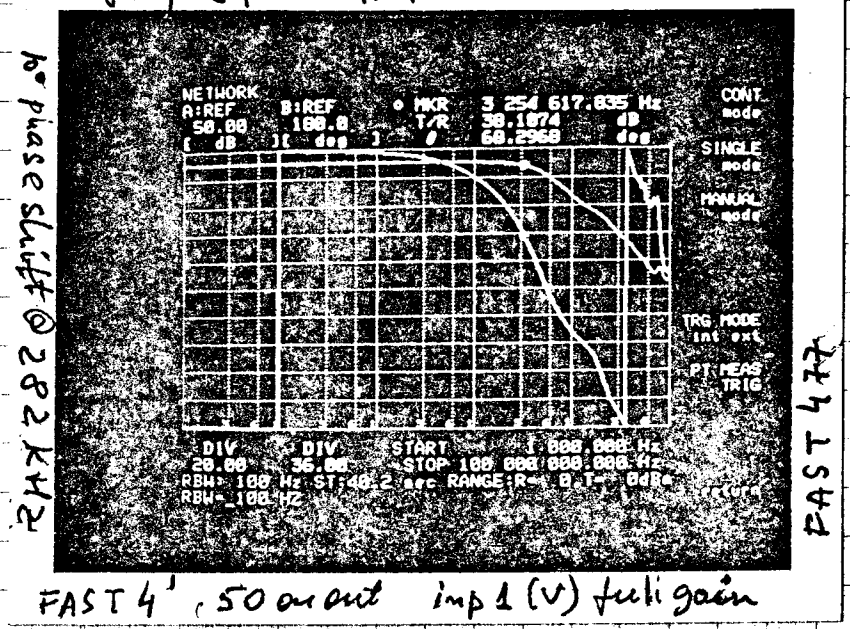


Cables matched, going thru a T's connected

To obtain the correct phase response of the amplifiers in the 40m system servos, we decided to measure their response again, this time with the matched cable

The two ~~traces~~ transfer functions (opposite page) clearly illustrate the difference between using unmatched/matc cables. All the following transfer functions have been mea

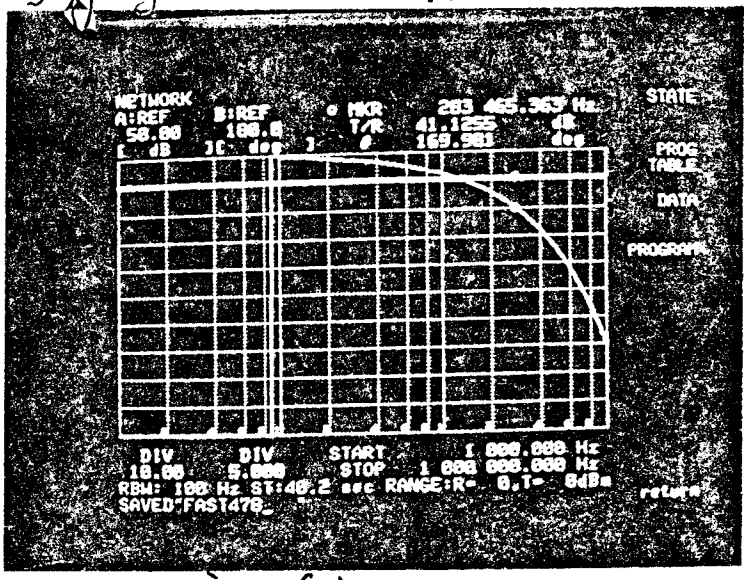
Saved with match cables (see cable response on p. 78Y overleaf)



0° phase shift @ 282 kHz

FAST 477

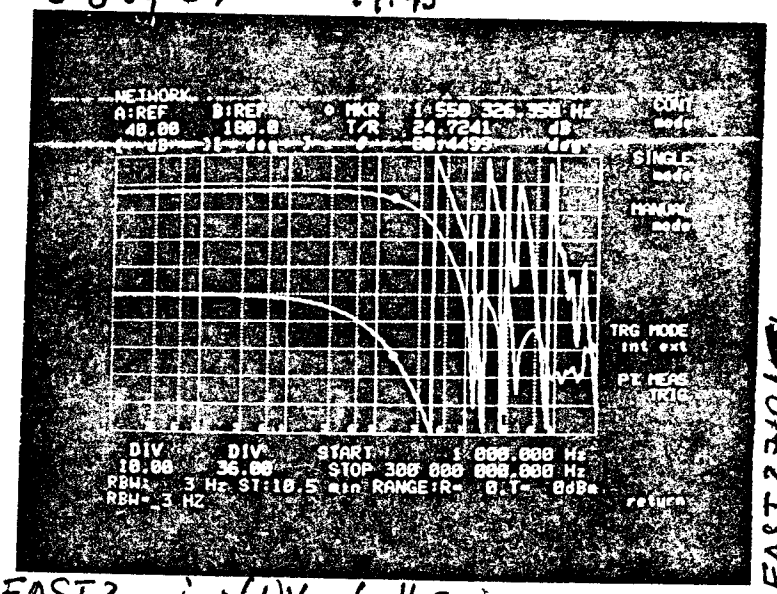
FAST 4', 50 ohm out imp 1 (V) full gain



FAST478

FAST4' imp 1 (V)

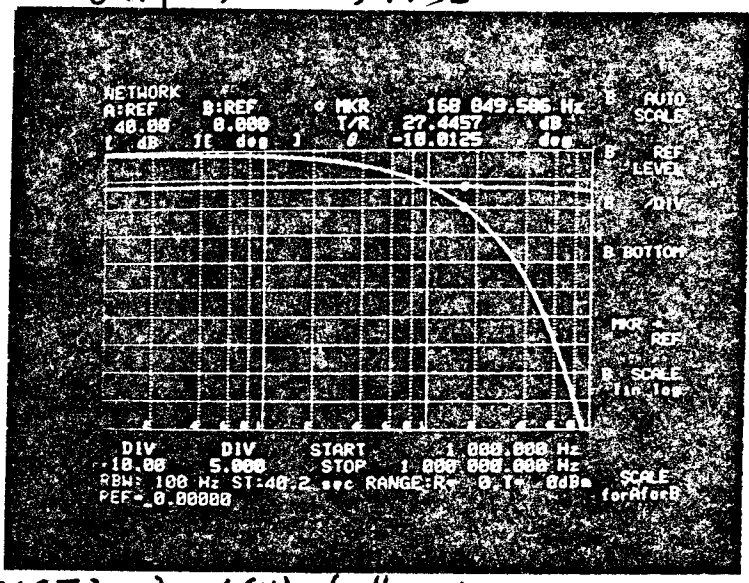
13-July-89 14:45



FAST2 inp(1)V full gain

FAST 2 7101

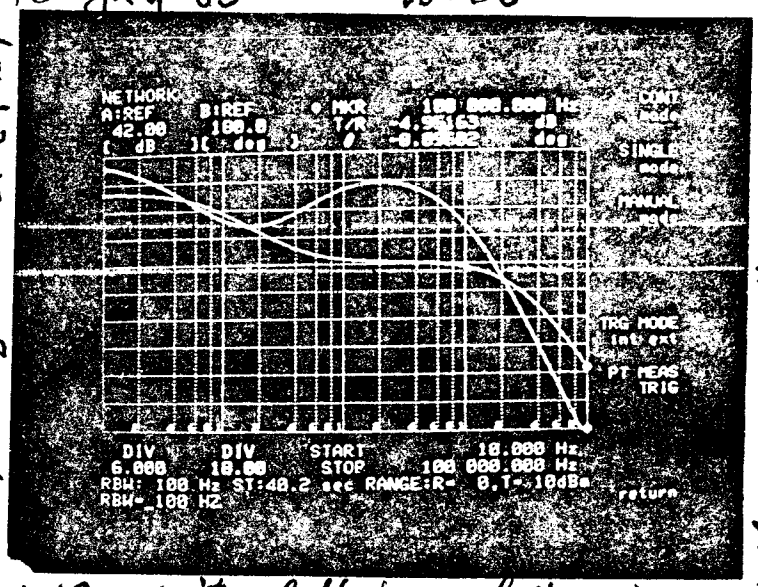
13-July-89 14:35



FAST2. inp1(V) full gain

FAST 2 7102

13-July-89 15:30

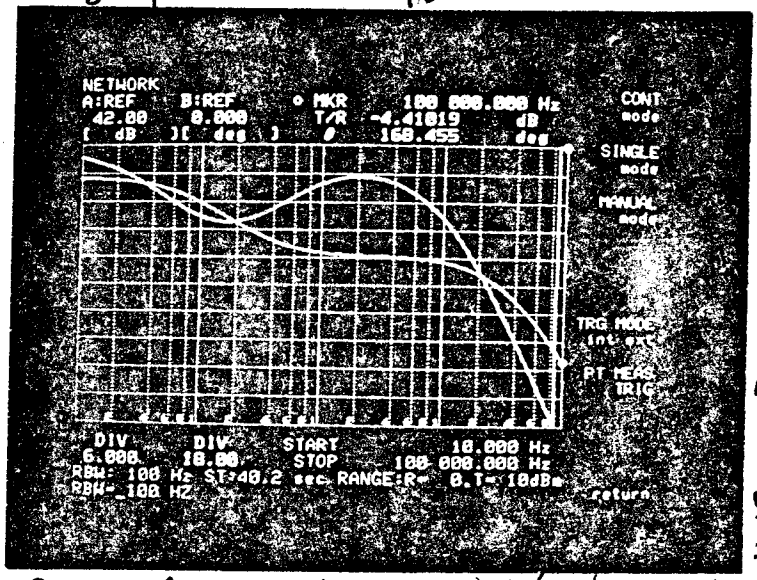


Low Z ITHACO, 50Ω out

HV3710 wide open

HV3 monitor, left channel, through ITHACO x10

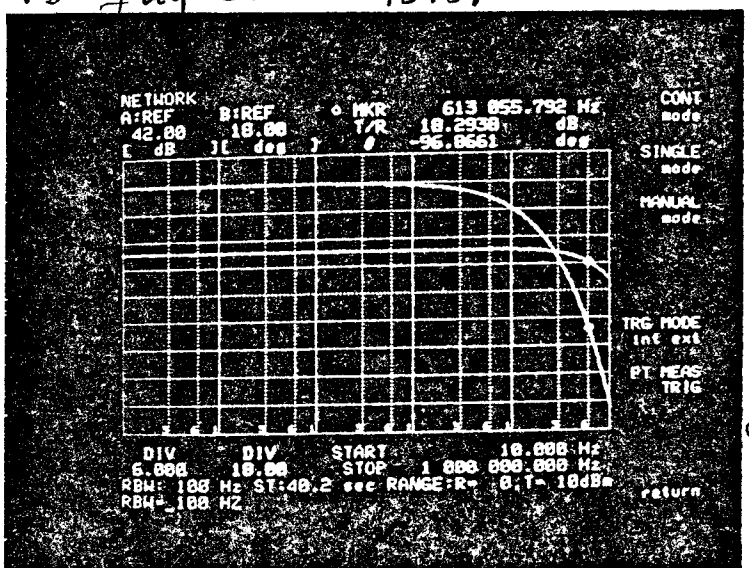
13-July-89 15:40



HV3710R

HV3 monitor, as 15:30, right channel

13-July-89 15:51



HI Z in

ITHACO 710

ITHACO x10, 50Ω out, wide open