LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO-T970052-00-D 2/6/97

NPRO-PSL Performance Data and System Documentation

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This is an internal working note
of the LIGO Project.

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CALIFORNIA INSTITUTE OF TECHNOLOGY
Laser Interferometer Gravitational Wave Observatory (LIGO) Project

CONTENTS

updated 1/17/97

Laser Power:

At 126 output: 600 mW

Into reference cavity (including side bands): 10 mW

Into PSPD (YAG 444): 16 mW

Into PSPD (YAG 200A): 20 mW

Laser controller readings:

Pwr: 554 mW

DC: 2.12 A

DPM: -1.44V

DT: 20.5 C

DTEC: 1.2 V

LT: 43.2 C

LTEC: -0.1 V

T: +42.1038

12.33 MHz RF drive:

Oscillator attenuators: switch: 10, knob: 4

5 Watt Amp attenuators: switch: -10, knob: 0

Phase shifter: 300 deg.

Measured RF Out: 4.5 V P-P directly into 50 ohms

Reference Cavity:

RFPD DC out locked: -48.5 mV

RFPD DC out unlocked: -136 mV

Reference cavity visibility: 88% (1-15/128)

Discriminant P-P (at PCTI out): 4.5 V P-P

PSPD:

DC out (YAG444): -7.2 V

DC out (YAG200A): -8.3 V

Frequency Stabilization Amplifier Settings:

Slow Adjust: 0.40

Fast Adjust: 1.04

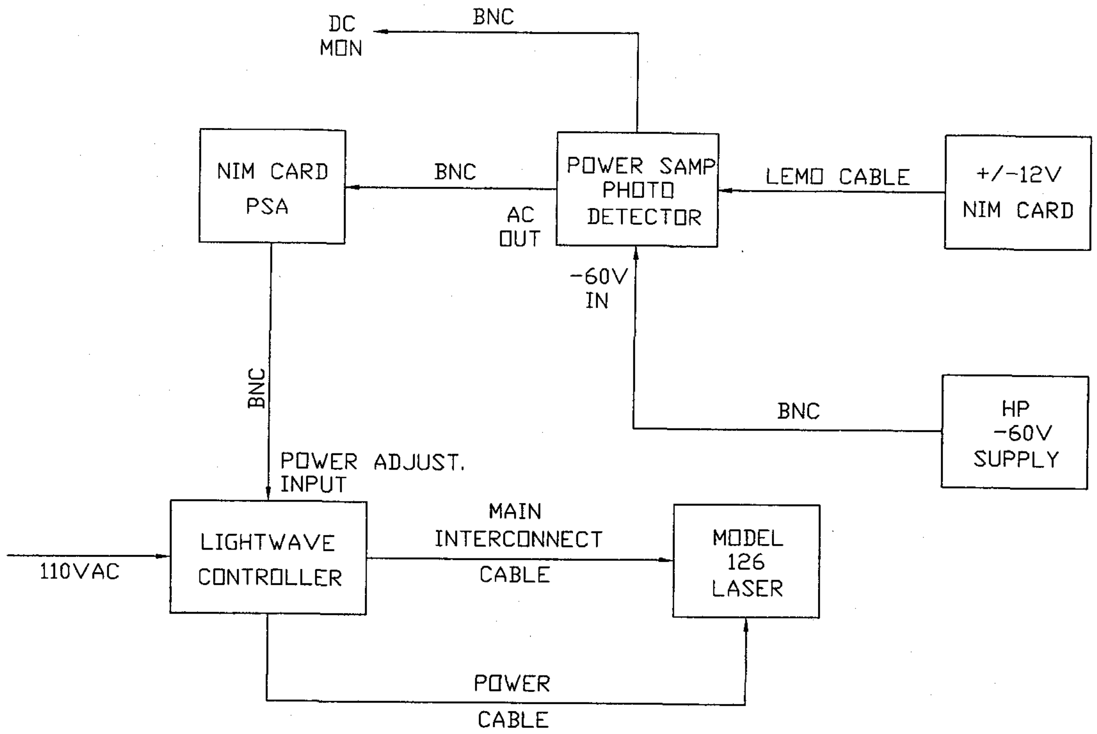
In Adjust: 0.91

Power Stabilization Amplifier Settings:

Gain Switch: 10

Gain Pot: 3.4

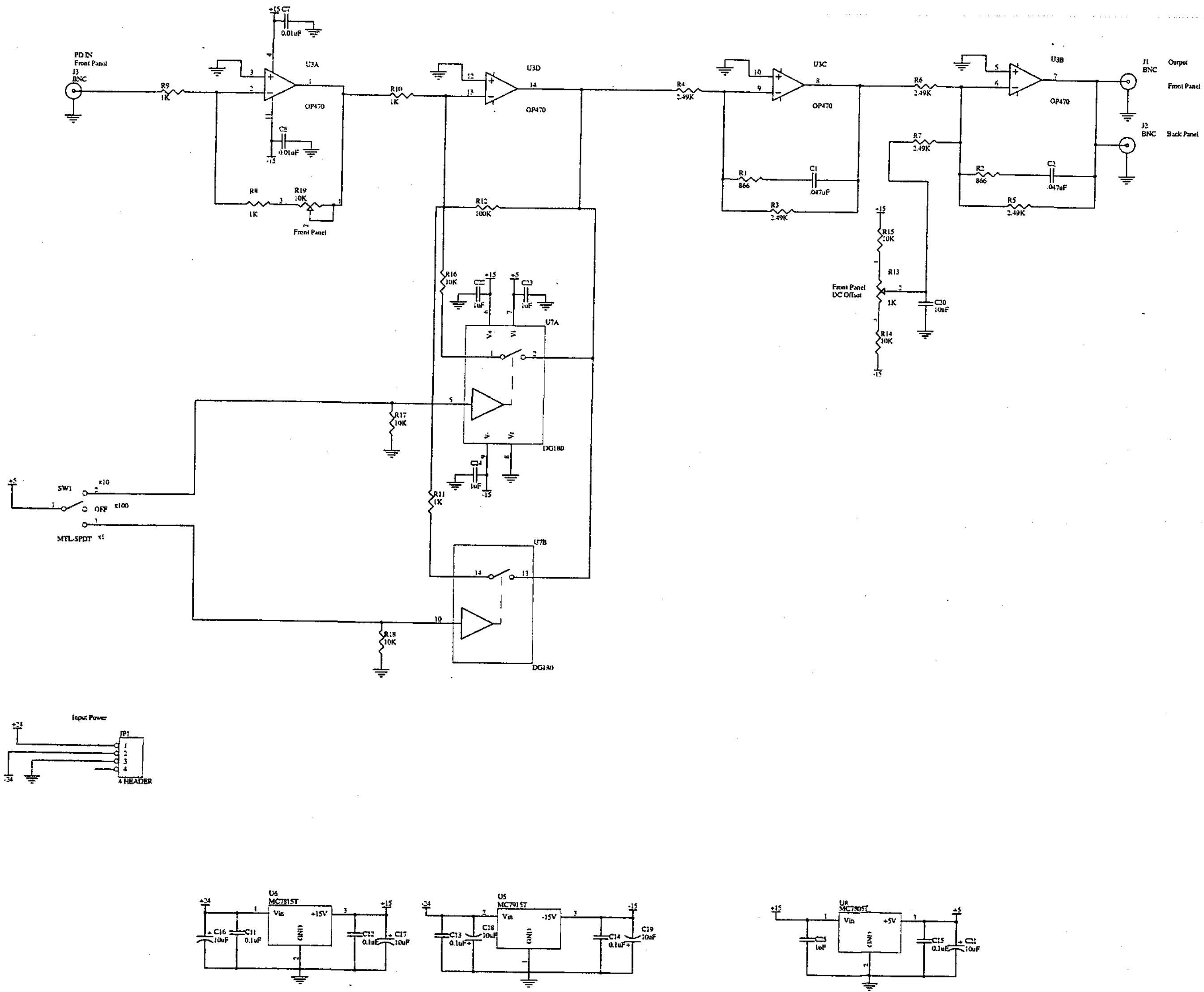
DC Offset Pot: 5.0



LIGO	CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Title	NPRO POWER STAB. SERVO
CAD FILE	-
SIZE	C
DWG. NO.	STD
REV.	A
SCALE	-
SHEET	1 OF 1

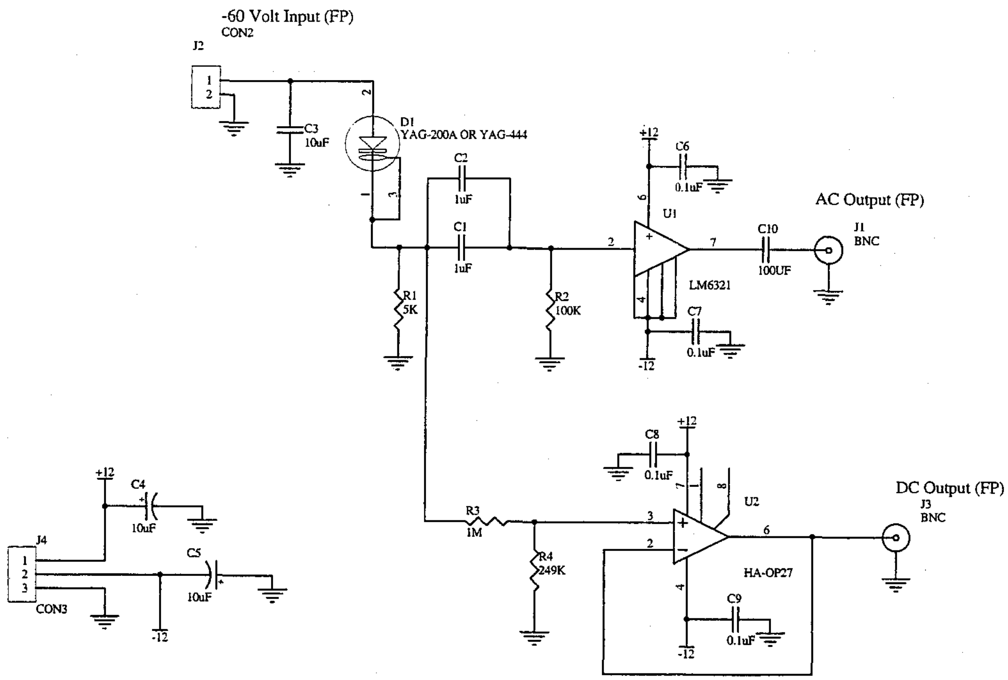
REV	DESCRIPTION	DRWN	DATE
00	PRE-RELEASE	TONY T	1/31/97

DO NOT SCALE THIS DRAWING
USED ON
NEXT ASS'Y



Title			LIGO Project
NPRO-PSL Power Stabilization Amplifier			California Institute of Technology Massachusetts Institute of Technology
Size: C	Number: D96-1246	Revision:	Engineer: J. Heefner
File:	Date: 6-Feb-1997	Time: 09:56:36	Sheet 1 of 1

LIGO



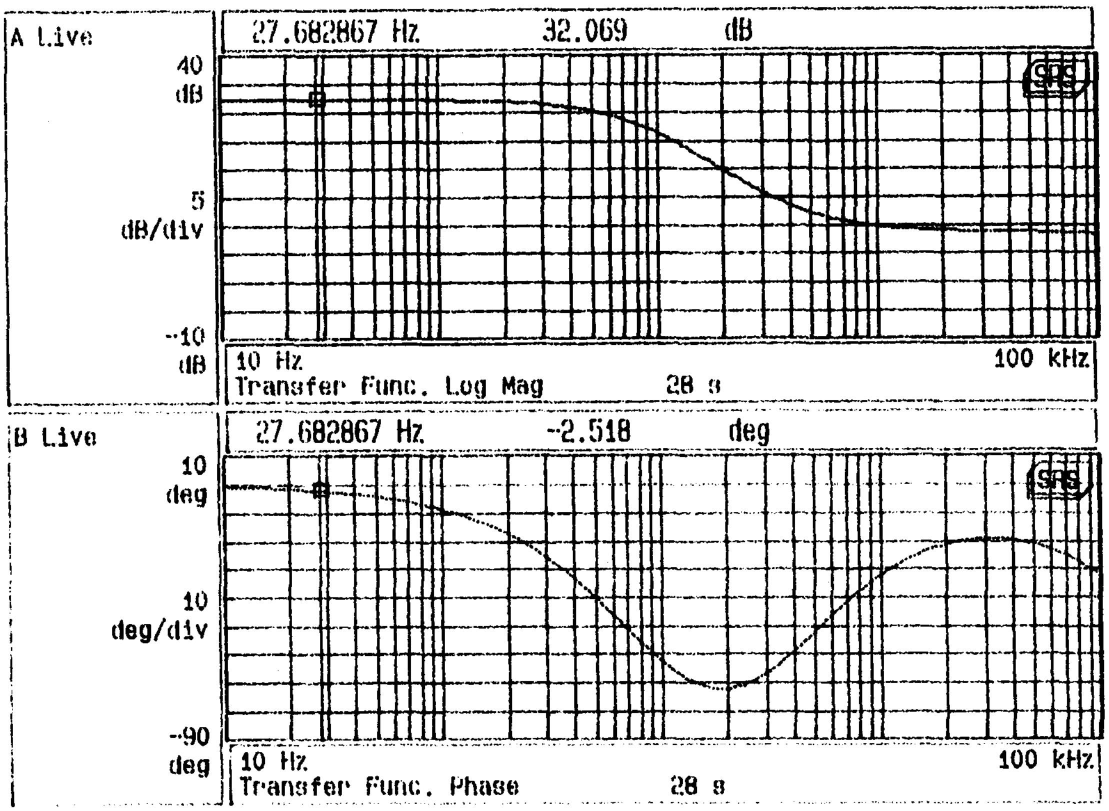
11 Sept. 1996:
Added R3 and R4 to prevent overdrive of U2 causing oscillation. The 100uf capacitor, U10, is there to block the small
DC offset present at the output of the buffer.

Revision:	Date:	Change:	Approved:
1	8/23/96	Change R1 to 5K, add U2, C8, C9	JH
2	9/11/96	See above annotation on sheet	

Title: *NPRO-PSL Power Stab. Photodet. PSPD-2*			*LIGO Project* *California Institute of Technology* *Massachusetts Institute of Technology*
Size: B	Number: D96-1247	Revision: 2	J. Heefner
File: I:\CAD\LIGO\NPRO_PSL\PWR_PD.SCH 6-Feb-1997	Time: 09:54:32	Sheet 1 of 1	LIGO

1/14/96
RA+RLS

Pwr. Stab. Amp. trans. fctn.
gain knob: 3.4
gain switch: 10
Source level: 10 mV
(verified no change w/
source at 20mV)



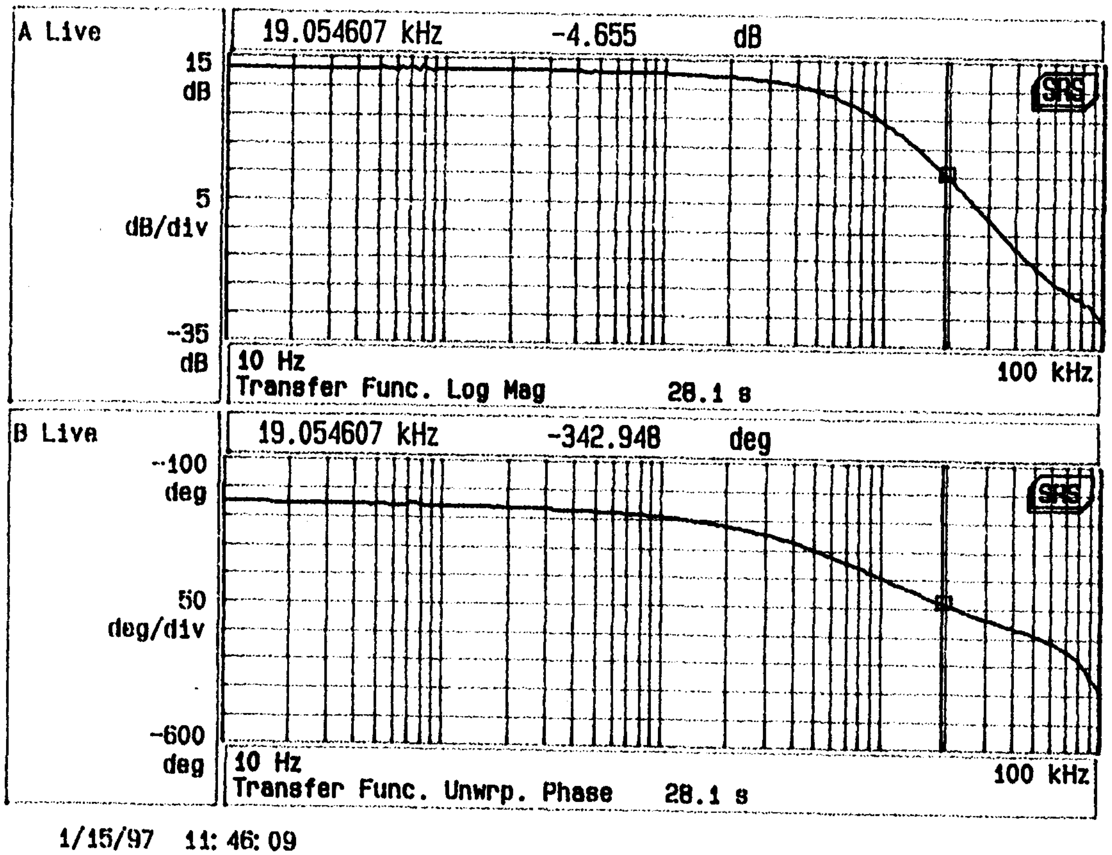
1/14/97 14:45:01

1/15/97
RA+RLS

Transfer Function:
Pwr adjust in to YAG444 out

NE OFF

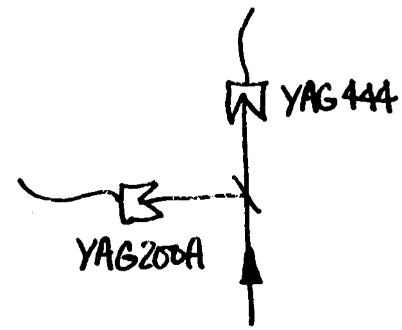
Source level 50 mV.



File TF444BM

File: TF444BP

1/14/97
RA+RLS

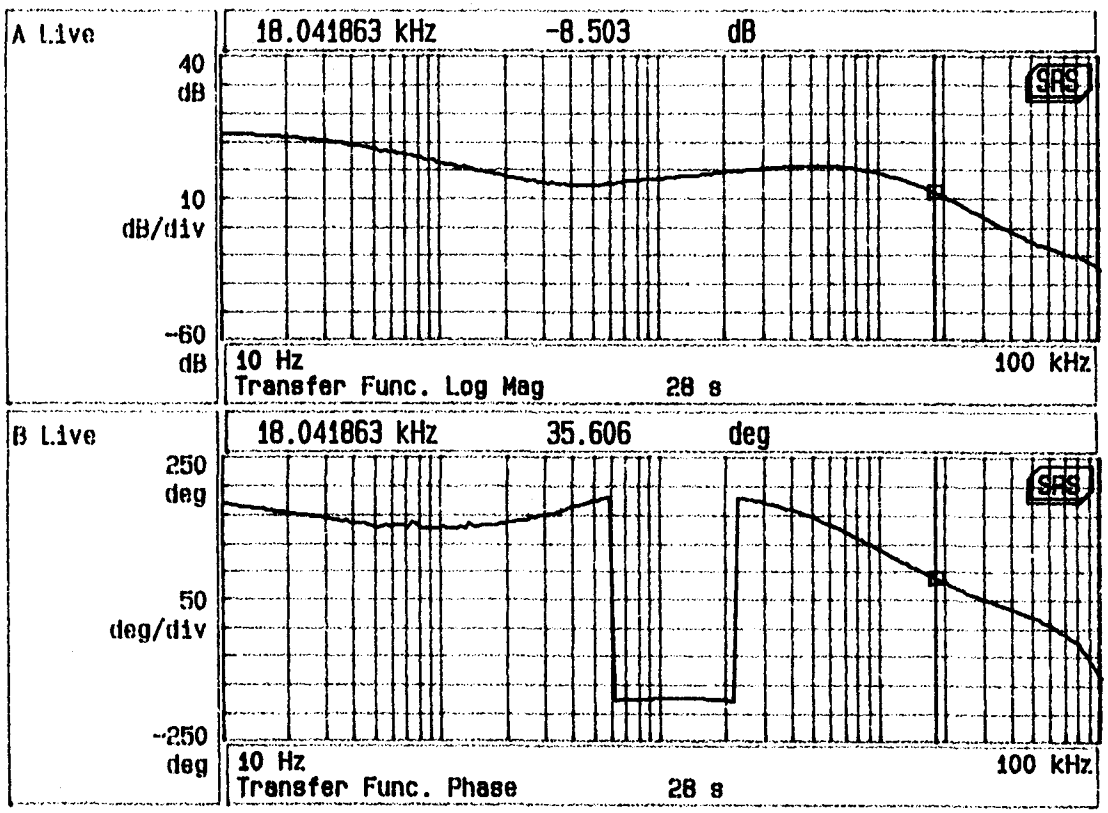


Transfer function: Pwr adjust in to PSPD out for YAG 444 PSPD mounted at 45° wrt table surface in H location

DC level: -7.0 V

Source level: 50mV

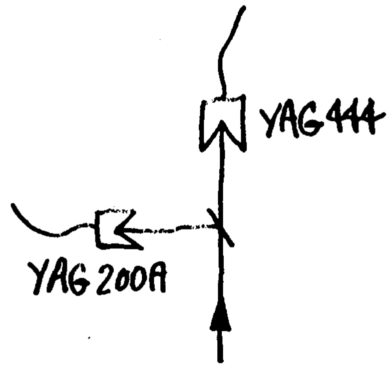
PSPD response: ~ 5V/mA



1/14/97 15:36:33

NE ON

1/14/97
RA & RLS

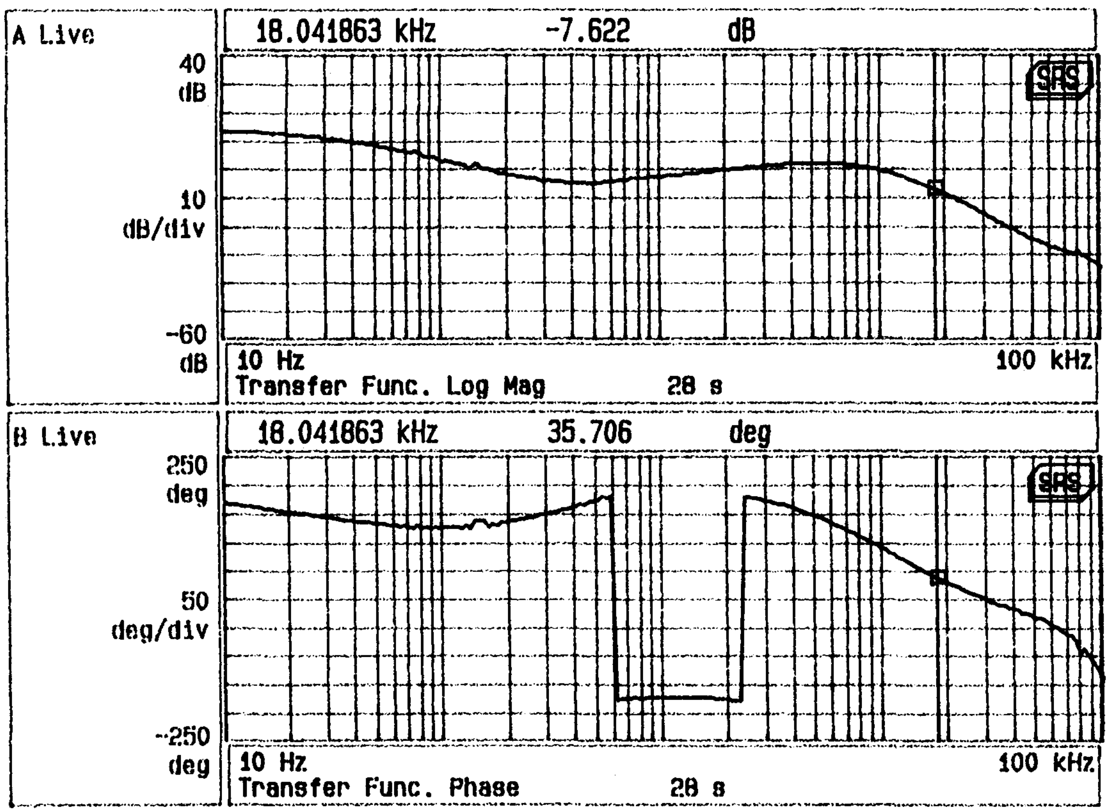


Transfer fctn.: Pwr. adjust iris to PSPD out for YAG200A PSPD mounted at 45° to table surface at ⊥ position

DC level -8.15V

Source level = 50mV

PSPD response ~ 5V/mA



1/14/97 15:27:44

NE ON

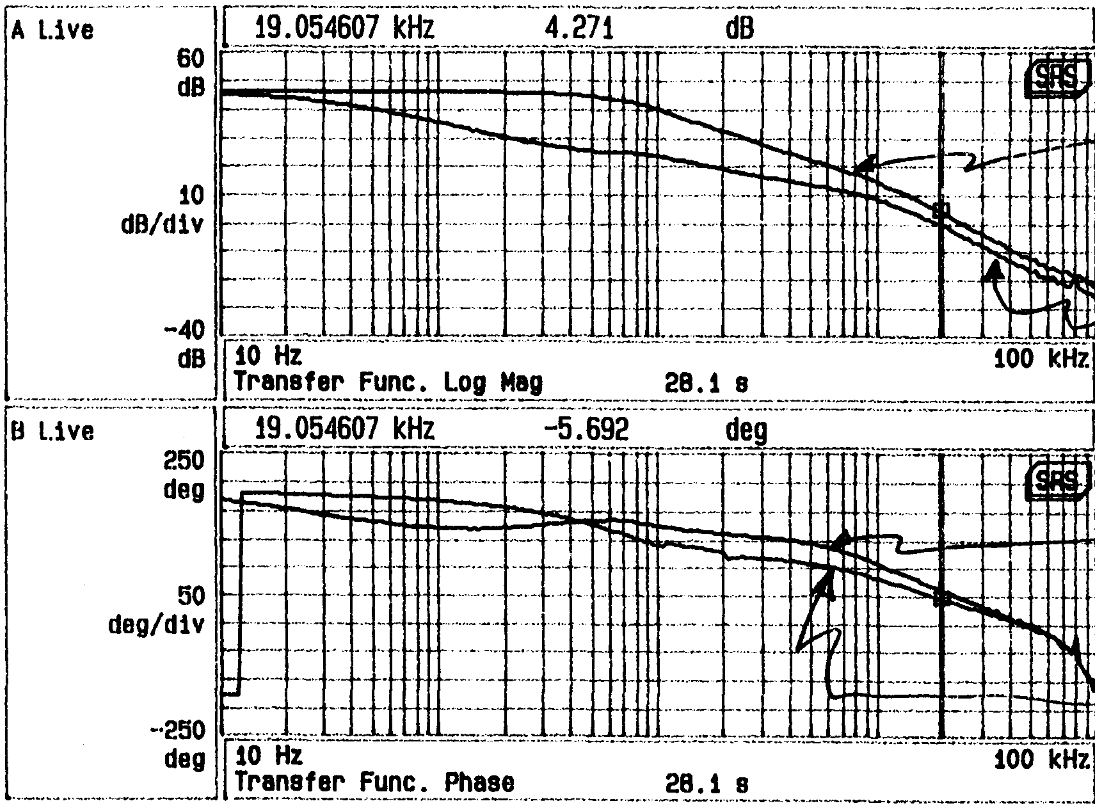
1/15/97
RLS

Pwr Stab Loop Transfer Function

PSA IN to YAG 444 out

Source level: 25 mV (increased above 1kHz)

PSA gain : 3.4 (knob)
: 10 (switch)



NE OFF
file: TF444CM

NE: ON
file TF444AM

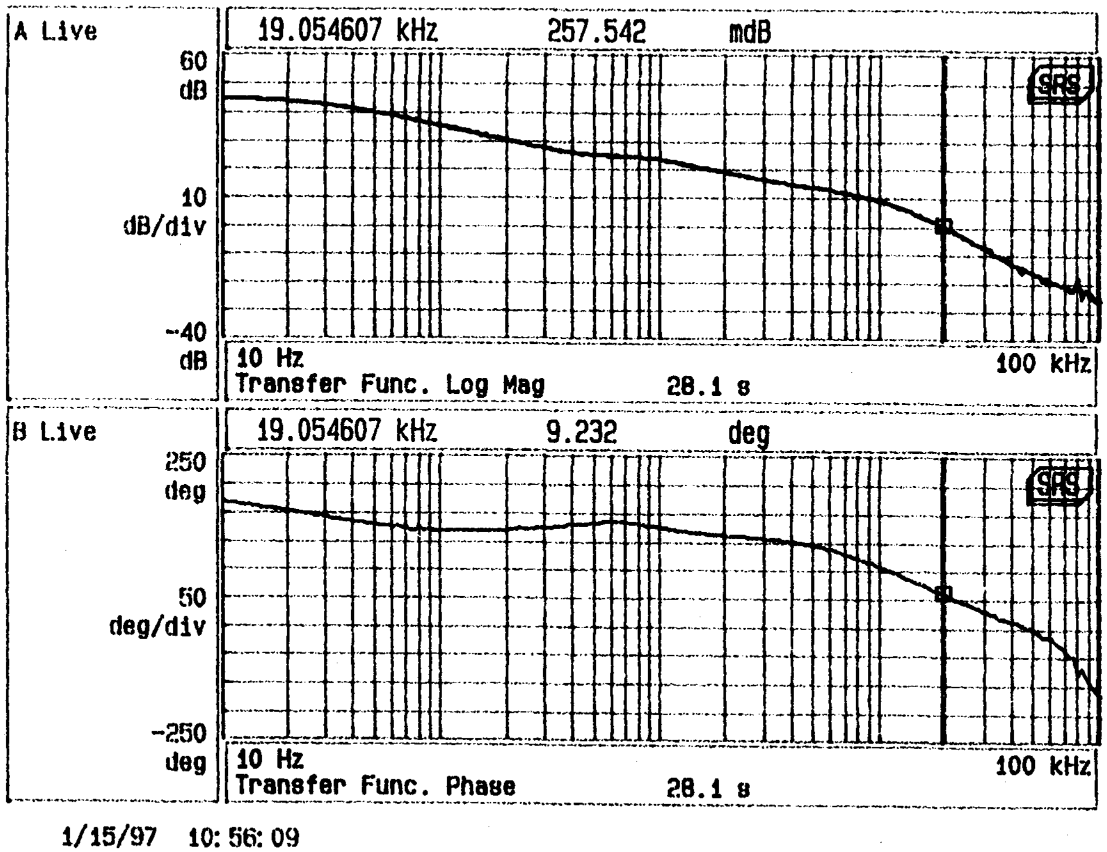
NE ON
file: TF444AP

NE OFF
file: TF444CP

1/15/97 13:45:31

1/15/97
RA+RLS

Pwr Stab Loop Transfer function
PSA IN to YAG200A out
Source level 2.5 mV
PSA gain knob: 3.4
switch: 10



file TF200AM

file TF200AP

NE ON

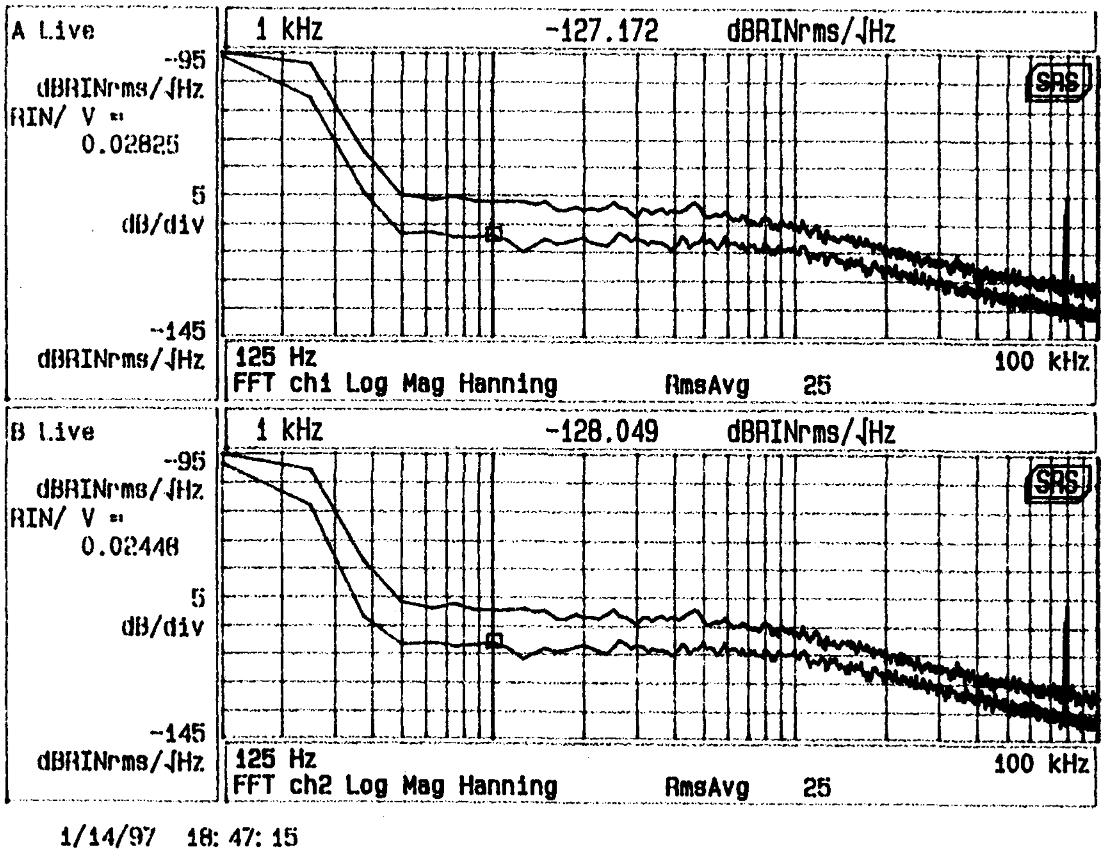
1/14/97
RLS

Free-running Relative Intensity Noise of Model 126 NPRO

Upper traces: NE OFF

lower traces: NE ON

Pwr adjust input term 50 Ω



PSPD w/ YAG 444A

DC out: 7.08×5 V

PSPD w/ YAG 200A

DC out: 8.17×5 V

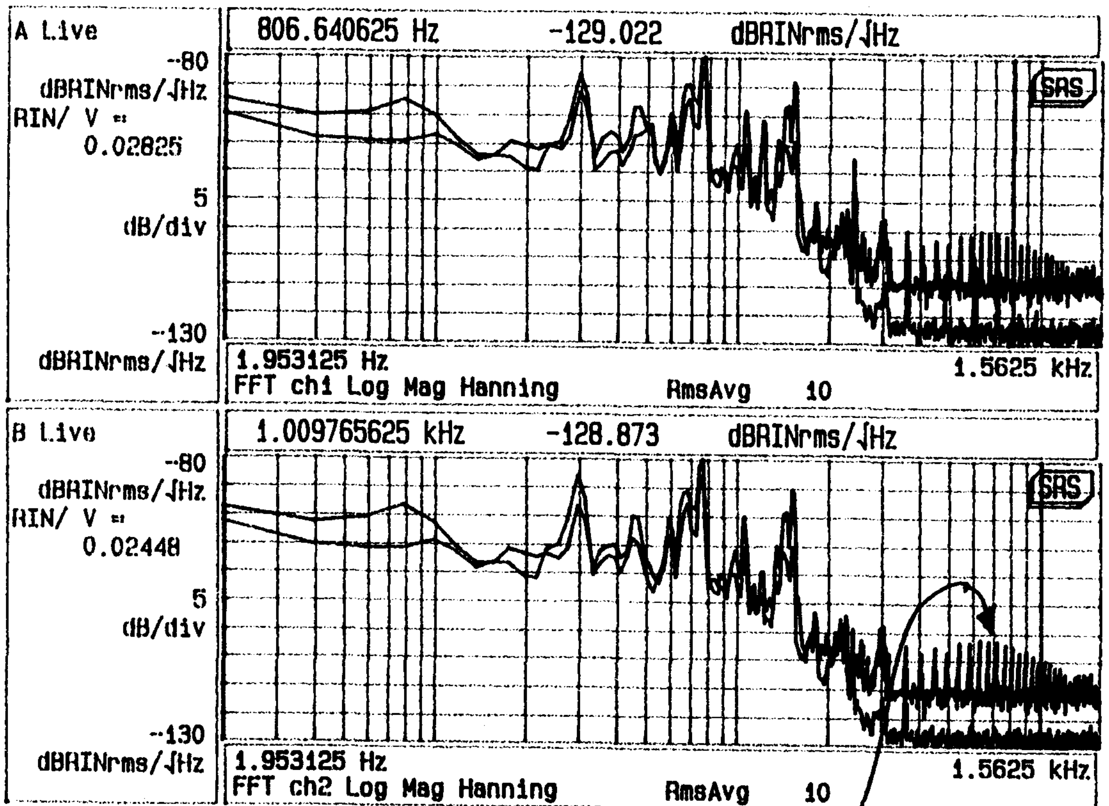
Lights on, AC off

1/14/97
RLS

Same as 18:47 plot except for freq. axis

Settings: FILE RINSET.78S

Pwr. adjust input term 50 Ω



PSPD w/ YAG 444

File: RIN 444.18D

NE OFF

NE ON

PSPD w/ YAG 200mA

File: RIN200.18D

NE OFF

NE ON

1/14/97 19:21:31

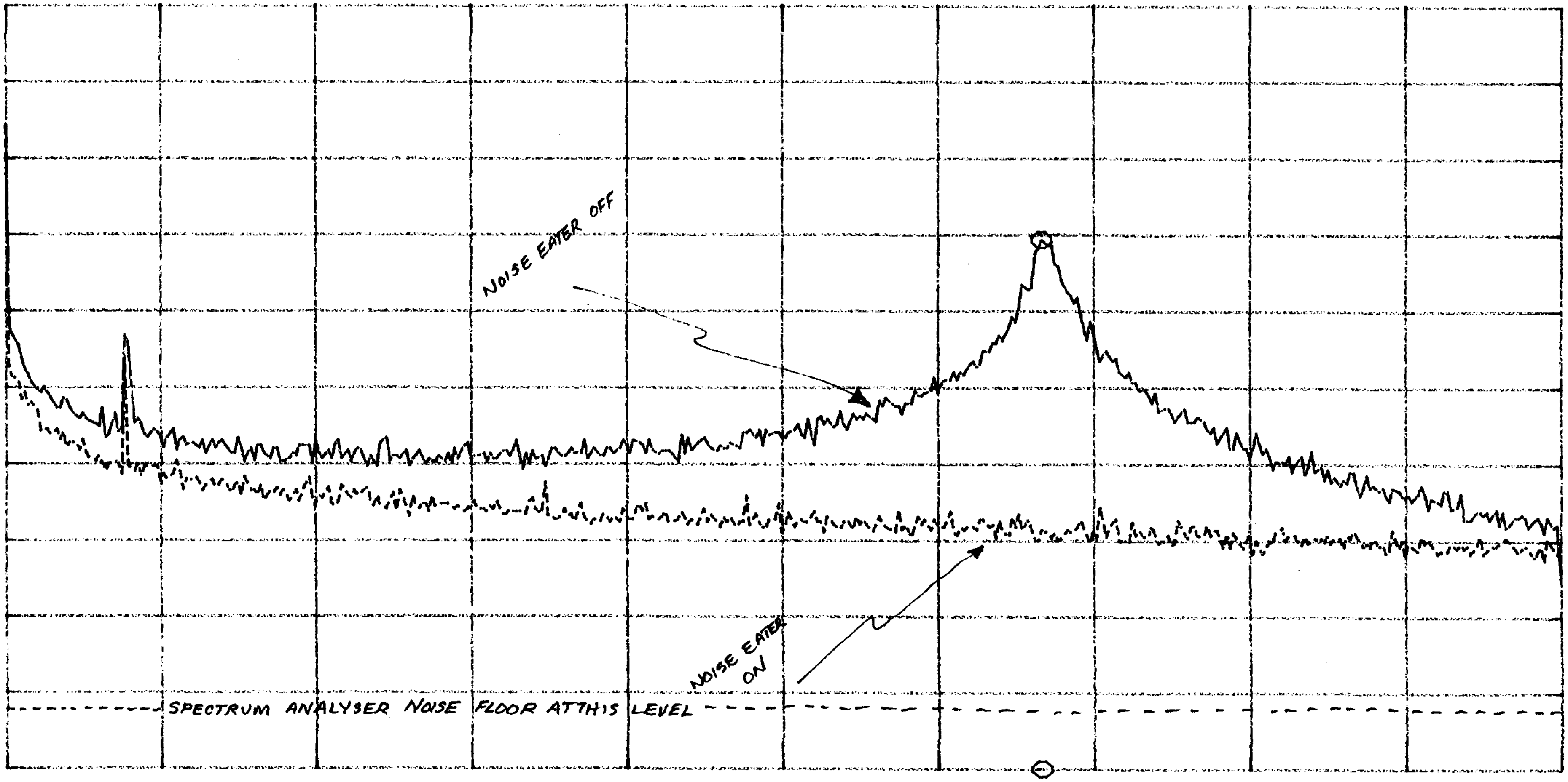
room lights?

Lights ON, AC OFF

126 INTENSITY NOISE AS MEASURED USING YAG 444 PHOTODIODE.
R1 ATTEN. = 10dB ON ANALYSER.

15 JANUARY 1997 R.A.
1606

SPECTRUM
A: REF B: REF ○ MKR 667 533.250 Hz
-10.00 -10.00 MAG -40.8149 dBm
[dBm] [ ] MAG



DIV DIV START 100.000 Hz
10.00 10.00 STOP 1 000 000.000 Hz
RBW: 300 Hz ST: 2.53 min RANGE: R=-10, T=-20dBm

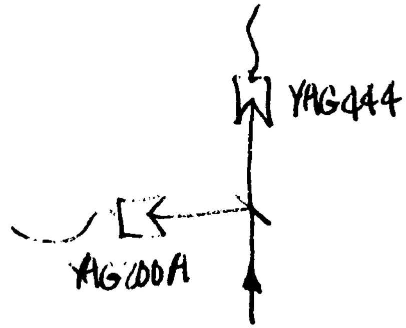
1/14/97 RLS

Stabilized RIN NPRO S/N 17[illegible]

PSA Gain knob: 3.4

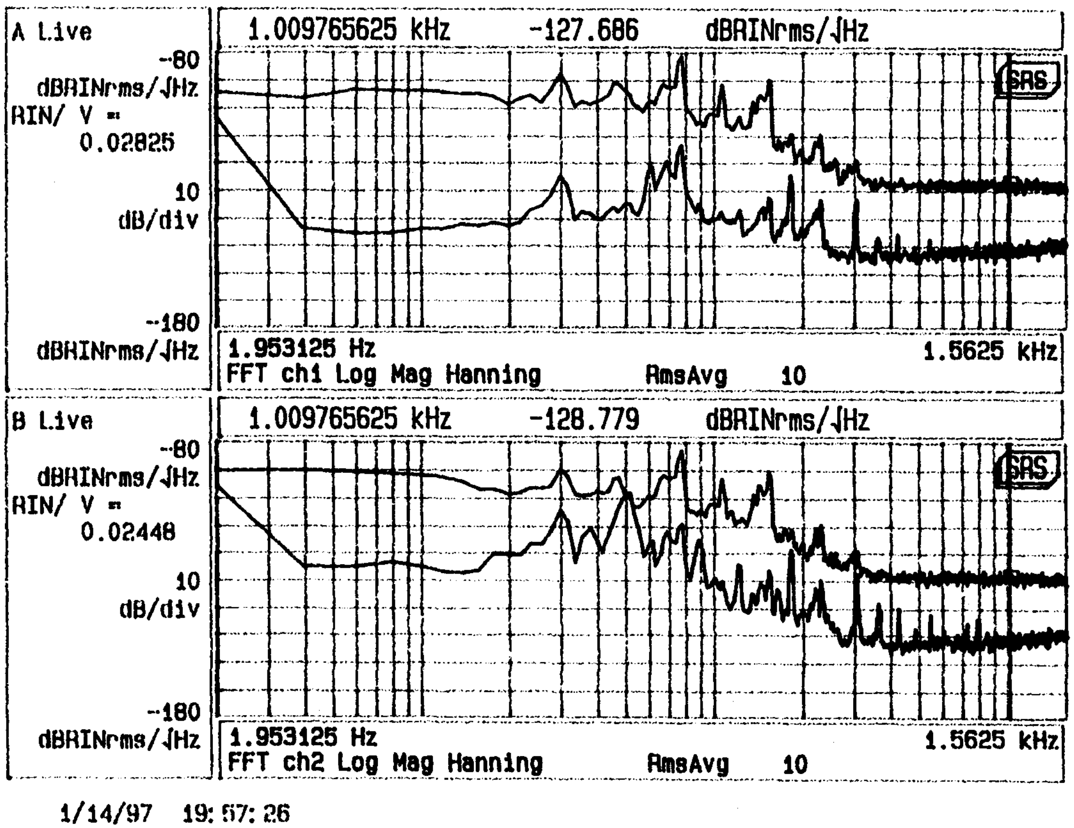
switch: 10

PSA input YAG 444 (in-line)



"inside the loop"

"outside the loop"



PSPD w/ YAG 444

File: RIN444FR (free running)

File: RIN444A

PSPD w/ YAG 200A

File: RIN200FR (free running)

File: RIN200A

Lights OFF, AC OFF, NE ON

1/14/97 RLS

Stabilized RIN NPRO S/N 170

PSA gain knob: 3.4

switch: 10

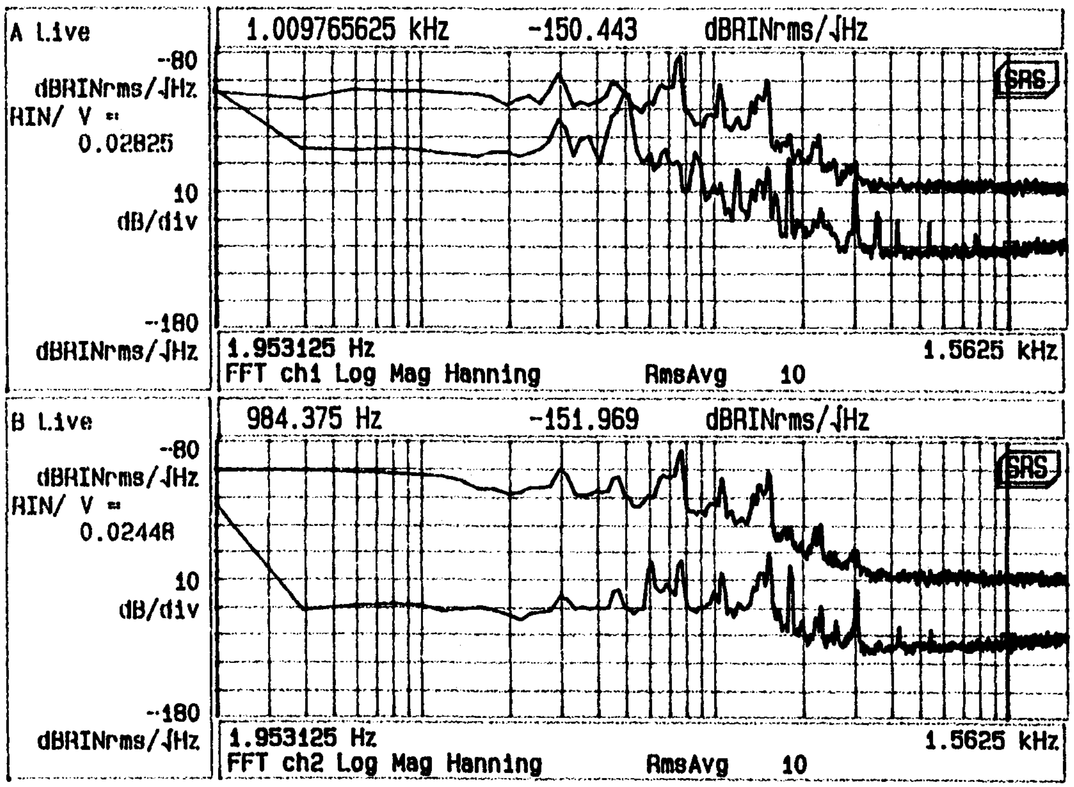
PSA input YAG 200 (perpendicular)
off-line

upper traces: free-running pwr adj input term 50 Ω

lower traces: loop locked

"outside the loop"

"inside the loop"



1/14/97 20: 13: 58

PSPD w/ YAG444

File: RIN444FR

File: RIN200B

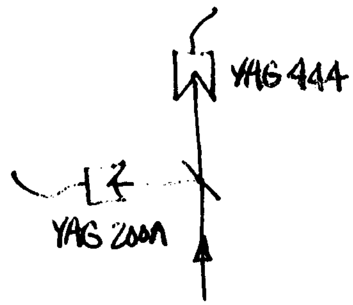
PSPD w/ YAG200A

File: RIN200FR

File: RIN200B

Lights off, AC off, NE ON

1/14/97 RLS



Stabilized RIN NPRO S/N 1?C

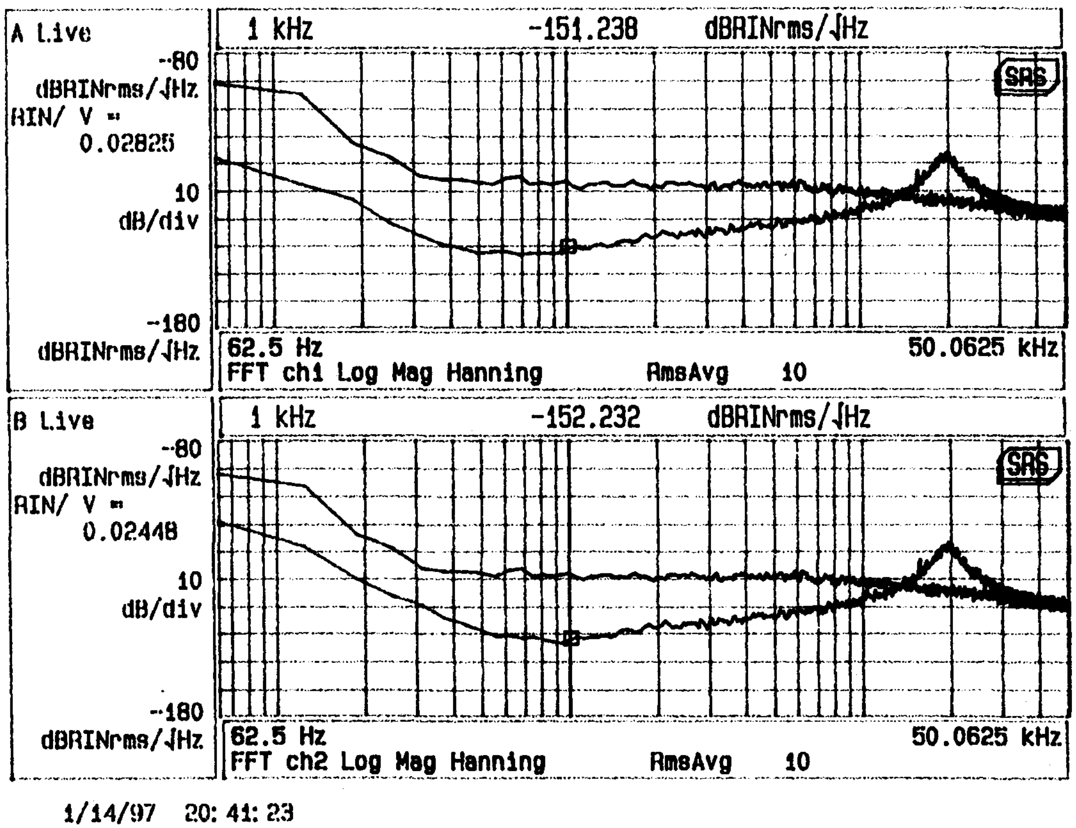
PSA Gain knob: 3.4

Switch ~~pot~~ : 10

PSA input YAG 444 (in-line)

"inside the loop"

"outside the loop"



PSPD w/ YAG 444

upper trace - file RIN44FRA

lower trace - file RIN444C

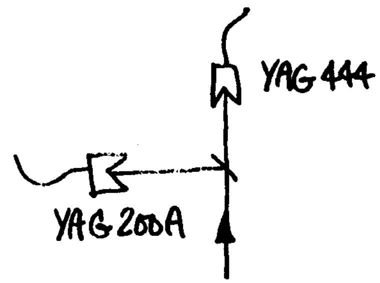
PSPD w/ YAG 200A

upper trace - file RIN20FRA

lower trace - file RIN200C

Lights off, AC off, NE on

1/15/97
RA + RLS



Stabilized RIN NPRO S/N 170

PSA Gain Knob: 3.4
Switch: 10

PSA input YAG 200A (perpendicular

"outside" loop

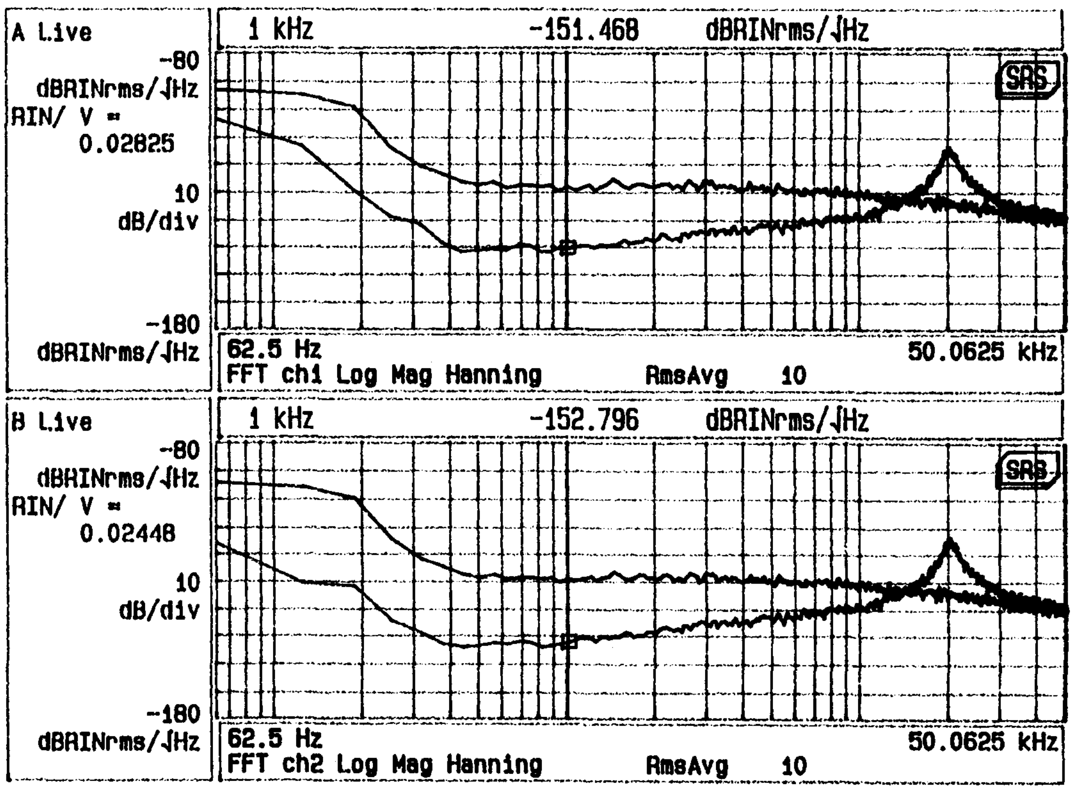
PSPD w/ YAG 444

file: RIN 444D

"inside" loop

PSPD w/ YAG 200A

file: RIN200D

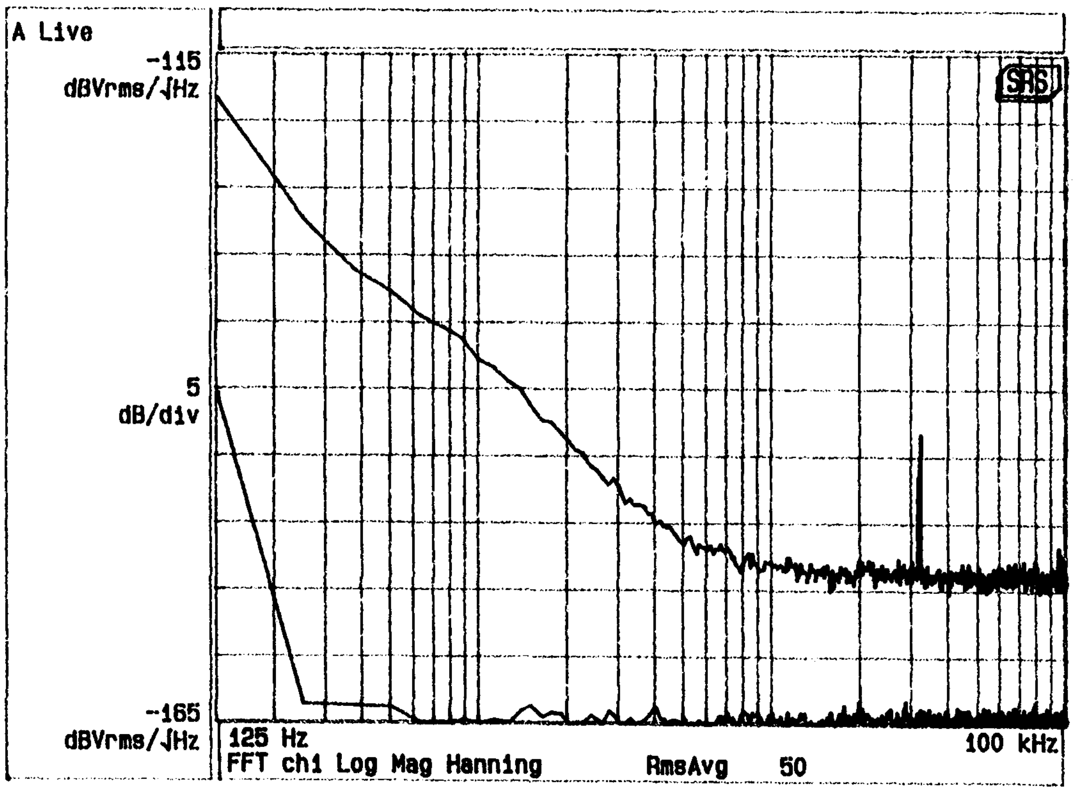


1/15/97 10: 15: 04

Lights off, AC off, NE ON

1/16/96
RA + RLS

PSA output noise does not increase PSPD output noise when loop is open. ie. PSPD output noise w/ PSA input term in 50 Ω same as w/ PSPD input term in 50 Ω (PSA disconnected).



1/16/97 17: 15: 52

PSA output noise
w/ standard gain settings
switch - 10
knob - 3.4

PSA out, input term in 50 Ω
file: PSANoutA

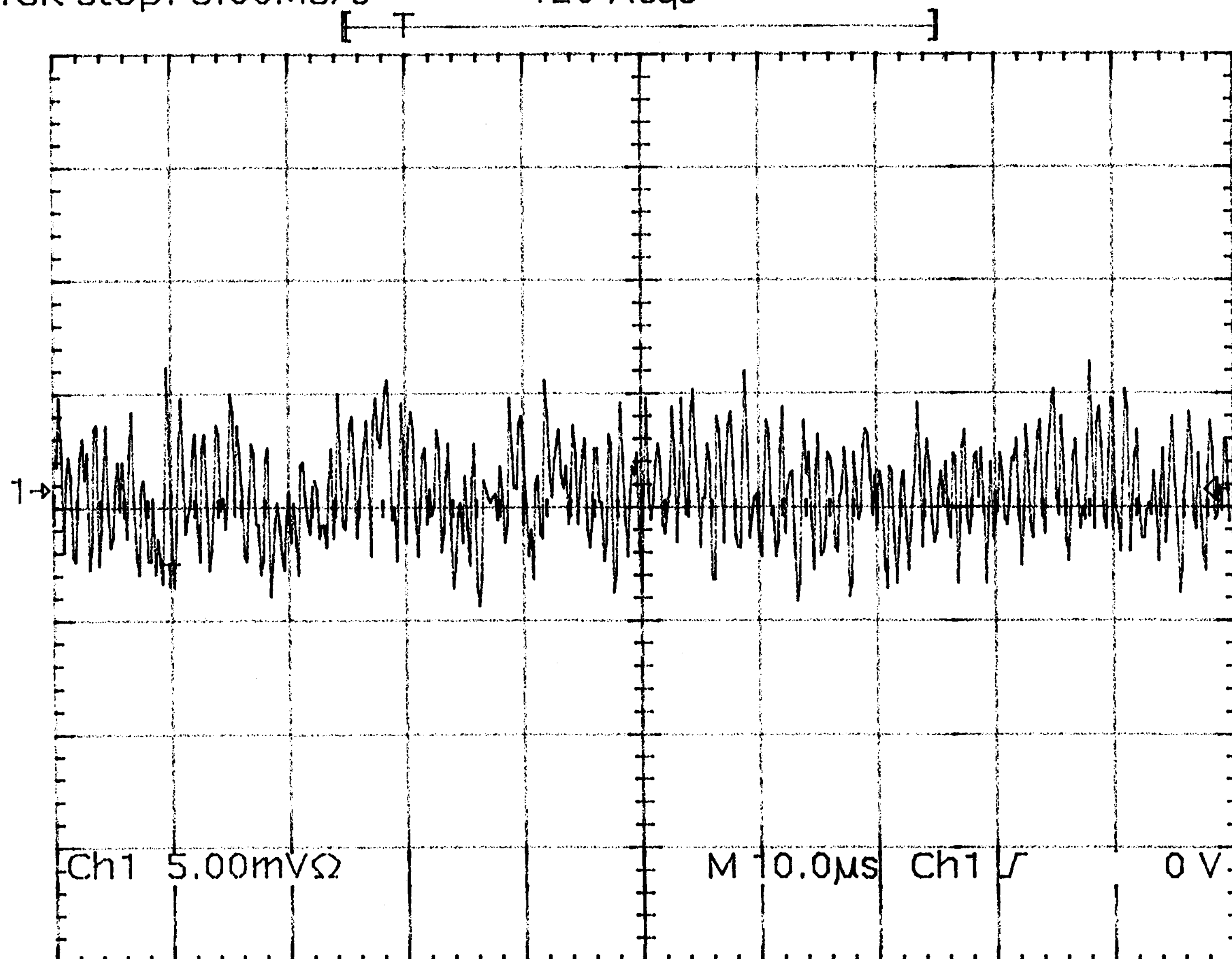
FFT input terminated in 50 Ω

PSA input w/ loop locked using YAG444 PSPD
standard gain settings (34 x 10)

(lights on)

1/16/96
RAY RLS
17:30.

Tek Stop: 5.00MS/s 126 Acqs

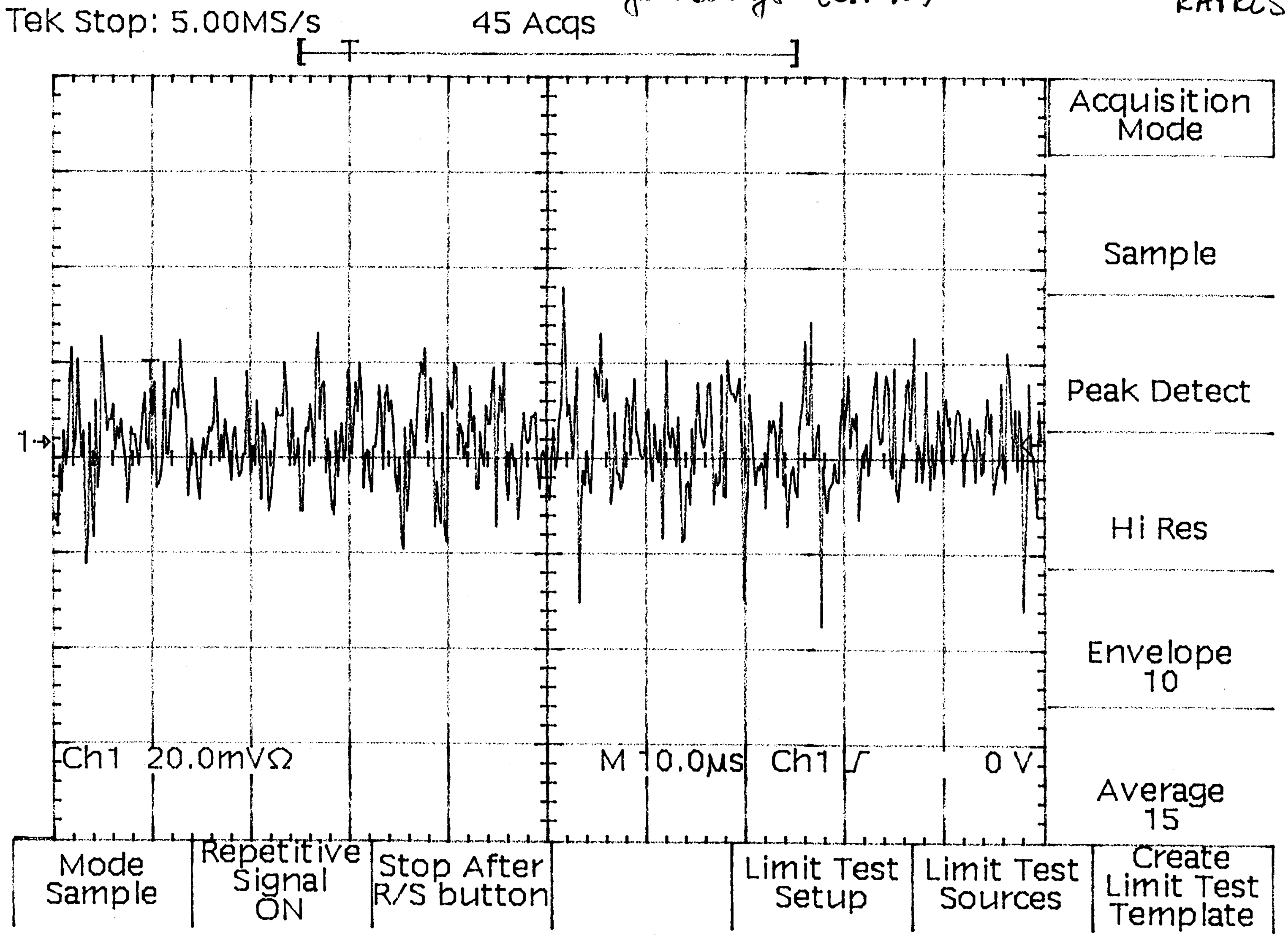


Hardcopy Port
GPIB
RS-232
Centronics
File

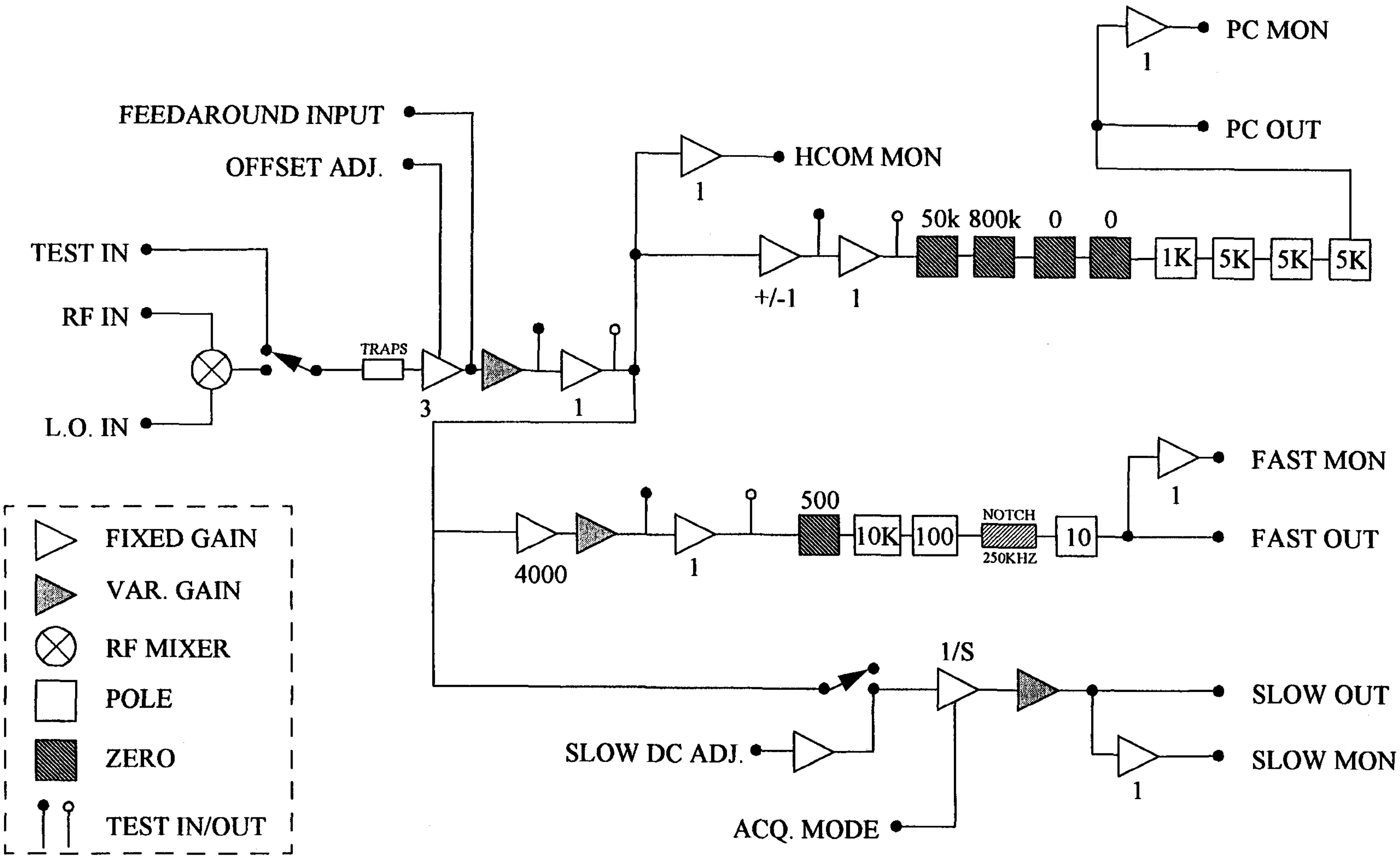
Format HPGL	Layout Landscape		Port GPIB	Clear Spool		File Utilities

Pwr. adjust input w/ loop locked using YAG 444
Standard gain settings (3.4x10)

1/16/96
17:45
RA+RCS

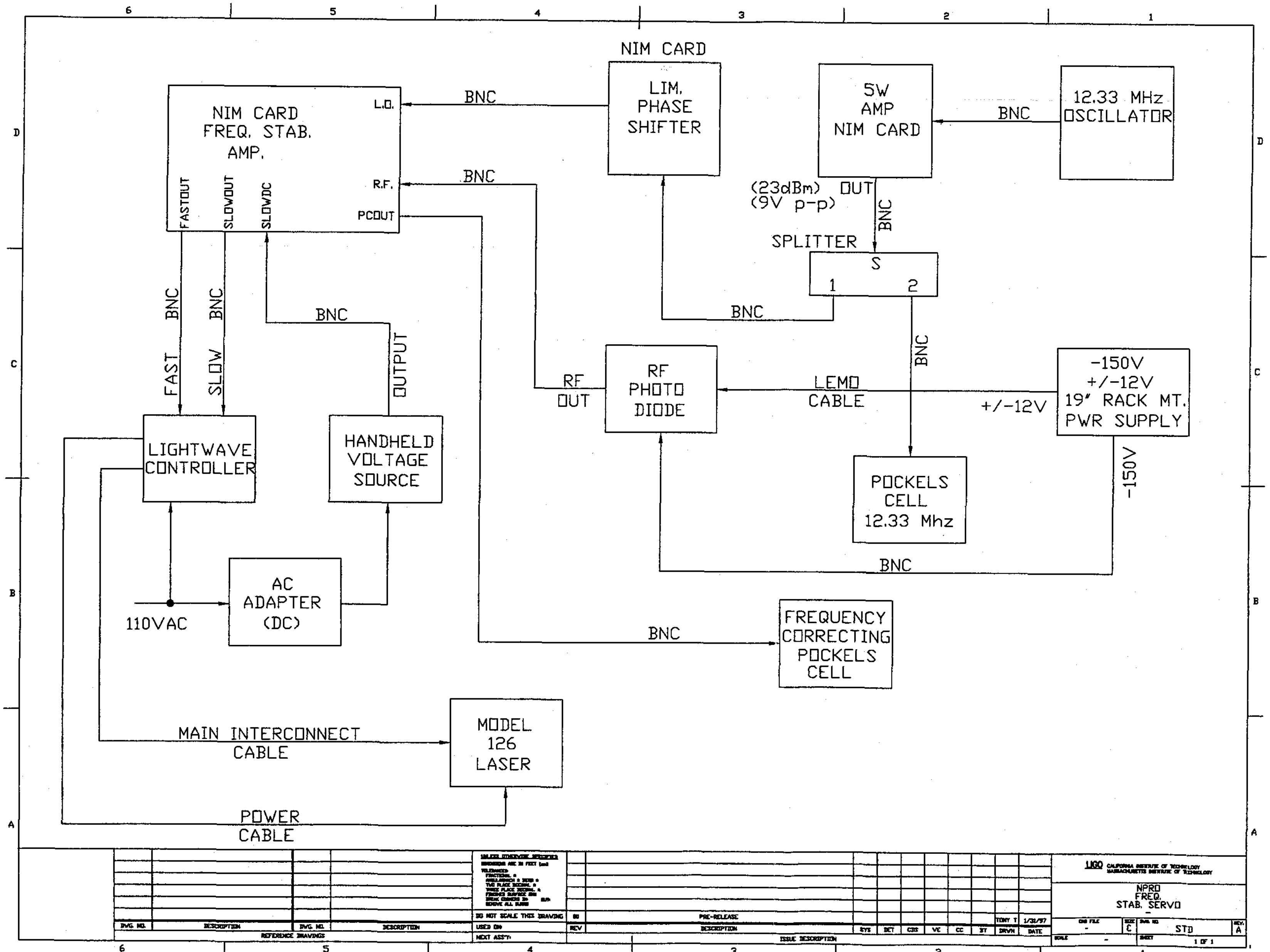


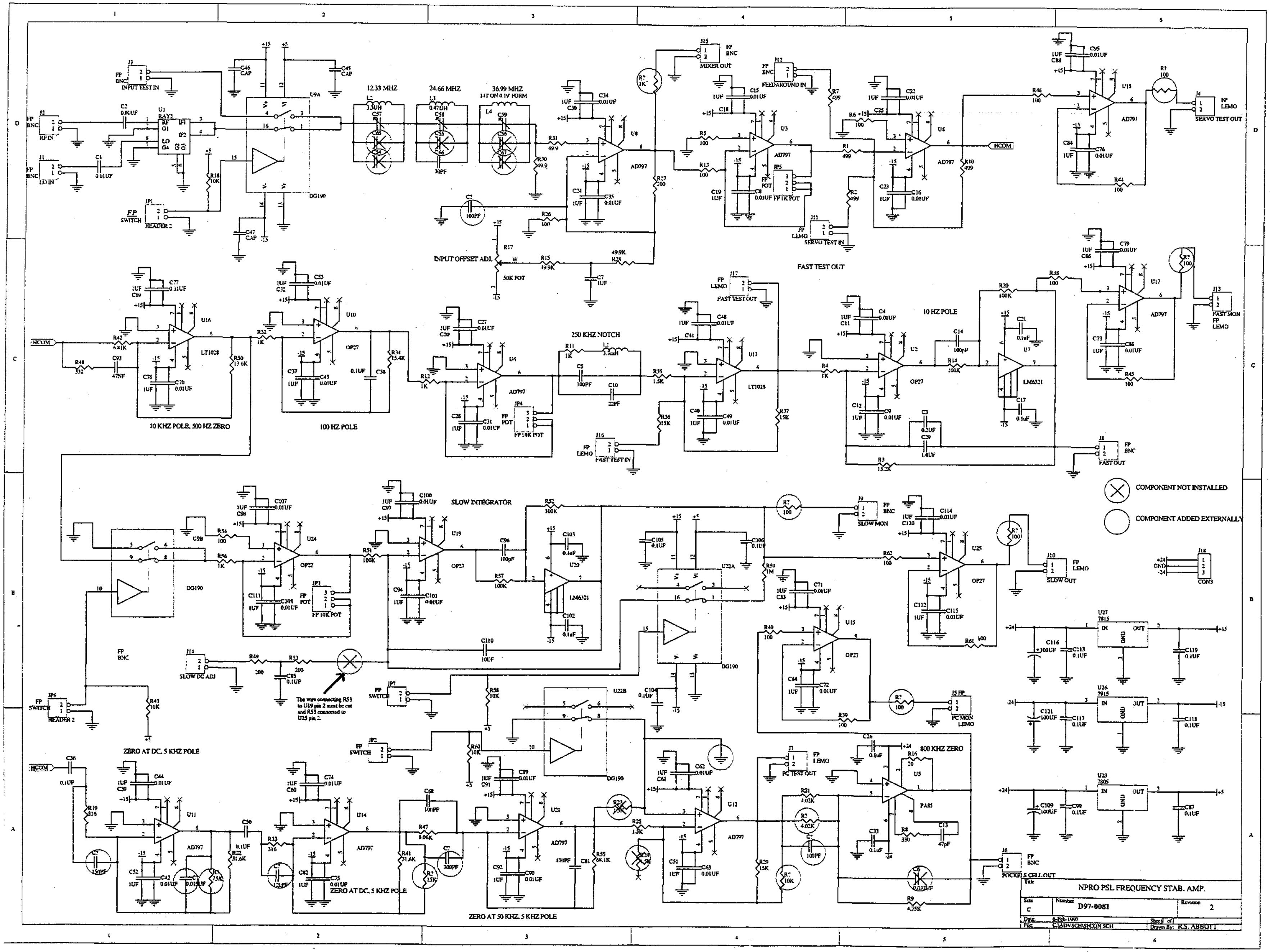
NPRO FREQ. STAB. SERVO



Front Panel Features For NPRO Servo Electronics.

1. **SLOWMON**: Buffered monitoring point for the output of the slow loop.
2. **FASTTO**: Output of fast loop test amplifier (U13).
3. **FASTTI**: Input to fast loop test amplifier (U13).
4. **SLOW ADJ**: Slow loop gain adjust pot.
5. **FAST ADJ**: Fast loop gain adjust pot.
6. **FASTOUT**: Output of the fast loop (U7).
7. **MIXROUT**: Output of the first stage after the mixer (U8), through a 1K resistor. This results in a gain of 5.2dB from that at the plane of the mixer itself.
8. **PCTO**: Pockels cell test output (U12).
9. **SLOW DC**: DC adjustment input for the slow loop. This input is used in initial locking to align laser frequency to the desired value in preparation for lock acquisition.
10. **FASTMON**: Buffered monitoring point for output of the fast loop.
11. **PCOUT**: Output of the pockels cell loop.
12. **FEEDIN**: Feed around input.
13. **MAINTI**: Used for overall closed loop transfer function measurement. Input to U4.
14. **PCMON**: Buffered monitoring point for output of the pockels cell loop.
15. **SLOWOUT**: Output of the slow loop (U25).
16. **MAINTO**: Output used in conjunction with MAINTI for closed loop transfer function verification. Output of U18.
17. **INTI**: Test input that when the RFSW is in the "ON" position, allows for injection of signals at the output of the mixer. Used for aligning the traps among other things.
18. **AQ/SLAQ**: Switch to go between integrator (SLAQ) mode and reduced gain mode (AQ) for the slow loop. Used during lock acquisition.
19. **CLOSE/SLOW LOOP**: Switch used to close the feedback path (CLOSE) for the slow loop electronics. The switch should be closed during normal locked operation. When the loop loses lock, the loop must be taken to the downward position to remove feedback to the slow actuator.
20. **ON/RFSW**: Switch used to select between INTI (ON) and normal mixer feedback path (U9A).
21. **INADJ**: Adjustment of the overall electronics gain or common gain. This will change the gain of all paths simultaneously.
22. **RF**: Input from the RF Photodiode.
23. **LO**: Local Oscillator input from reference phase shifter. Nominal level of 9 V P-P or 23 dBm.

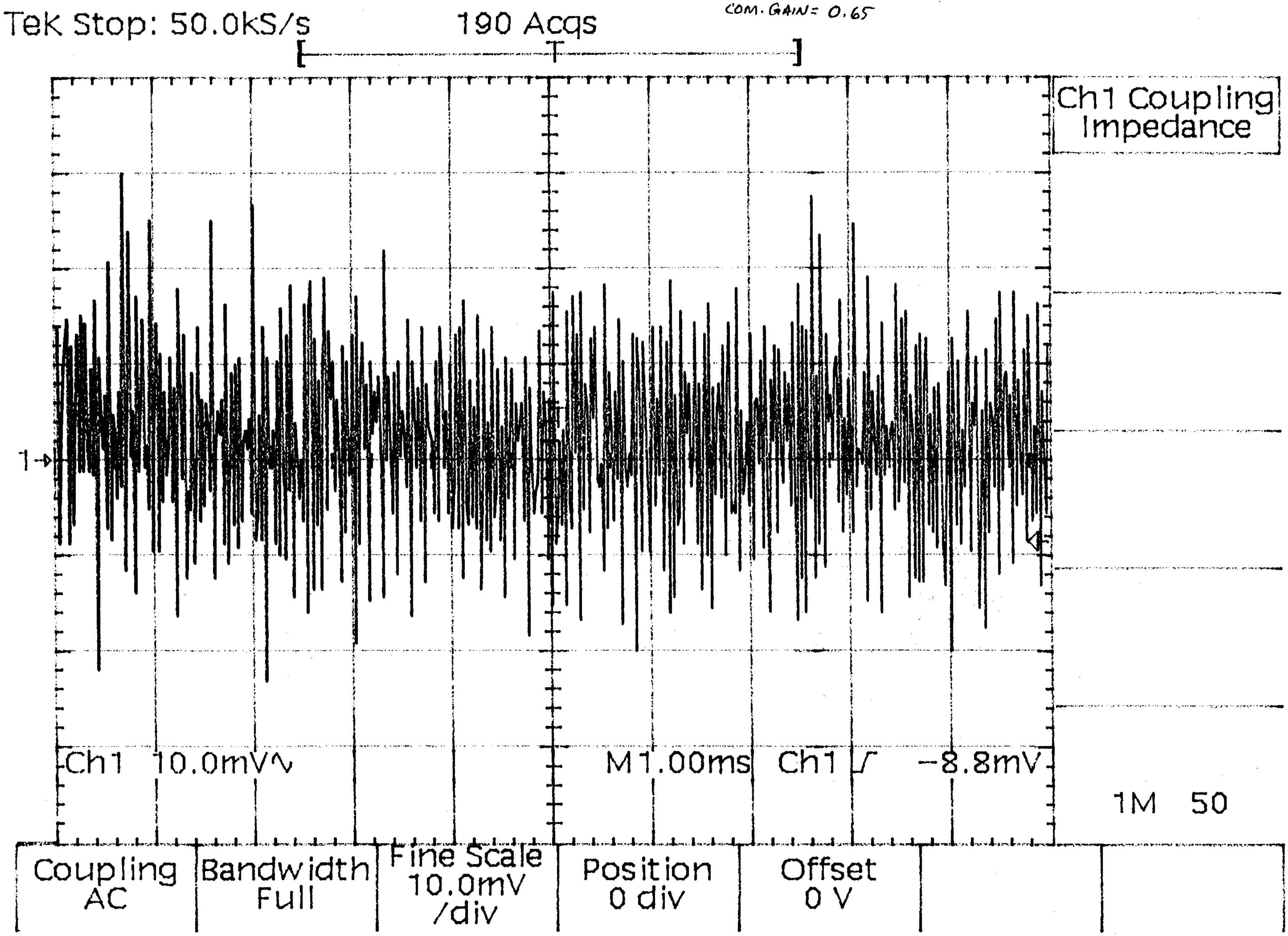

NIM CARD
FREQ. STAB.
AMP.
L.O.
R.F.
PCOUT
FASTOUT
SLOWOUT
SLOWDC
NIM CARD
LIM.
PHASE
SHIFTER
BNC
5W
AMP
NIM CARD
12.33 MHz
OSCILLATOR
(23dBm) OUT
(9V p-p)
SPLITTER
S
1
2
FAST
SLOW
OUTPUT
RF
OUT
RF
PHOTO
DIODE
LEMO
CABLE
-150V
+/-12V
19" RACK MT.
PWR SUPPLY
+/-12V
-150V
LIGHTWAVE
CONTROLLER
HANDHELD
VOLTAGE
SOURCE
POCKELS
CELL
12.33 Mhz
AC
ADAPTER
(DC)
110VAC
FREQUENCY
CORRECTING
POCKELS
CELL
MAIN INTERCONNECT
CABLE
MODEL
126
LASER
POWER
CABLE
PRE-RELEASE
TONY T 1/31/97
LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
NPRO
FREQ.
STAB. SERVO
C
STD
A
1 OF 1



12.33 MHZ
24.66 MHZ
36.99 MHZ
14T ON 0.1" FORM
RF IN
LO IN
INPUT TEST IN
MIXER OUT
FEEDAROUND IN
SERVO TEST OUT
SERVO TEST IN
FAST TEST OUT
INPUT OFFSET ADJ.
50K POT
10 KHZ POLE, 500 HZ ZERO
100 HZ POLE
250 KHZ NOTCH
10 HZ POLE
FAST MON
FAST OUT
FAST TEST IN
COMPONENT NOT INSTALLED
COMPONENT ADDED EXTERNALLY
SLOW INTEGRATOR
SLOW MON
SLOW OUT
SLOW DC ADJ
The wire connecting R53 to U19 pin 2 must be cut and R53 connected to U25 pin 2.
PC MON
PC TEST OUT
800 KHZ ZERO
ZERO AT DC, 5 KHZ POLE
ZERO AT 50 KHZ, 5 KHZ POLE
POCKELS CELL OUT
NPRO PSL FREQUENCY STAB. AMP.
D97-0081
Revision 2
Date: 6-Feb-1997
File: C:\ADVSCH\SHCON.SCH
Drawn By: R.S. ABBOTT

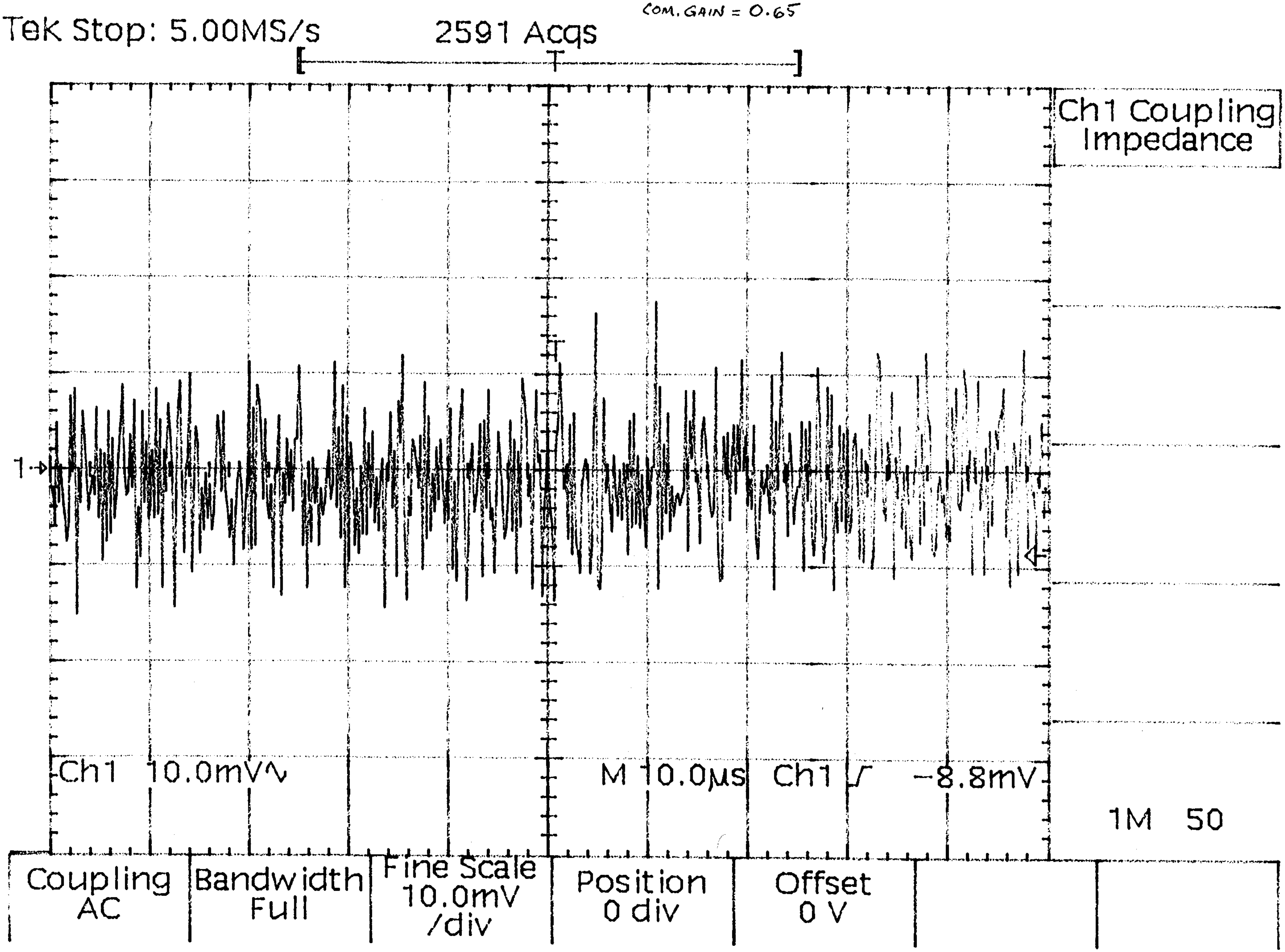
23 JAN 1997 RA

TIME SERIES OF FAST ACTUATOR DURING
LOCK OF FSS. SLOW GAIN = 0.4, FAST GAIN = 1.04
COM. GAIN = 0.65



23 JAN 1997 RA

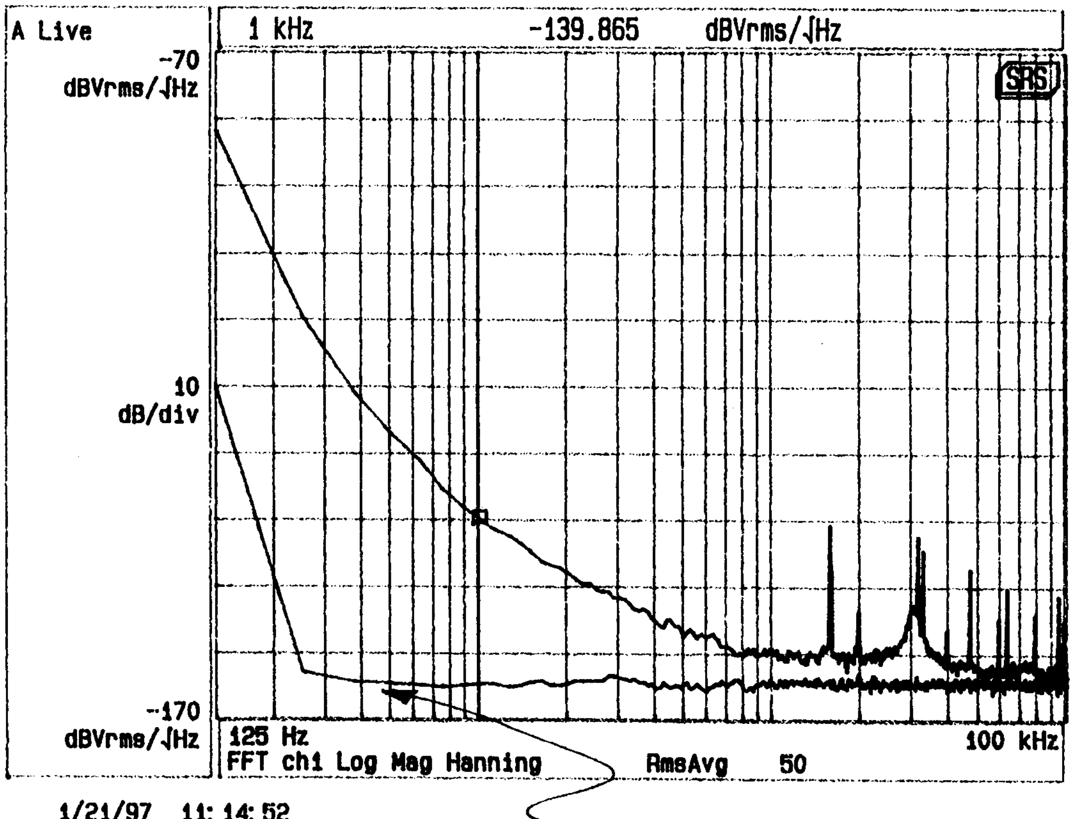
TIME SERIES OF FAST ACTUATOR DURING
LOCK OF FSS. SLOW GAIN = 0.4, FAST GAIN = 1.04
COM. GAIN = 0.65



11:15 21 JAN 97 RA

OUTPUT REFERED NOISE OF FAST LOOP IN FSS. FAST GAIN = 1.04, COM GAIN = ~~0.65~~ 0.9
IN = 50Ω. TAKEN @ FAST OUT. RFSW "ON".

FILENAME: F3NOA.

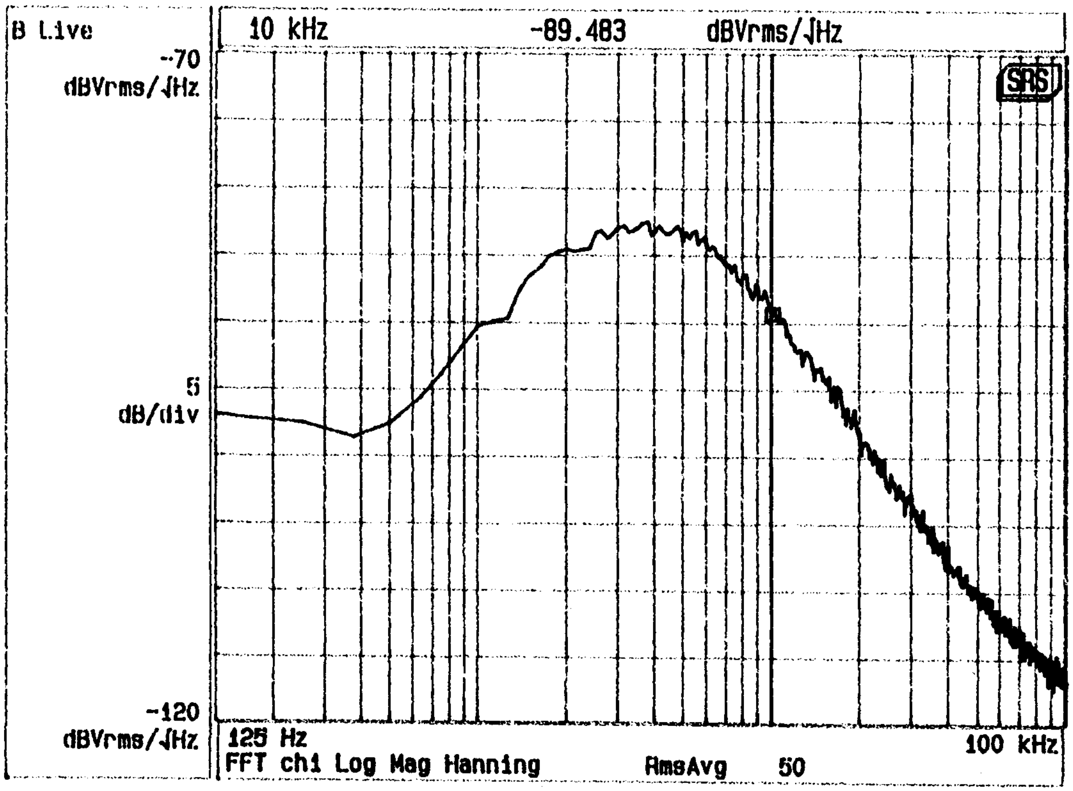


ANALYSER NOISE FLOOR

21 JAN 97 RA

OUTPUT REFERRED NOISE OF FSS POCKELS CELL LOOP. COM GAIN = 0.9
INT1 = 50Ω RFSW ON.

FILENAME: FSPCNO.



1/21/97 15: 08: 14

15:30 23 JAN 97 RA

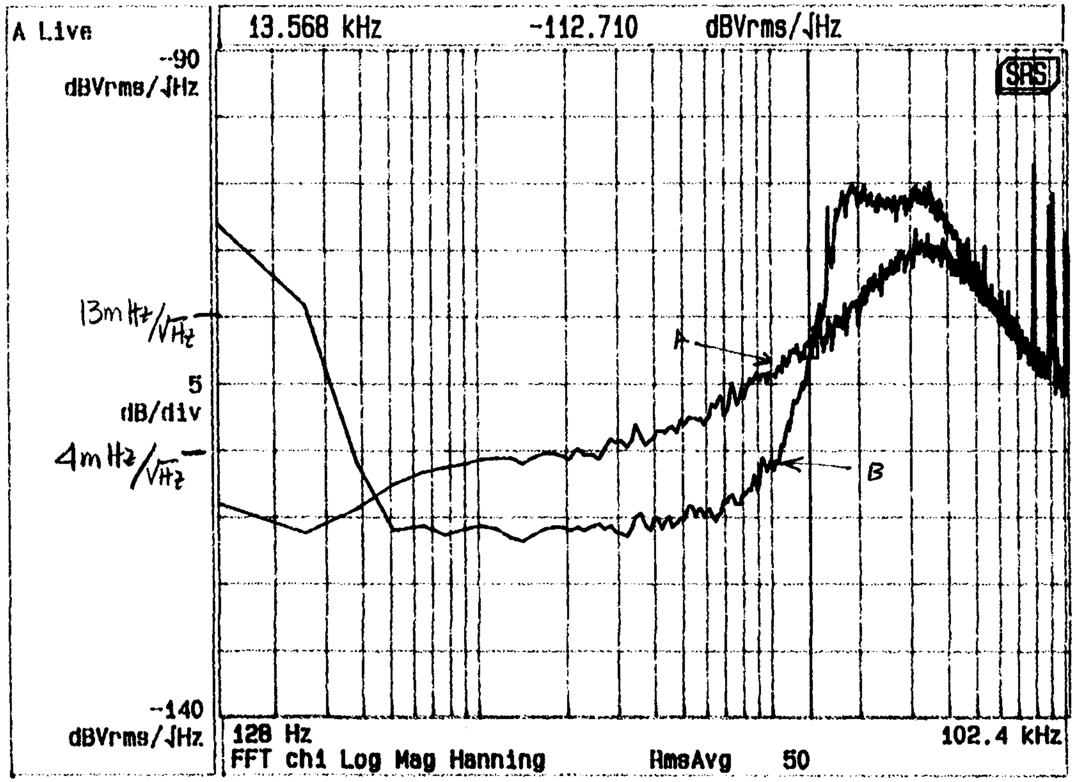
HIGH FREQUENCY RESIDUAL NOISE OF FSS. TRACE "A" IS PSA OFF. TRACE "B" IS PSA ON.

FREQ. DETECTOR GAIN AT THIS PLANE = $\frac{1 \text{ VOLT}}{4.15 \text{ KHz}}$ => -112 dBc = 10 mHz / $\sqrt{Hz}$

SETTINGS: FSS: SLOW = 0.4, FAST = 1.04, COM = 0.65

PSA GAIN = 3.4, OFFSET = ~~..~~ 5.0 ~~....~~ (NO OFFSET)

TAKEN @ MIXER TEST PORT



1/23/97 15: 29: 14

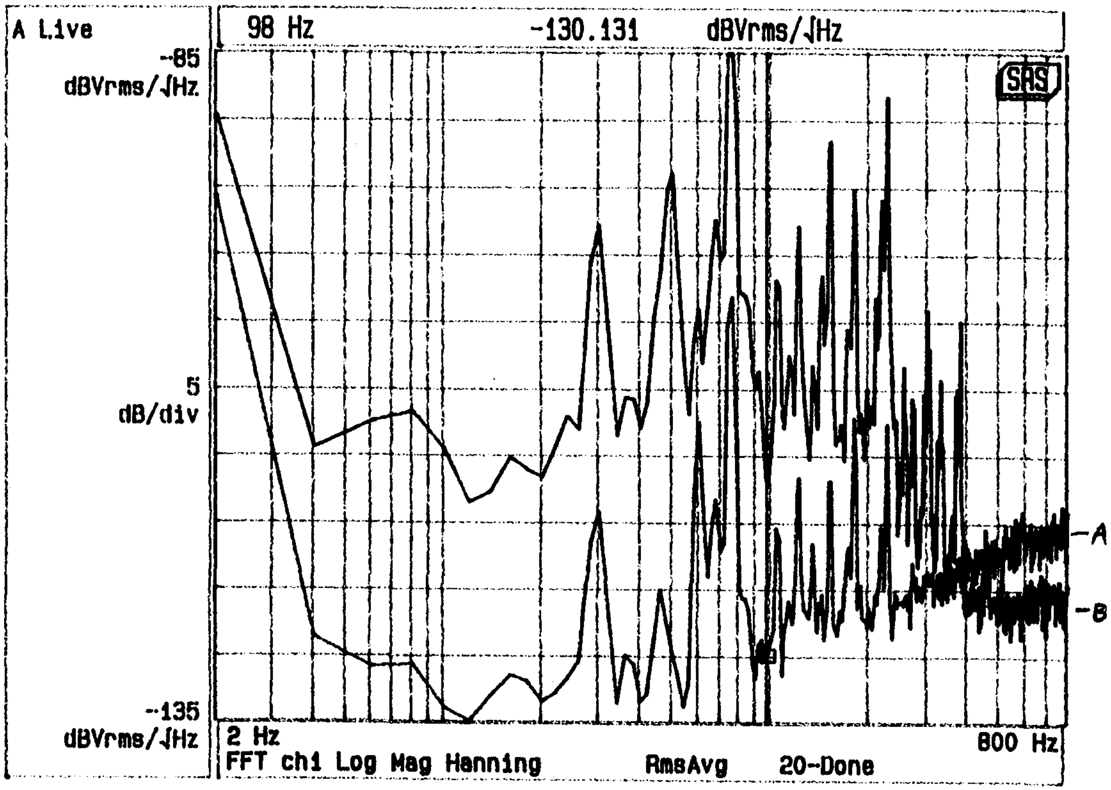
15:00 23 JAN 97 RA

LOW FREQUENCY RESIDUAL NOISE OF FSS. TRACE "A" IS PSA (POWER STAB. AMP) OFF. TRACE "B" IS PSA ON. FREQ. DET. GAIN AT THIS PLANE = $\frac{1\ \text{VOLT}}{4.15\ \text{KHz}}$ => $\frac{-112\ \text{dBVRMS}}{\sqrt{\text{Hz}}} = \frac{10\ \text{mHz}}{\sqrt{\text{Hz}}}$

SETTINGS: FSS - SLOW = 0.4, FAST = 1.04, COM = 0.65

PSA - GAIN = 3.4, OFFSET = 5.0 (NO OFFSET)

TAKEN @ MIXER TEST PORT.

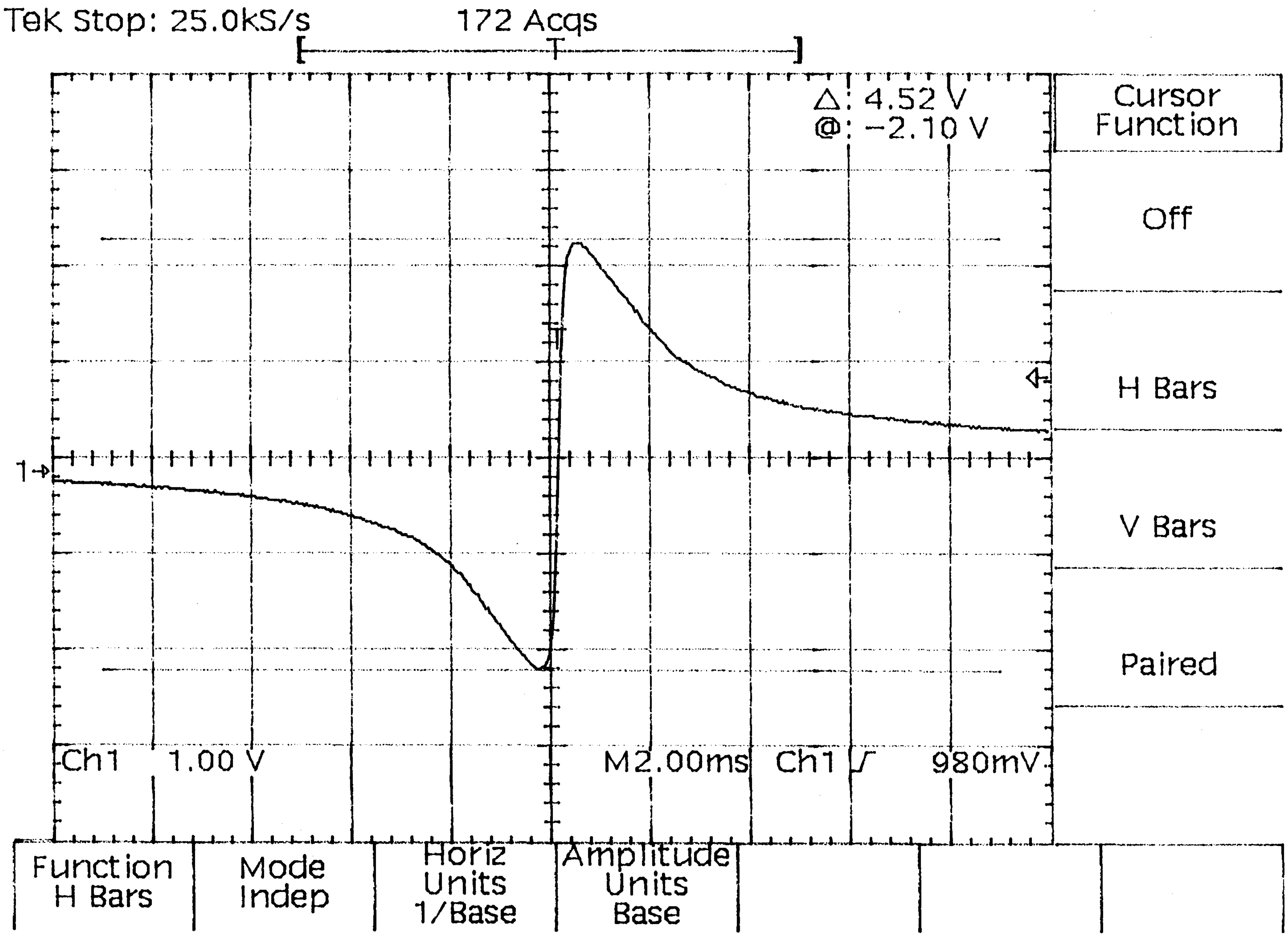


1/23/97 11: 42: 21

13:30 22 JAN 97 RA

FSS FREQUENCY DETECTOR DISCRIMINANT. SWEPT FAST IN @ 10Hz 2V P-P

OUTPUT TAKEN @ MIXER TEST PORT. VISIBILITY = 88%. F. DET GAIN = $\frac{1\ \text{VOLT}}{4.15\ \text{KHz}}$



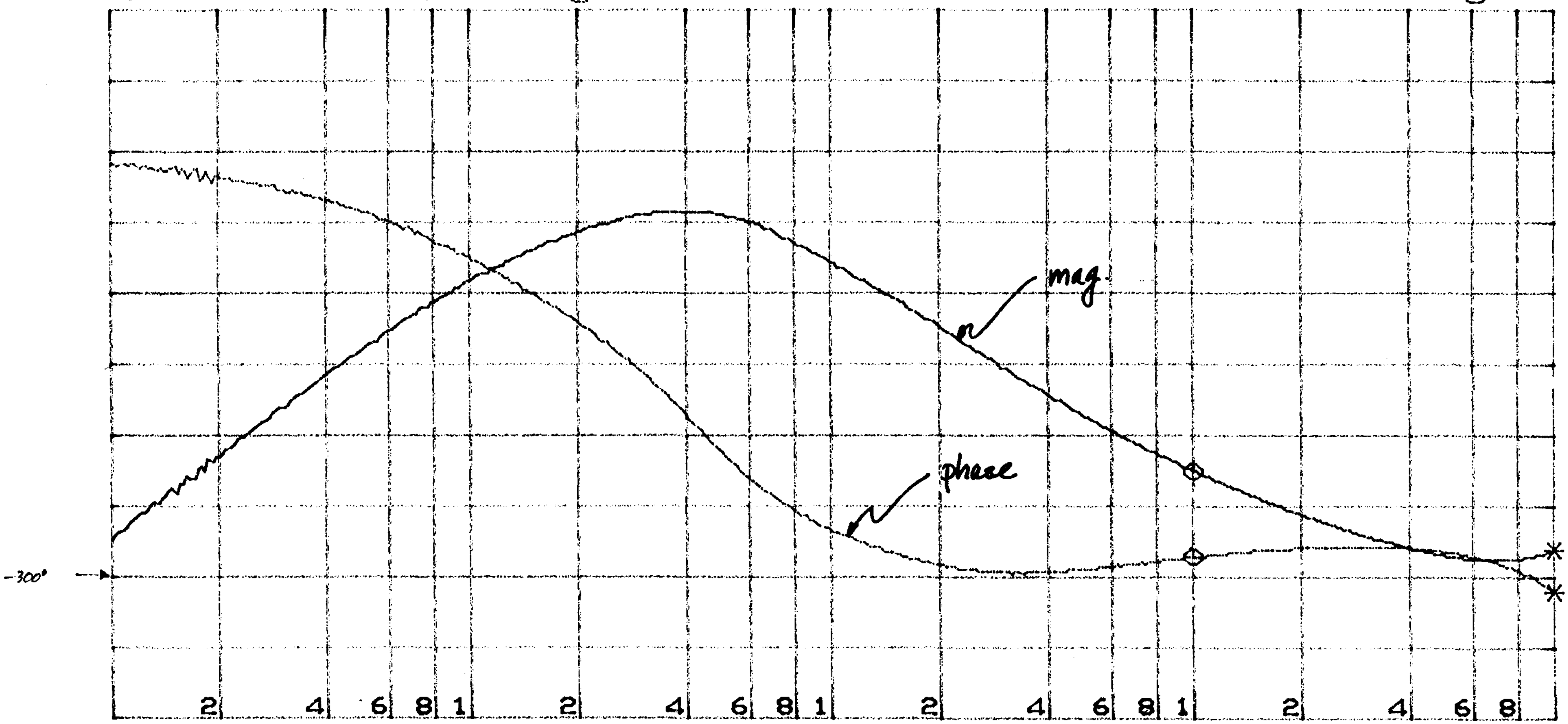
FREQ. STAB. SERVO ELECTRONICS. "INT1" TO "PC OUT"   21 JAN '97 RA.

1447

PLOT RE-TAKEN (THIS PLOT IS CORRECT.) WITH HIGH Z PROBE ON NWA "T" PORT.

NETWORK

A: REF	B: REF	* MKR	1 000 000.000 Hz
110.0	100.0	T/R	33.8060 dB
[dB]	[deg]	θ	-309.999 deg



DIV	DIV	START	100.000 Hz
10.00	50.00	STOP	1 000 000.000 Hz

RBW: 100 Hz ST: 40.2 sec RANGE: R= 0, T= 20dBm

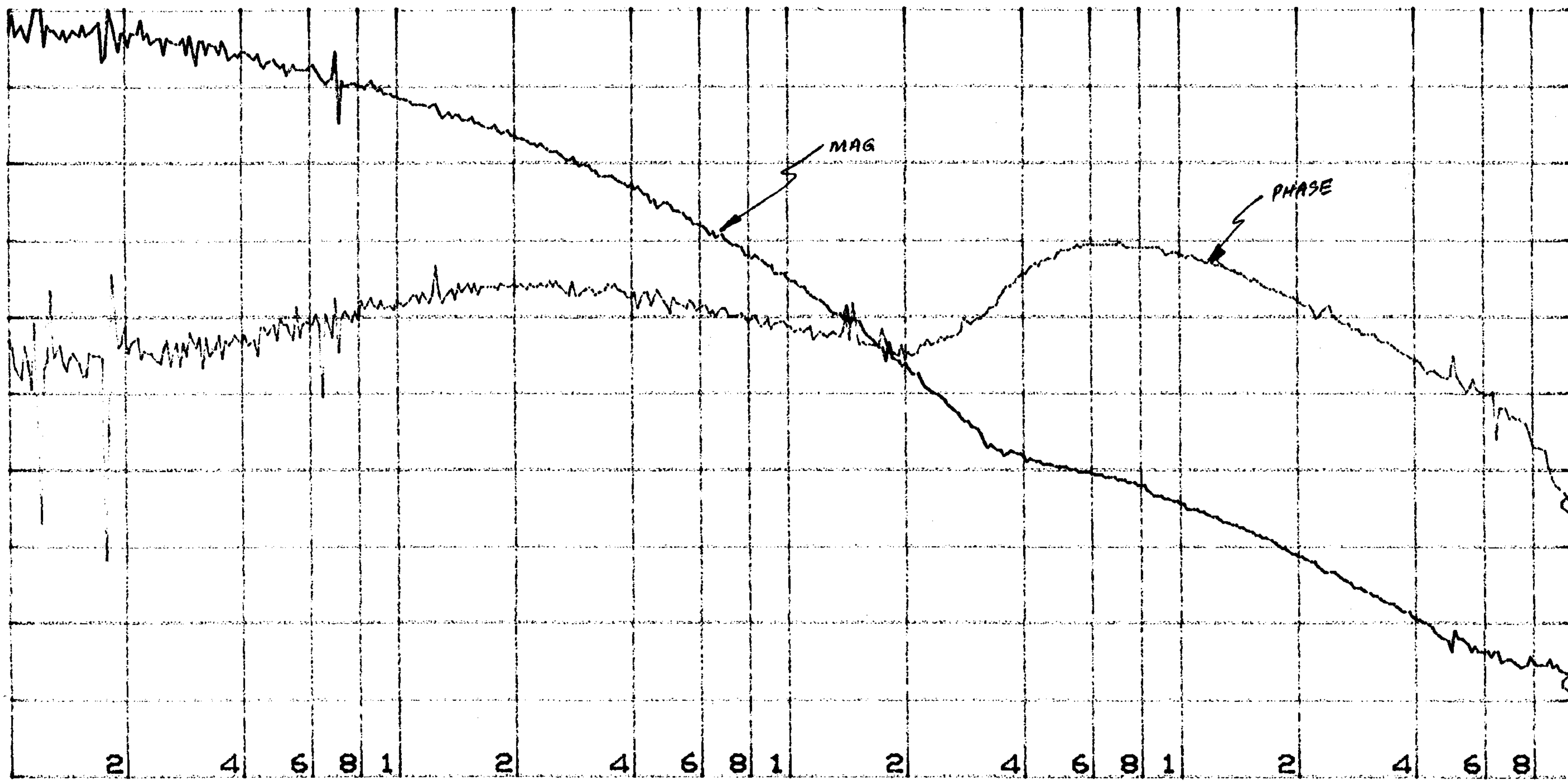
1440 23 JAN 97 RA

OPEN LOOP TRANSFER FUNCTION OF FSS. IN ON "MAIN TI" OUT ON "MAIN TO"

FAST = 1.04, SLOW = 0.4, COM = 0.65. PLOT TAKEN WITH SERVO LOCKED BY INVERTING TR. FUNCT. IN NWA.

NETWORK Math

A: REF	B: REF	o MKR	1 000 000.000	Hz
80.00	180.0	MAG	-7.97484	DB
[DB]	[ ]	θ	-51.6538	



DIV	DIV	START	100.000 Hz
10.00	36.00	STOP	1 000 000.000 Hz

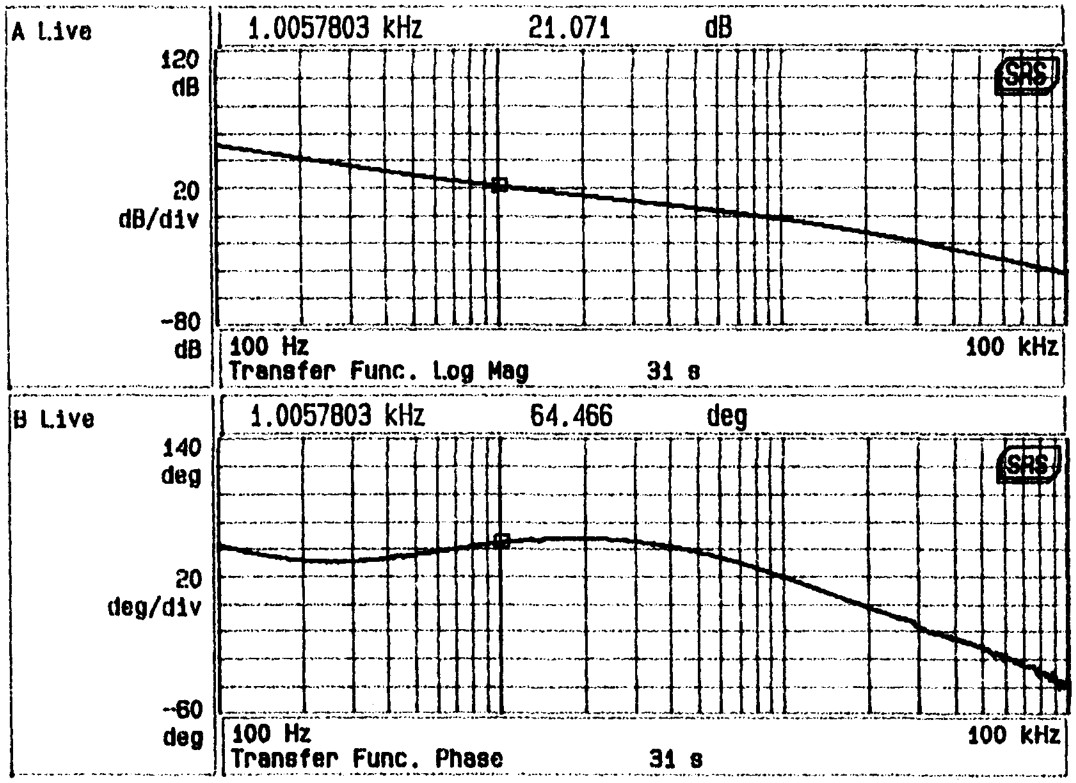
RBW: 10 Hz ST: 13.8 min RANGE: R=-10, T=-20dBm

11:38 21 JAN 97 RA

TRANSFER FUNCTION OF FSS FAST LOOP FROM "INT1" TO "FAST OUT". FAST T1 = 50Ω
SOURCE LEVEL ON ANALYSER = 30 mV. HAD TO ADJUST INPUT OFFSET POT ON
BOARD FOR NO CLIPPING. RF SW "ON"

FAST GAIN = 1.04
SLOW GAIN = 0.4
PC (COMGAIN) = 0.90

FILE NAMES: FSTFMA. MAGNITUDE
FSTFPA. PHASE



1/21/97 11:37:59

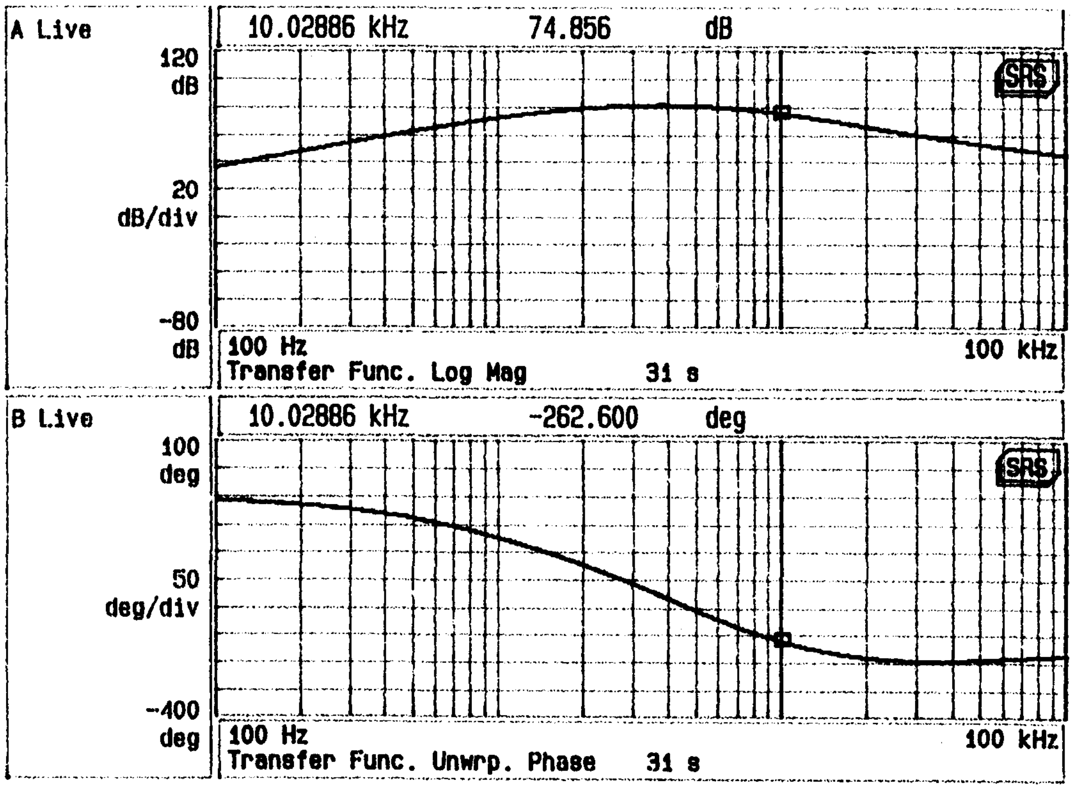
11:50 21 JAN 97 RA

FSS POCKELS LOOP TRANSFER FUNCTION. INT1 TO PC OUT. RFSW "ON"

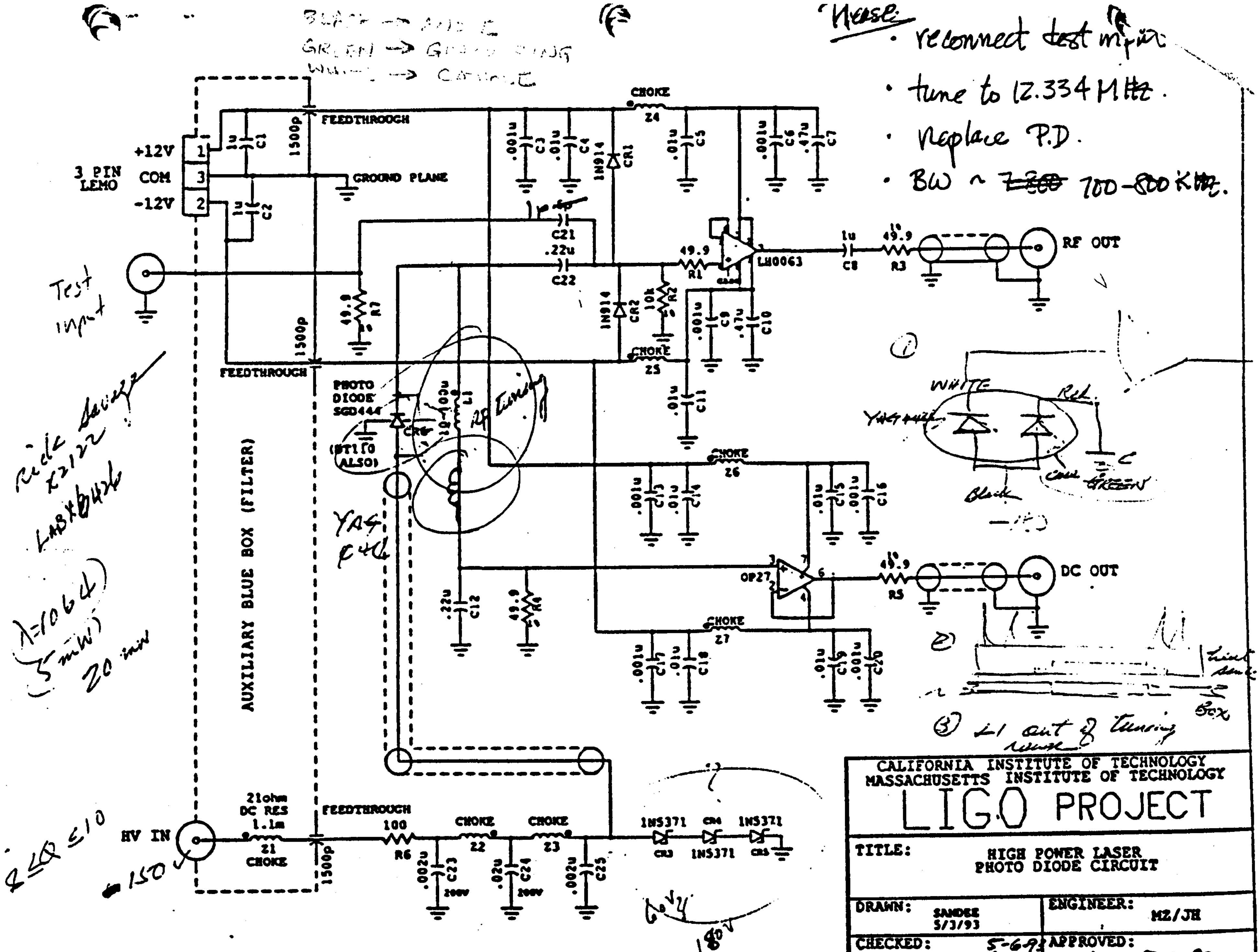
NOMINAL SETTINGS: COM GAIN = 0.9

FILENAMES:

FSPCTFM. MAGNITUDE
FSPCTFP. PHASE



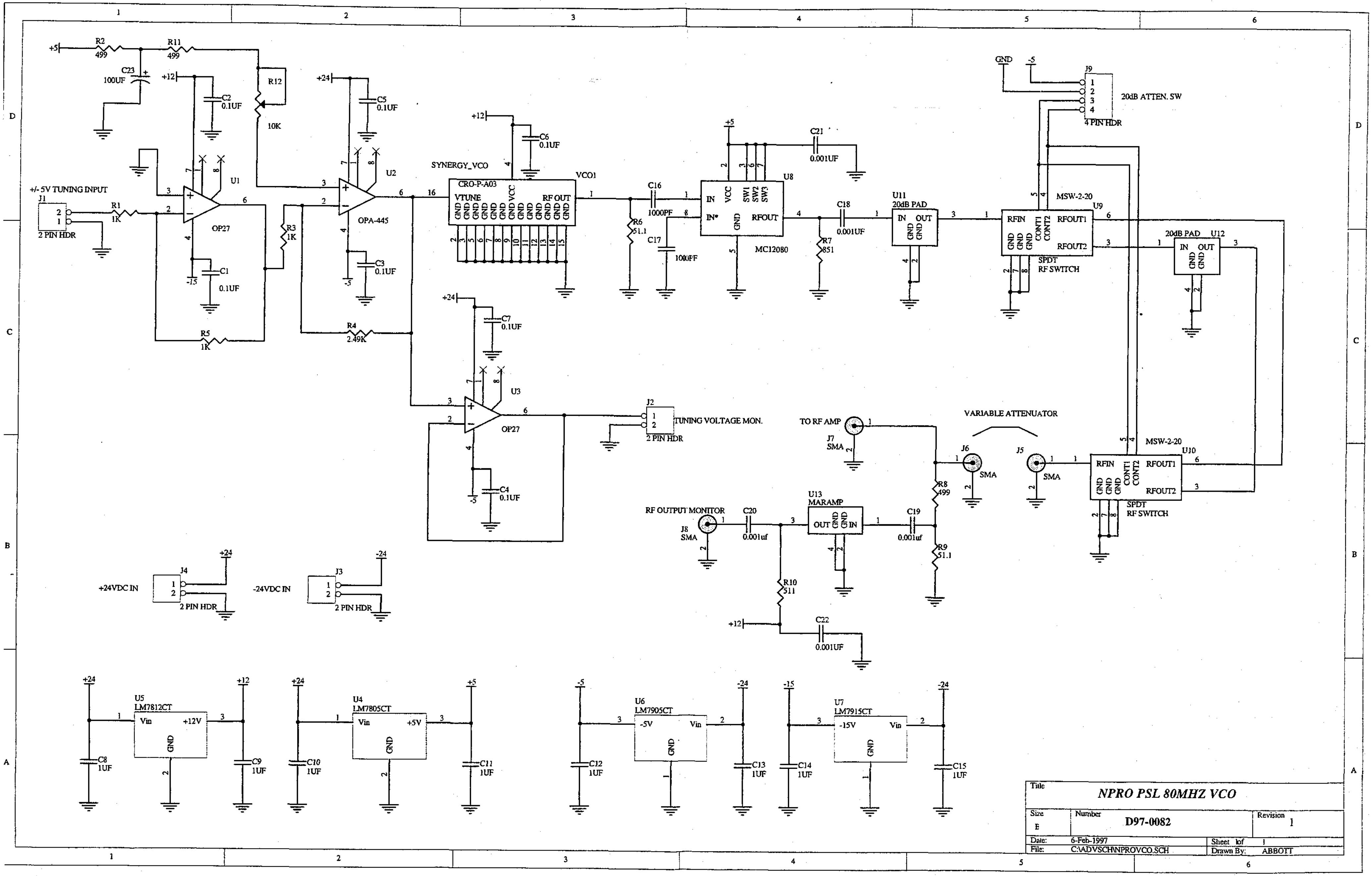
1/21/97 11:53:37



CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO PROJECT

TITLE: HIGH POWER LASER PHOTO DIODE CIRCUIT	
DRAWN: SANDEE 5/3/93	ENGINEER: MZ/JH
CHECKED: 5-6-93 Lawrence Chu	APPROVED: JC 5-6-93
DRAWING NUMBER: 1206030-3	SCALE: · PAGE: 1 OF 1 · REV: --



+/-5V TUNING INPUT
J1
2 PIN HDR
R1 1K
R2 499
R11 499
C23 100UF
R12 10K
C2 0.1UF
C1 0.1UF
R5 1K
U1 OP27
R3 1K
+24
C5 0.1UF
U2 OPA-445
C3 0.1UF
R4 2.49K
SYNERGY_VCO
CRO-P-A03
VCO1
VTUNE
RF OUT
C6 0.1UF
C7 0.1UF
U3 OP27
C4 0.1UF
J2
TUNING VOLTAGE MON.
2 PIN HDR
C16 1000PF
C17 100PF
R6 51.1
U8 MC12080
C21 0.001UF
C18 0.001UF
R7 851
U11 20dB PAD
J9
20dB ATTEN. SW
4 PIN HDR
MSW-2-20
U9
SPDT RF SWITCH
20dB PAD U12
VARIABLE ATTENUATOR
TO RF AMP
J7 SMA
J6 SMA
J5 SMA
U10
R8 499
R9 51.1
U13 MARAMP
C19 0.001uf
C20 0.001uf
RF OUTPUT MONITOR
J8 SMA
R10 511
C22 0.001UF
+24VDC IN
J4
2 PIN HDR
-24VDC IN
J3
2 PIN HDR
U5 LM7812CT
C8 1UF
C9 1UF
U4 LM7805CT
C10 1UF
C11 1UF
U6 LM7905CT
C12 1UF
C13 1UF
U7 LM7915CT
C14 1UF
C15 1UF
Title NPRO PSL 80MHZ VCO
Size E
Number D97-0082
Revision 1
Date: 6-Feb-1997
File: C:\ADVSCH\NPROVCO.SCH
Sheet 1 of 1
Drawn By: ABBOTT

BATCH
START

STAPLE
OR
DIVIDER

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note **LIGO-T960082-00-D** 5/22/96

NPRO-PSL Design Requirements

A. Abramovici, R. Savage

Distribution of this draft:

R. Abbott, D. Coyne, P. Fritschel, J. Heefner, A. Kuhnert, D. Shoemaker, S. Whitcomb, M. Zucker, DCC

This is an internal working note
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1 INTRODUCTION

This document includes the performance requirements for the low-power Nd:YAG pre-stabilized laser (NPRO-PSL). The NPRO-PSL is the precursor of the Nd:YAG pre-stabilized lasers (PSL) that will be employed in the initial LIGO interferometers. Because the first PSL is not scheduled for delivery until early in 1998, the NPRO-PSL is being constructed in order to fill the interim needs for a 1.06 μm laser source. Specifically, an NPRO-PSL is scheduled to be integrated into the Phase Noise Interferometer (PNI) in the fall of 1996 and another will be installed in the 40-m Interferometer (40-m) in the spring of 1997. An NPRO-PSL may also be employed in the early shake-down phases of the LIGO facilities in the event that the deliveries of the PSLs are delayed.

2 PERFORMANCE REQUIREMENTS

The performance requirements for the NPRO-PSL have been derived from requirements provided by LIGO members responsible for the PNI and the 40-m programs. They are also intended to be consistent with the requirements for the initial LIGO detectors[1], except that the output power is less. This is a significant difference; while some of the techniques employed to stabilize the low-power NPRO-PSL may be similar to those that will be used for the high-power PSL, one should not presume that scaling to higher power will be a trivial step.

2.1. Power

2.1.1. D.C. level:

500 mW.

2.1.2. Relative power fluctuations

- $f \geq 100\,\text{Hz}$: $\leq$ 1x $10^{-8}\,/\text{Hz}^{1/2}$
- $f < 100\,\text{Hz}$: $\leq$ 1%

2.2. Polarization

Manufacturer specification: vertical, extiction ratio $\leq$ 1:300

2.3. Mode

Manufacturer specification: single-longitudinal, TEM_{00} mode, major diameter/minor diameter ratio =1.2.

2.4. Frequency fluctuations

$\Delta\nu \leq$ 1 mHz/Hz$^{1/2}$ between 100 Hz and 4 kHz.

1. Refer to LIGO-E950018-02-E, *LIGO Science Requirements Document (SRD)*

3 INTERFACES

3.1. Power

Standard 110 V mains, $\leq$ 1 kW

3.2. Ambient Temperature

Temperature variations $\Delta t \leq \pm 3.5^{o} F (\pm 2^{o} C)$. Refer to LIGO-L951015-00-E, *Revised Vibration and Acoustic Requirements for the LIGO Facilities.*

3.3. Physical Dimensions

3.3.1. Laser and optical components

The complete system, including reference and analyzer cavities, less than 5' x 6' x 2' high.

3.3.2. Electronics

All electronics modules to fit within one standard 19"-wide, six-foot-high rack.

3.4. Signal inputs

3.4.1. Feed-around input #1

Signal from mode cleaner control system.

3.4.2. Feed-around input #2

Signal from interferometer arm cavity or interferometer arm cavity common mode control system.

3.4.3. Frequency shift input

Correction signal from mode cleaner control system for frequencies up to 1 kHz.

BATCH
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Technical Note	LIGO-T960089-00-D	5/22/96

NPRO-PSL Conceptual Design

A. Abramovici, R. Savage

Distribution of this draft:

R. Abbott, D. Coyne, P. Fritschel, J. Heefner, A. Kuhnert, D. Shoemaker, S. Whitcomb, M. Zucker, DCC

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1 INTRODUCTION

This document describes the conceptual design of the low-power Nd:YAG pre-stabilized laser (NPRO-PSL). The design requirements for the NPRO-PSL are documented in LIGO-T960082-00-D, *NPRO-PSL Design Requirements.*

The heart of the NPRO-PSL is a Model 125-1064-700 diode-pumped, non-planar ring oscillator (NPRO) produced by Lightwave Electronics Corporation in Mountain View, California. It is a monolithic Nd:YAG laser that produces a maximum of approximately 700 mW of radiation at a wavelength of 1.064 μm in a single-longitudinal, TEM_{00} mode. Because the free-running power and frequency fluctuations of the NPRO are well above the NPRO-PSL performance requirements, the NPRO-PSL will utilize a feedback control system to stabilize the power and the frequency to the required levels. The design and implementation of this feedback control system constitute the majority of the effort for the NPRO-PSL task.

2 FEEDBACK CONTROL SYSTEM

The feedback control system for the NPRO-PSL is shown schematically in Fig. 1. It is composed of two sub-systems, the power stabilization loop and the frequency stabilization loop. The frequency stabilization loop and the power stabilization loop share neither sensors nor actuators and thus are, to first order, independent.

2.1. Power Stabilization Loop

2.1.1. Overview

The control system for power stabilization of the NPRO-PSL is shown schematically in Fig.1 and a functional diagram for the power stabilization loop is shown in Fig. 2.

The built-in laser power control was found to keep the output power constant within better than 1%. External active power control thus seems to be necessary only at frequencies where power fluctuations can affect interferometer sensitivity directly. In order to simplify this subsystem, a low frequency cut-off at 10 Hz was chosen for the power stabilization control system.

Preliminary measurements of the NPRO free-running power fluctuations were performed in the optics laboratory at Caltech.The measured free-running relative power fluctuations are plotted in Fig. 3. This measurement was made with the NPRO's internal noise reduction electronics active. This is the mode in which the NPRO-PSL will be operated. The low measured level of power fluctuations opens the possibility to suppress them actively down to 1e-8/rootHz, below ~1 kHz, with a control system of relatively low gain and unity gain frequency.

2.1.2. Power sampling photodetector

The concept for the power sampling photodetector is driven by the desire to make it as simple as possible (refer to Appendix 1, *Specifications*). The photodetector output is AC coupled in order to remove the requirement for a very accurate, low-noise reference voltage source. The large load resistor obviates the need for an ultra-low-noise amplifier at the photodetector output.

2.1.3. Power Adjust Actuator

A power adjust input is conveniently provided with the laser controller. Measurements of the transfer function between this input and laser power show that the actuator phase shift is less than 180 degrees up to ~40 kHz. Thus, this input can potentially provide all of the required power fluctuation correction and eliminate the need of a conventional "noise eater" (AOM) in the main laser beam.

2.1.4. Amplifier Characteristics

Refer to Fig. 2 for symbol definitions.

2.1.4.1 H_{PA}

- Gain:50 V/V
- Poles: two at 1 kHz
- Zeros: two at 4 kHz

2.1.5. Performance Predictions

An estimate of the performance of the power fluctuation suppression loop, obtained by taking the ratio between the measured power fluctuations (Fig. 3) and the proposed open-loop gain (Fig. 4), is shown in Fig. 5.

The required level of 1e-8/rootHz in residual power fluctuation corresponds to the shot noise limit for 3.5 mA of photo-current, which in turn requires that ~7 mW of light be photodetected.

2.1.6. Noise

The choice of a large load resistor in the photodetector circuit results in a rather relaxed noise requirement on the amplifier in the power stabilization loop, 30 nV/rootHz (refer to the specifications in Appendix 1).

2.1.7. Lock Acquisition

The AC-coupled design for the power stabilization loop results in a system which should not saturate. Thus, lock acquisition is expected to be trivial.

2.2. Frequency Stabilization Loop

2.2.1. Overview

The control system for frequency stabilization of the NPRO-PSL is shown schematically in Fig.1 and a functional diagram for the frequency stabilization loop is shown in Fig. 6. Simply stated, an error signal is generated by comparing the laser frequency with a Fabry-Perot resonance of the reference cavity. This error signal drives three actuators: the laser temperature actuator (labeled *SLOW*), the laser PZT actuator (labeled *FAST*), and the Pockels cell actuator (labeled *PC*).

Preliminary measurements of the NPRO free-running frequency fluctuations were performed in the optics laboratory at Caltech. An upper limit on the free-running frequency fluctuations is shown in Fig. 7. The upper, more noisy trace was taken with the room air conditioning, and various electronic components (with internal fans) operating; the lower trace was taken after those noise sources were switched off. The plotted data are a convolution of the frequency noise in the laser and the measurement noise. We believe that the acoustics and vibrations increased the measured frequency noise primarily via interaction with the reference cavity used to make the measurement (a TROPEL-style optical spectrum analyzer operated in air).

2.2.2. Frequency fluctuation sensor

The frequency fluctuation sensor utilizes a monolithic, fused silica spacer with mirrors optically contacted to each end[1]. This reference cavity differs from previous designs in that it has no length adjustment (typically implemented with PZT actuators sandwiched between one of the mirrors and the spacer). The reference cavity is suspended in vacuum using two loops of wire. The LIGO-standard Pound-Drever-Hall sensing technique is utilized to compare the laser frequency with the reference cavity resonance and generate the error signal. The phase modulation frequency is 12.33 MHz.

Because the reference cavity has no length adjustment, a frequency offset actuator is employed to shift the frequency of the light impinging on the reference cavity such that the frequency fluctuation sensor can remain on resonance while the NPRO-PSL output radiation frequency is locked to a secondary reference cavity, e.g. the mode cleaner or one of the interferometer arm cavities.[2]

2.2.2.1 Reference Cavity Parameters

- Length: 20 cm
  - free spectral range =750 MHz
- Material: fused silica
  - coefficient of expansion $5 \times 10^{-7}\ K^{-1}$
- Mirror transmission: 300 PPM
  - finesse ~ 10,000
  - bandwidth ~ 7.5 KHz
- Mirror radius: 50 cm, concave
- Temperature-induced resonant frequency change (1.064 μm light) ~ 150 MHz per deg K

2.2.3. Frequency Offset Actuator

The frequency offset generator, shown schematically in Fig. 1, is used to maintain resonance with the fixed-length reference cavity while the NPRO-PSL output radiation frequency is locked to a secondary reference cavity. The actuator employs a double-passed acousto-optic modulator

1. Refer to LIGO-T950118-00-R, *Prestabilized NPRO: Frequency Sensing and Shifting*
2. This technique has been successfully demonstrated on the Glasgow 10-m interferometer.

(AOM) operating at a center frequency of 80 MHz. The frequency range of the AOM is ±5 MHz, and because it is double-passed, it can shift the frequency of the laser light by as much as ±10 MHz. This range was chosen after analysis of data from the 40-m interferometer and the 12-m mode cleaner and is expected to be sufficient.

2.2.4. Laser Temperature Actuator (SLOW Input)

The NPRO SLOW input controls the laser temperature actuator which utilizes a termo-electric cooler.

- Gain: 4 GHz/V
  - DC to 0.2 Hz

- Safe operating range (no mode hopping): ±1 V
  - corresponding frequency correction range: ±4 GHz

2.2.5. Laser PZT Actuator (FAST Input)

The NPRO FAST input controls the laser PZT actuator.

- Gain: 4 MHz/V
  - flat within 1 dB to 100 kHz

- Safe operating range: ±50 V
  - corresponding frequency range: ±200 MHz

2.2.6. Pockels Cell Actuator

The NPRO-PSL utilizes a model 4004-D electro-optic modulator (Pockels cell) manufactured by New Focus, Inc. in Santa Clara, Ca.

- Gain: 15 mrad/V
  - corresponding frequency shift at 30 KHz: 450 Hz/V

- Safe operating range: ±200 V
  - corresponding frequency correction at 30 kHz: ±90 kHz.

2.2.7. Overall Loop Range

Determination of the ranges to be specified for the SLOW and FAST actuators of the frequency control loop proceeds as follows:

1. Use the design maximum ambient operating temperature variation of ±2 °C and a **safety margin** of a factor of 2.5 to set the temperature range at ±5 °C.
2. The ±5 °C temperature range corresponds to a reference cavity frequency change of ±750 MHz.
3. Because the ambient temperature fluctuations are very low frequency, they can easily be com-

pensated for by the SLOW actuator. The required range for the SLOW actuator is thus ±187 mV (±200 mV).

4. Although the safe operating range of the FAST actuator is specified by the manufacturer at ±50 V, concerns over beam quality, pointing fluctuations, and subjecting the laser to undue stresses in general lead us to set the gain ratio between the FAST and SLOW actuators at 10 (at frequencies below 0.1 Hz). This reduces the voltage range for the SLOW input to ±20 V (±24 V).
5. The ±20 V range for the FAST actuator corresponds to ±80 MHz which is more than enough range to suppress the free-running laser frequency fluctuations at 100 Hz (~300 Hz/Hz$^{1/2}$, refer to Fig. 7). This range is also sufficient at frequencies above 0.1 Hz to keep the laser in lock with the reference cavity, as demonstrated by laboratory measurements.

In order to keep the operating range of the Pockels cell actuator well below the manufacturer-specified safe operating range, we specify ±100 V for the Pockels cell maximum input voltage. This corresponds to ±45 kHz at 30 kHz and is more than is required for the correction of the free-running frequency variations at frequencies above 30 kHz.

2.2.8. Cross-over Frequencies

- SLOW/FAST: 0.1 Hz
- FAST/PC: 100 kHz

2.2.9. Amplifier Characteristics

Refer to Fig. 6 for symbol definitions.

2.2.9.1 H_{COM}

- Gain: 100 V/V
- Poles: none
- Zeros: none

2.2.9.2 H_{PC}

This amplification stage is part of the Laser Loop Servo Preamplifier (LLSPA), a tested design, which will be modified to provide the lower drive voltage required for the PC actuator used.

2.2.9.3 $H_{S/F}$

- Gain: 10 V/V
- Poles: none

- Zeros: none

2.2.9.4 H_{FAST}

- Gain: 10 V/V
- Poles: two at 500 Hz, one at 1500 Hz
- Zeros: three at 30 kHz

2.2.9.5 H_{SLOW}

- Gain: 0.1 V/V
- Poles: two at 0.025 Hz
- Zeros: two at o.1 Hz

2.2.10. Performance Predictions

A model for the free-running frequency noise is plotted in Fig. 8. Measured frequency fluctuation data are used up to 2.5 kHz, above which the noise is assumed to fall as the inverse of the frequency. The calculated open-loop response of the of the proposed frequency stabilization loop is plotted in Fig. 9. Fig. 10 shows the predicted gain-limited residual frequency noise. Also plotted in Fig. 10 is the shot-noise-limited frequency noise for the frequency fluctuation sensor[1].

2.2.11. Noise

The front end of the frequency stabilization system is an existing module (LLSPA), previously used and tested with the Argon ion PSL. Its input-referred noise is ~4 nV/rootHz, which is adequate given that the mixer output noise is ~10-15 nV/rootHz (for ~0.25 mA of photocurrent, using the conventional LIGO RF photodetector design).

2.2.12. Lock Acquisition

The range over which the NPRO frequency can be tuned using the FAST actuator is only +/- 80 MHz, not enough to cover the reference cavity free spectral range, 750 MHz. The SLOW actuator has to be utilized to bring the laser frequency close enough to a reference cavity resonance for the control system to acquire lock. The following lock acquisition procedure, which has been successfully employed to lock the NPRO to the TROPEL cavity, will be used:

First Time Acquisition

1. Divide the free spectral range of the reference cavity (750 MHz) into steps comparable to the range of the FAST actuator, ~100 MHz. This step size corresponds to 25 mV at the SLOW input.

1. Refer to LIGO-T950118-00-R, *Prestabilized NPRO: Frequency Sensing and Shifting*

2. With the frequency control loop open, change the voltage at the SLOW input in 25 mV increments, allowing the frequency to settle for ~30 s after each step.

3. When the demodulator output moves away from 0 V, indicating that the reference cavity resonance is nearby, closing the frequency control loop should result in lock.

Re-acquisition After Loss of Lock Due to a Fast Disturbance

This procedure has not been tested yet.

1. A specialized device (sample-and-hold or computer) continuously monitors and stores the voltage at the SLOW input.

2. When lock is lost, the stored value is applied to the SLOW input. The laser frequency will thus be close to the reference cavity resonance, and lock should be re-acquired.

3 PHYSICAL CONFIGURATION

3.1. Electronics

Initially, the NPRO-PSL electronics will be implemented in NIM modules. It is likely that the electronics design will be converted to the standard LIGO CDS VME technology during the final design phase of this project.

3.2. Optics

The NPRO-PSL optics layout is shown schematically in Fig. 11. All of the optical components, including the reference cavity and an analyzer cavity are mounted on a 5' x 6' optical table. The nominal beam height is 5.5".

4 FIGURES

Figure Captions

1. Schematic diagram of the NPRO-PSL feedback control system.

2. Functional diagram of the NPRO-PSL power stabilization control loop.

3. Amplitude spectral density of relative power fluctuations of the free-running NPRO.

4. Open-loop response of the power stabilization control loop.

5. Power stabilization control loop performance prediction.

6. Functional diagram of the NPRO-PSL frequency stabilization control loop.

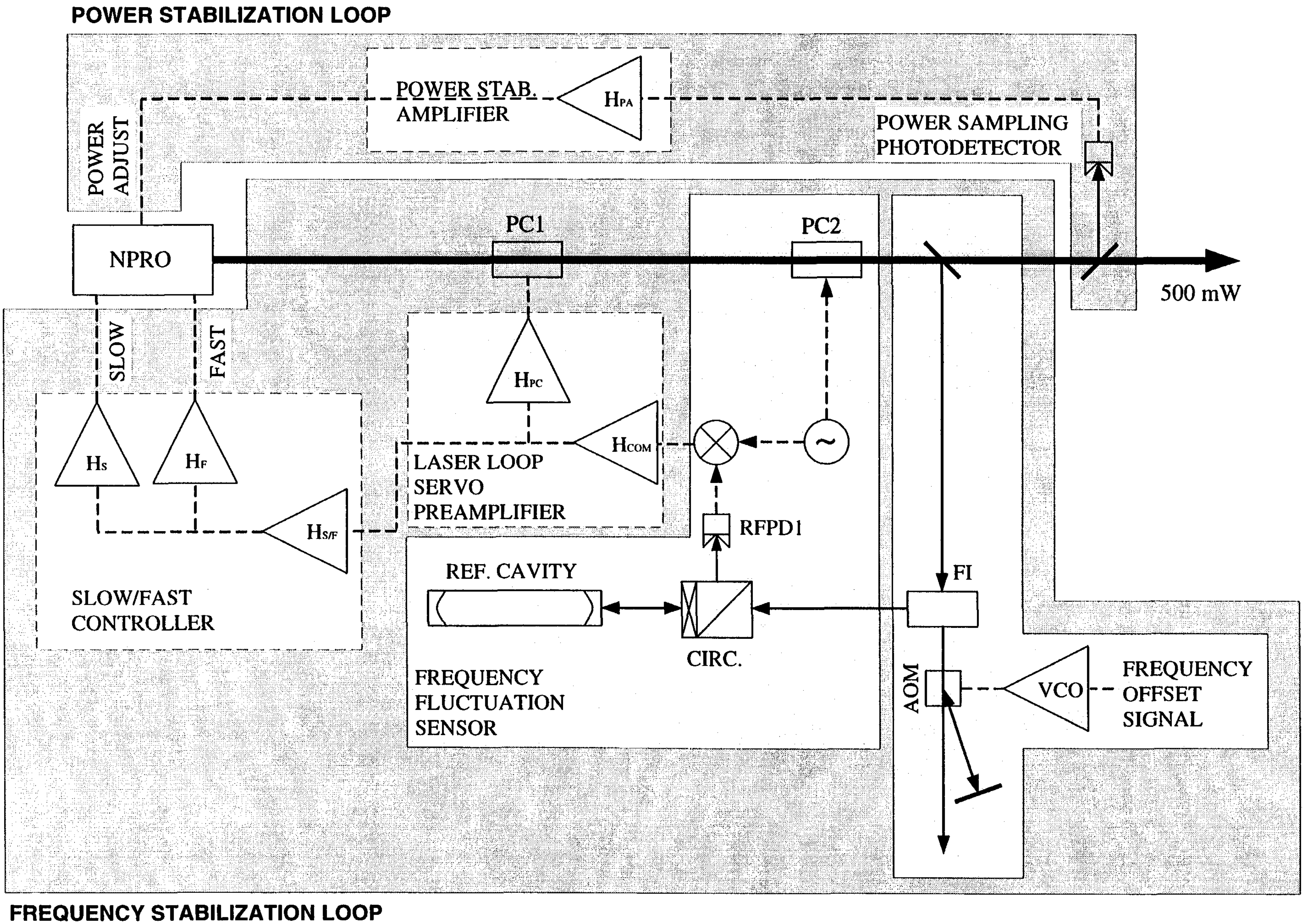
7. Amplitude spectral density of frequency fluctuations of the free-running NPRO (upper limit).

8. Free-running frequency noise model.

9. Open-loop response of the frequency stabilization control loop.

10. Frequency stabilization control loop performance prediction.

11. NPRO-PSL optics layout.



POWER STABILIZATION LOOP
POWER STAB.
AMPLIFIER
HPA
POWER ADJUST
POWER SAMPLING
PHOTODETECTOR
NPRO
PC1
PC2
500 mW
SLOW
FAST
HPC
HCOM
Hs
HF
HS/F
LASER LOOP
SERVO
PREAMPLIFIER
RFPD1
REF. CAVITY
FI
SLOW/FAST
CONTROLLER
CIRC.
FREQUENCY
FLUCTUATION
SENSOR
AOM
VCO
FREQUENCY
OFFSET
SIGNAL
FREQUENCY STABILIZATION LOOP

Fig. 1

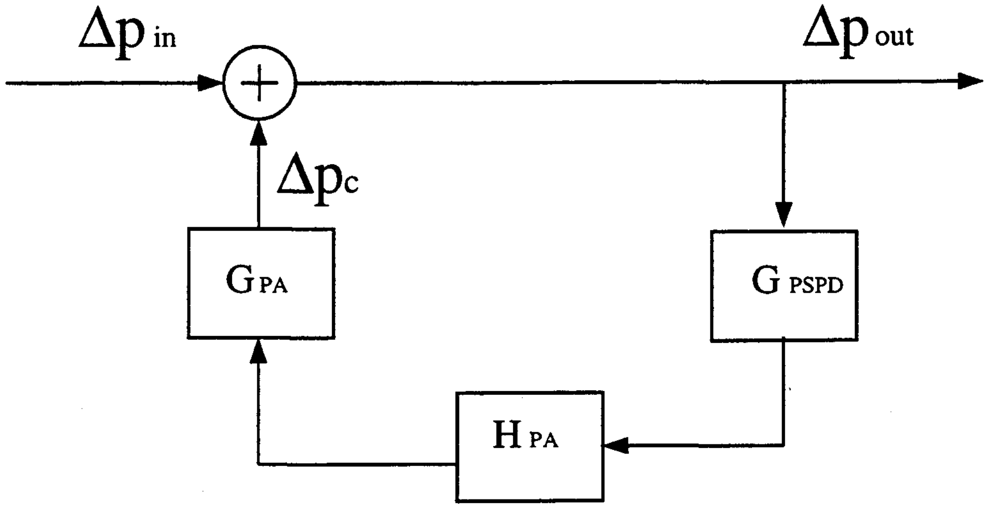
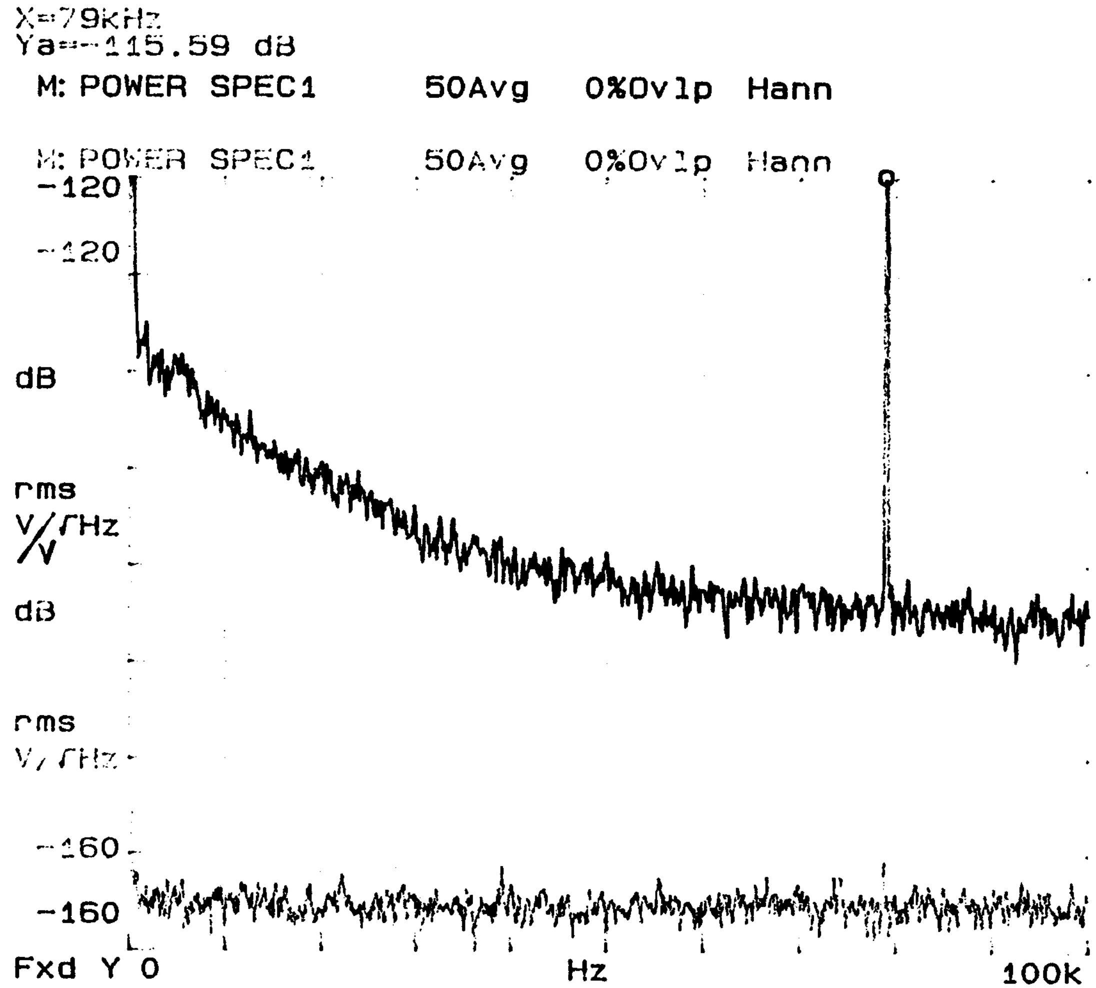


Fig. 2.

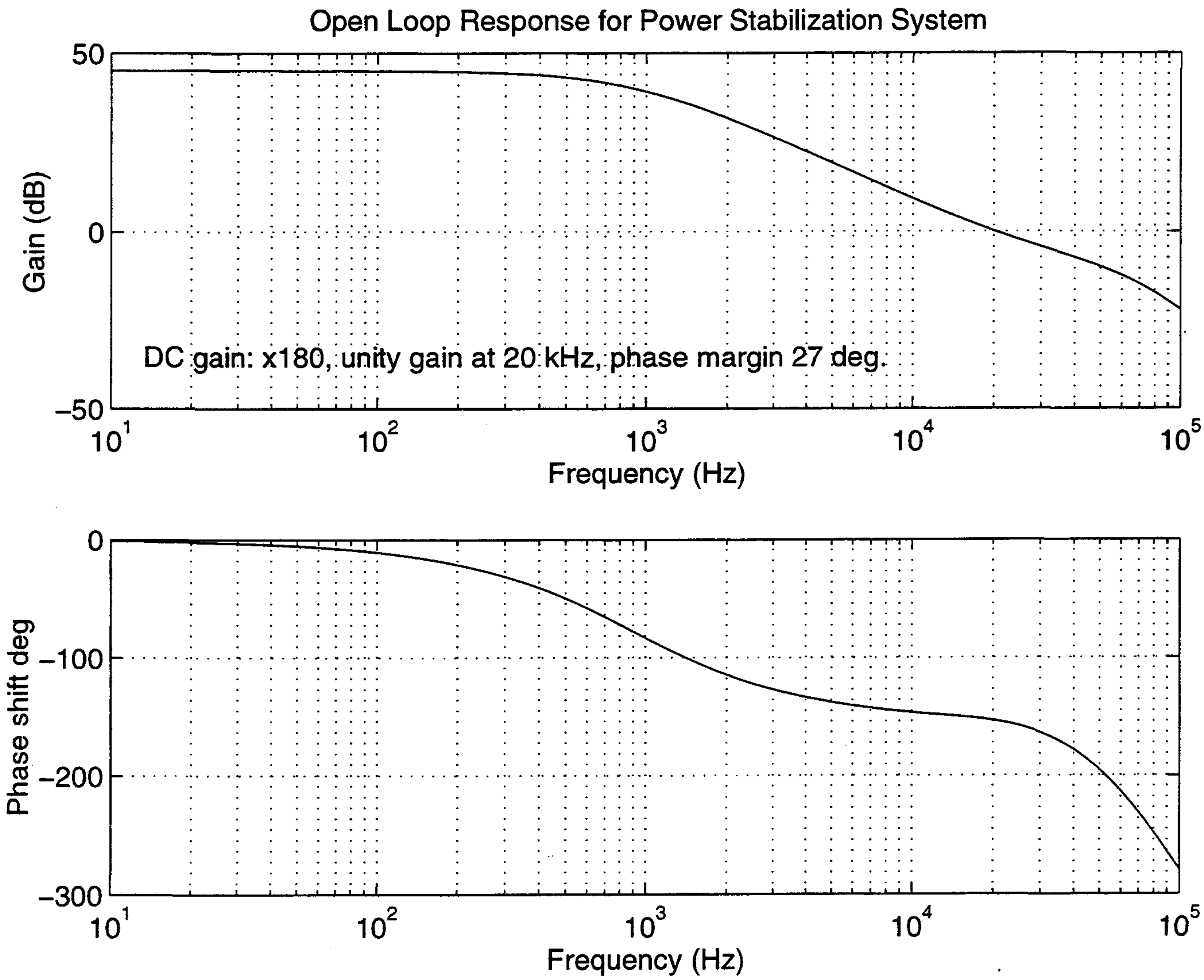
3/4/96 17:30.

Relative intensity noise of Lightwave NPRO
NE - ON



Thorlabs PD signa ÷ 2.11V.

beam blocked in front Thorlabs PD ÷ 2.11



Open Loop Response for Power Stabilization System
50
0
-50
Gain (dB)
DC gain: x180, unity gain at 20 kHz, phase margin 27 deg.
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
0
-100
-200
-300
Phase shift deg
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

Fig. 4

/home/rick/Matlab/ps_loop_pred.m

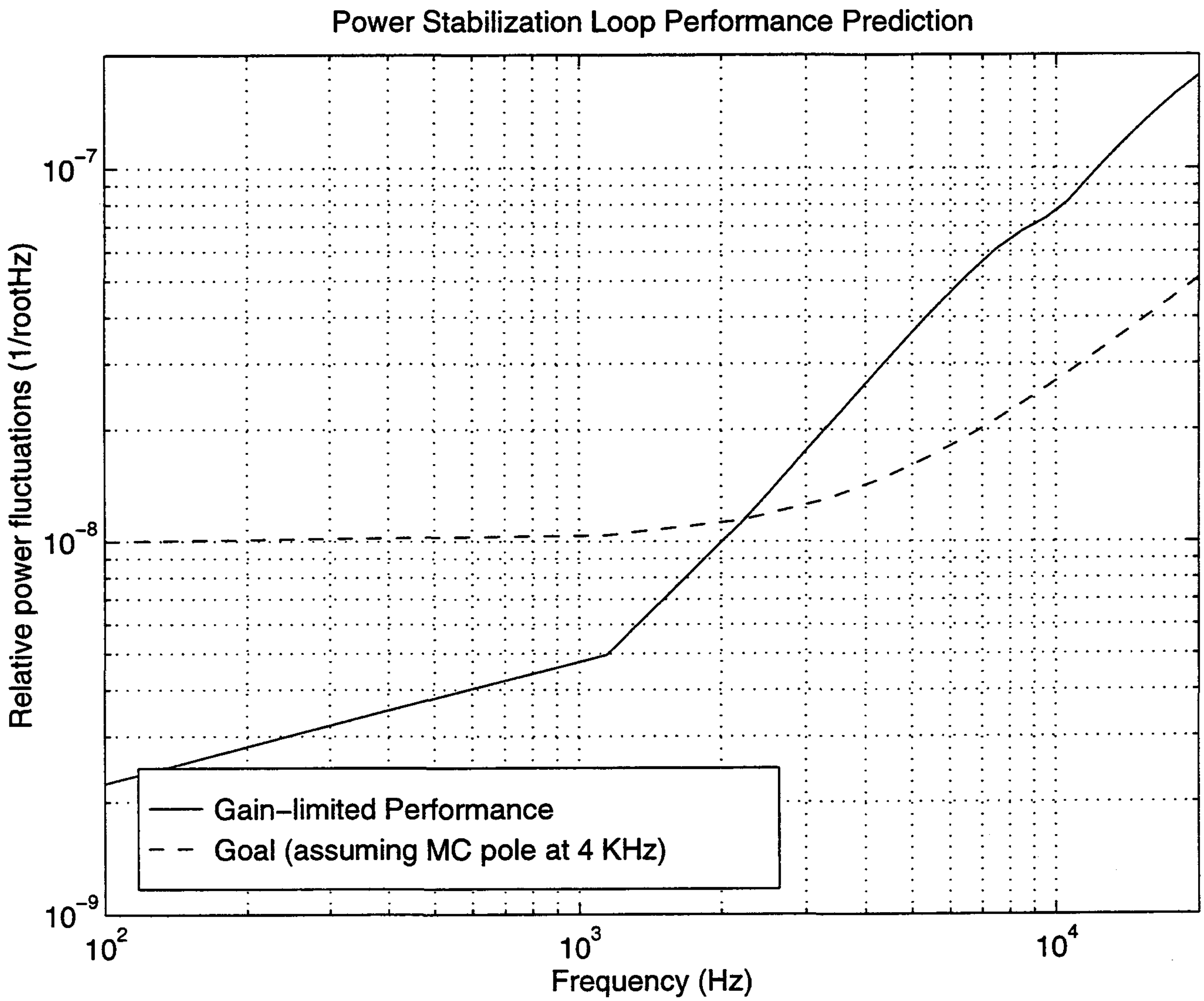
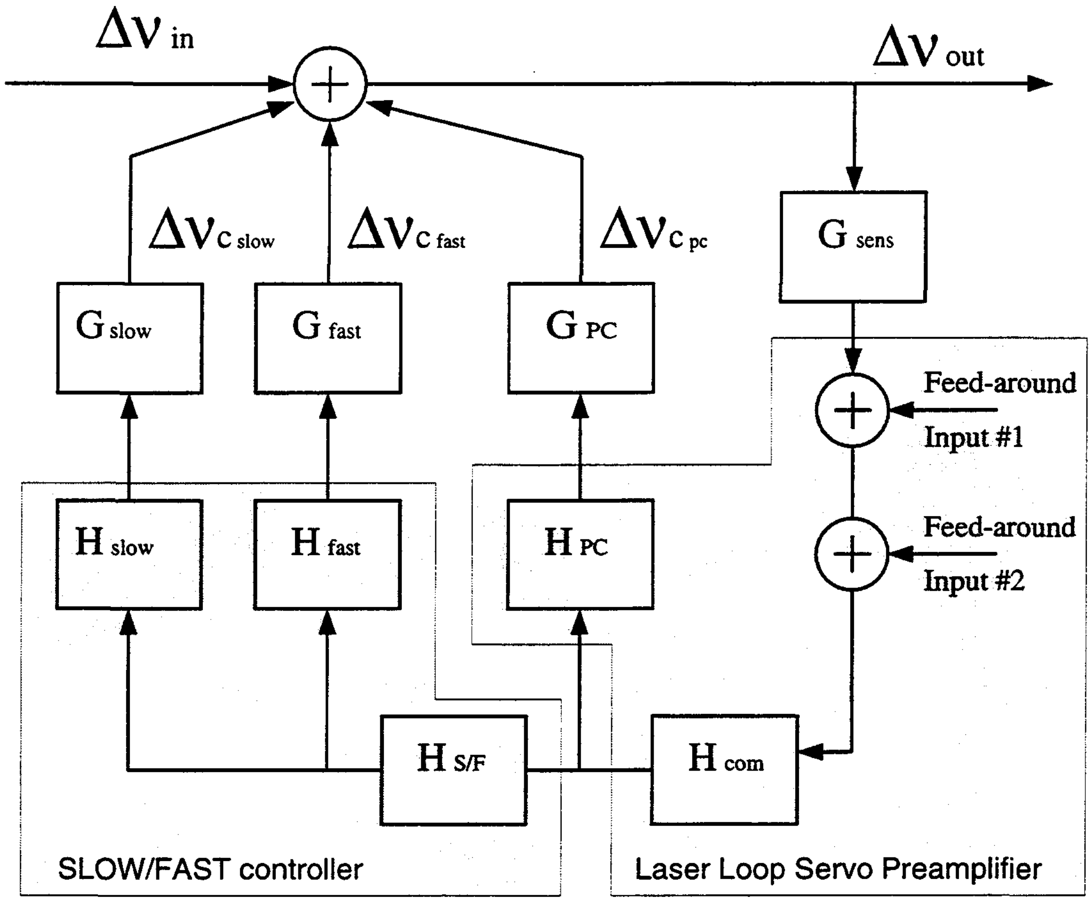


Fig 5.

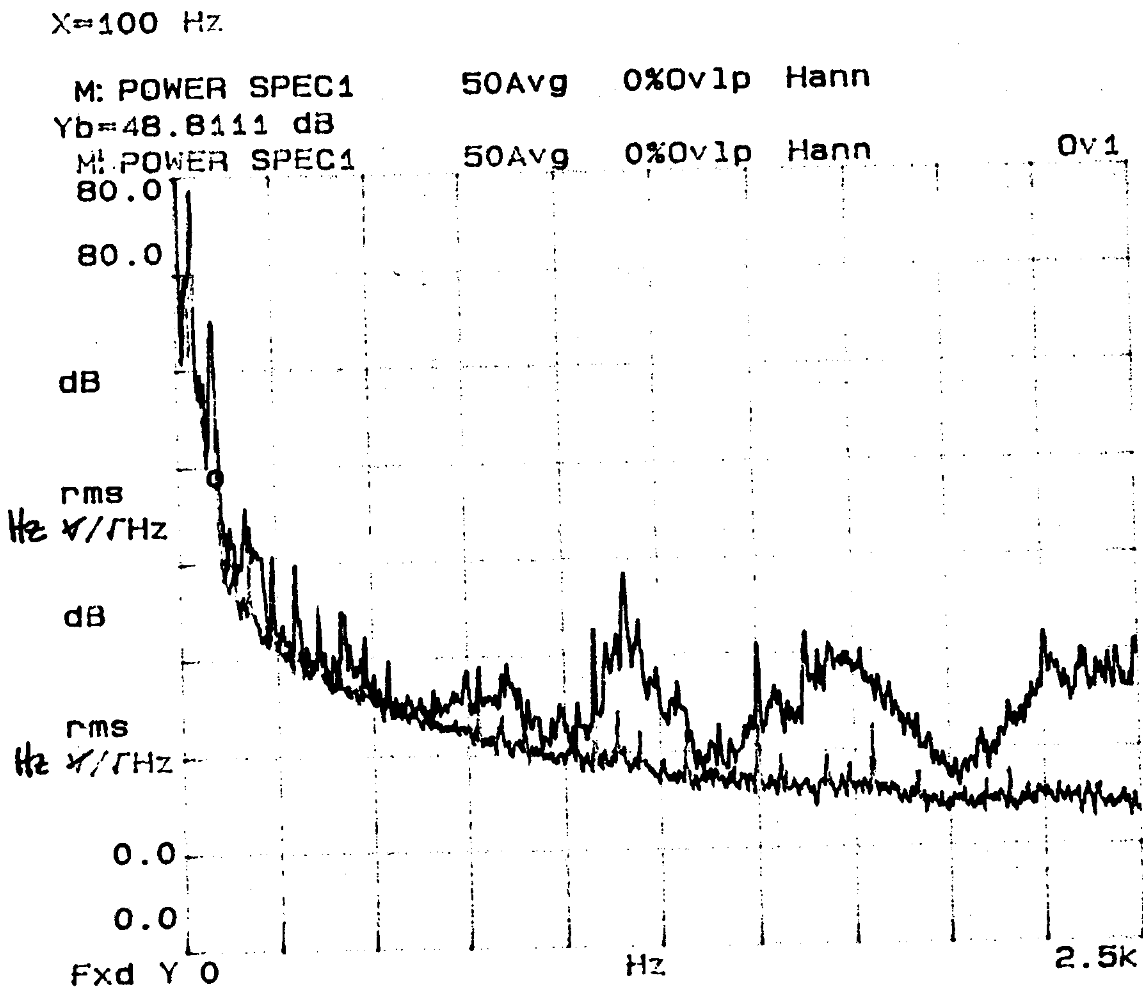


Δν in
Δν out
Δν C slow
Δν C fast
Δν C pc
G sens
G slow
G fast
G PC
Feed-around
Input #1
Feed-around
Input #2
H slow
H fast
H PC
H S/F
H com
SLOW/FAST controller
Laser Loop Servo Preamplifier

Fig. 6.

4/2/96. 16:05

NPRO Frequency Noise Upper Limit
(probably dominated by Tropel noise).



signal = voltage at NPRO fast input w/ control loop locked.

Vert scale = signal × $4 \cdot 10^6$ Hz/V

w/ scopes on, AC on, 3562A next to laser table, etc.

w/ scopes off, AC off, 3562A out of room, etc.

Fig. 7

Spectrum analyzer noise ~ −5dB

Control loop unity gain freq. ~ 3kHz - see plot on p.50 (solid line)

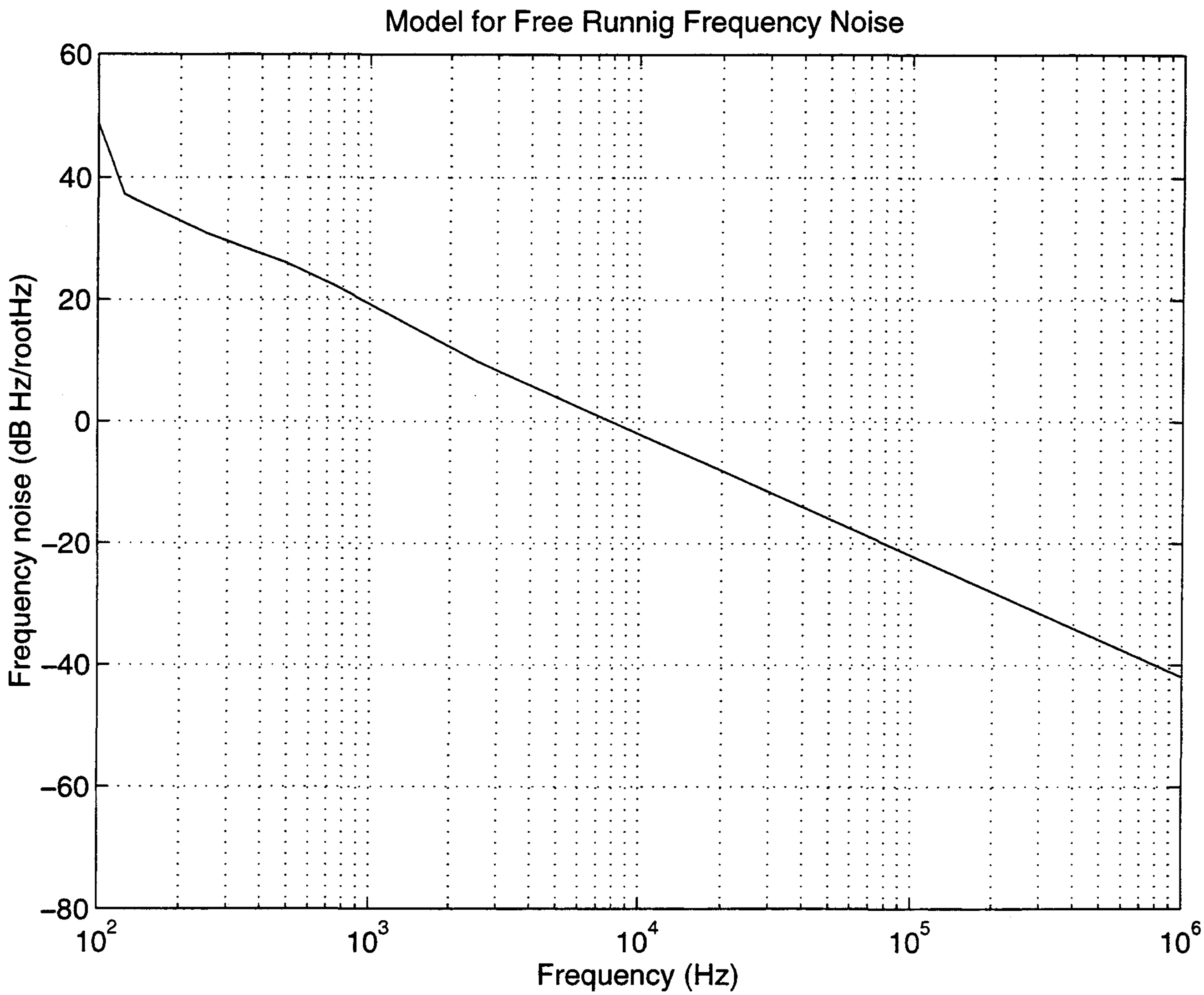
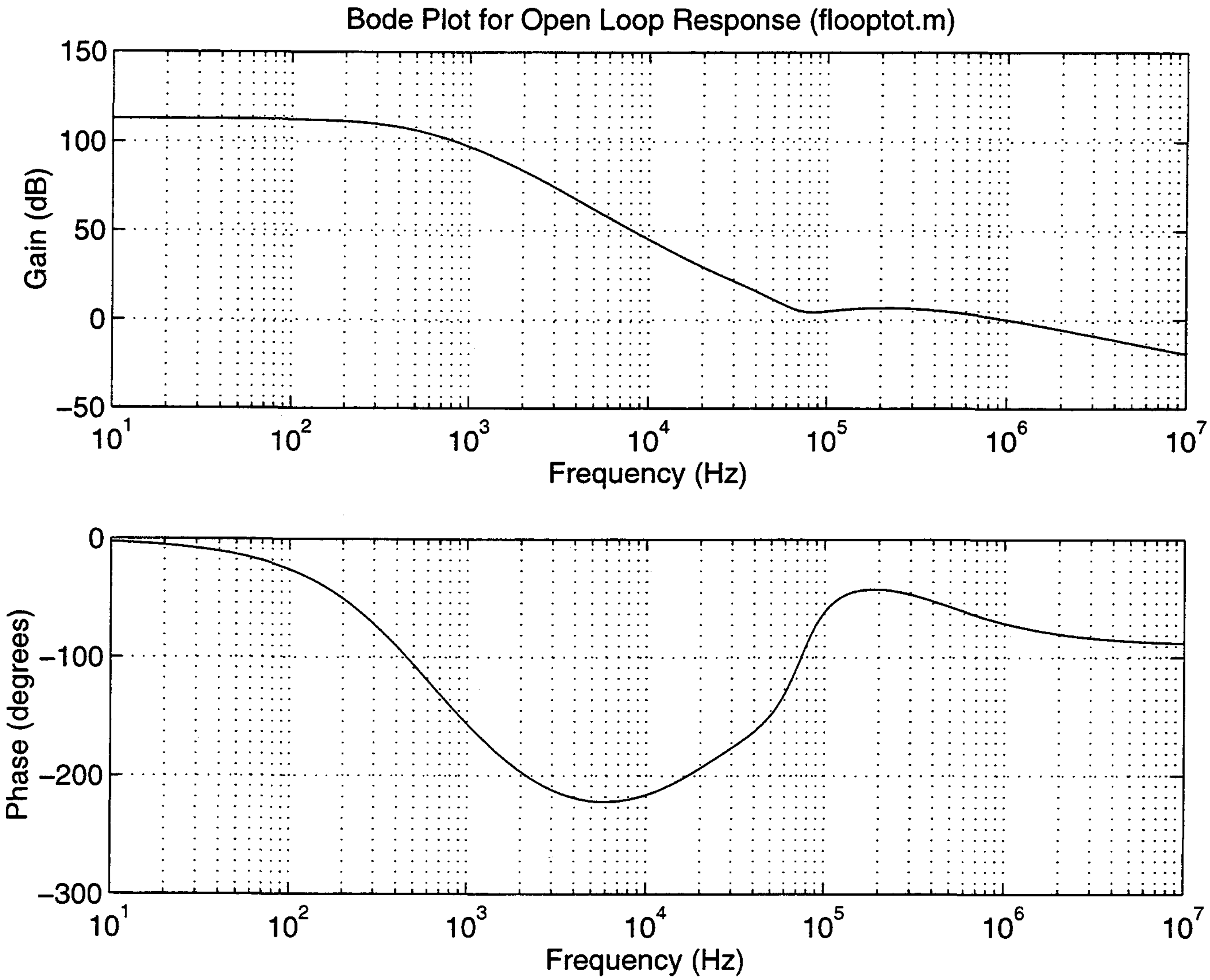
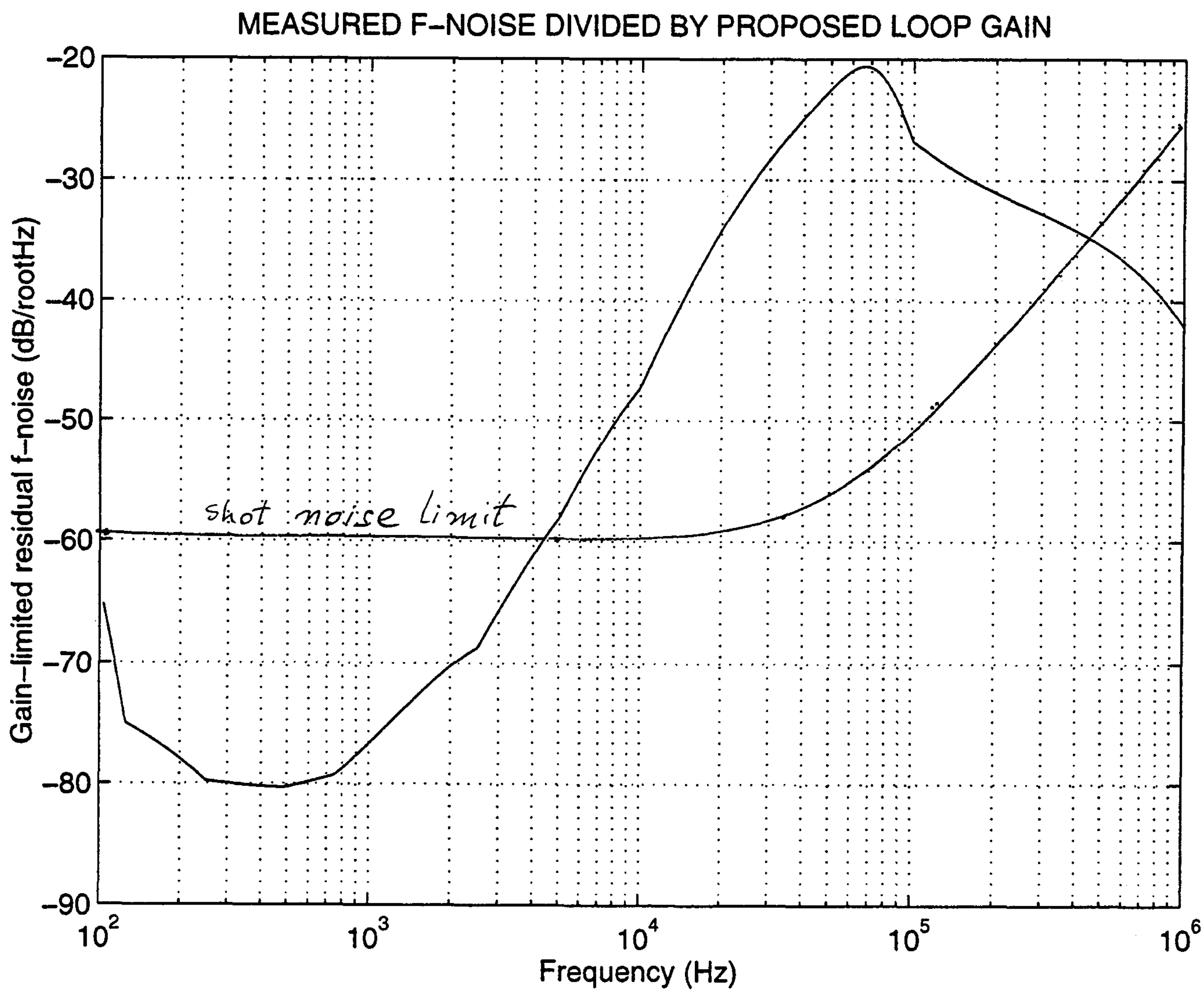

Model for Free Runnig Frequency Noise
60
40
20
0
−20
−40
−60
−80
Frequency noise (dB Hz/rootHz)
10^2
10^3
10^4
10^5
10^6
Frequency (Hz)

Fig.8.



Bode Plot for Open Loop Response (flooptot.m)
150
100
50
0
−50
Gain (dB)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Frequency (Hz)
0
−100
−200
−300
Phase (degrees)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Frequency (Hz)

Fig. 9.



MEASURED F-NOISE DIVIDED BY PROPOSED LOOP GAIN
-20
-30
-40
-50
-60
-70
-80
-90
Gain-limited residual f-noise (dB/rootHz)
shot noise limit
10^2
10^3
10^4
10^5
10^6
Frequency (Hz)

Fig. 10

NPRO-PSL OPTICS LAYOUT

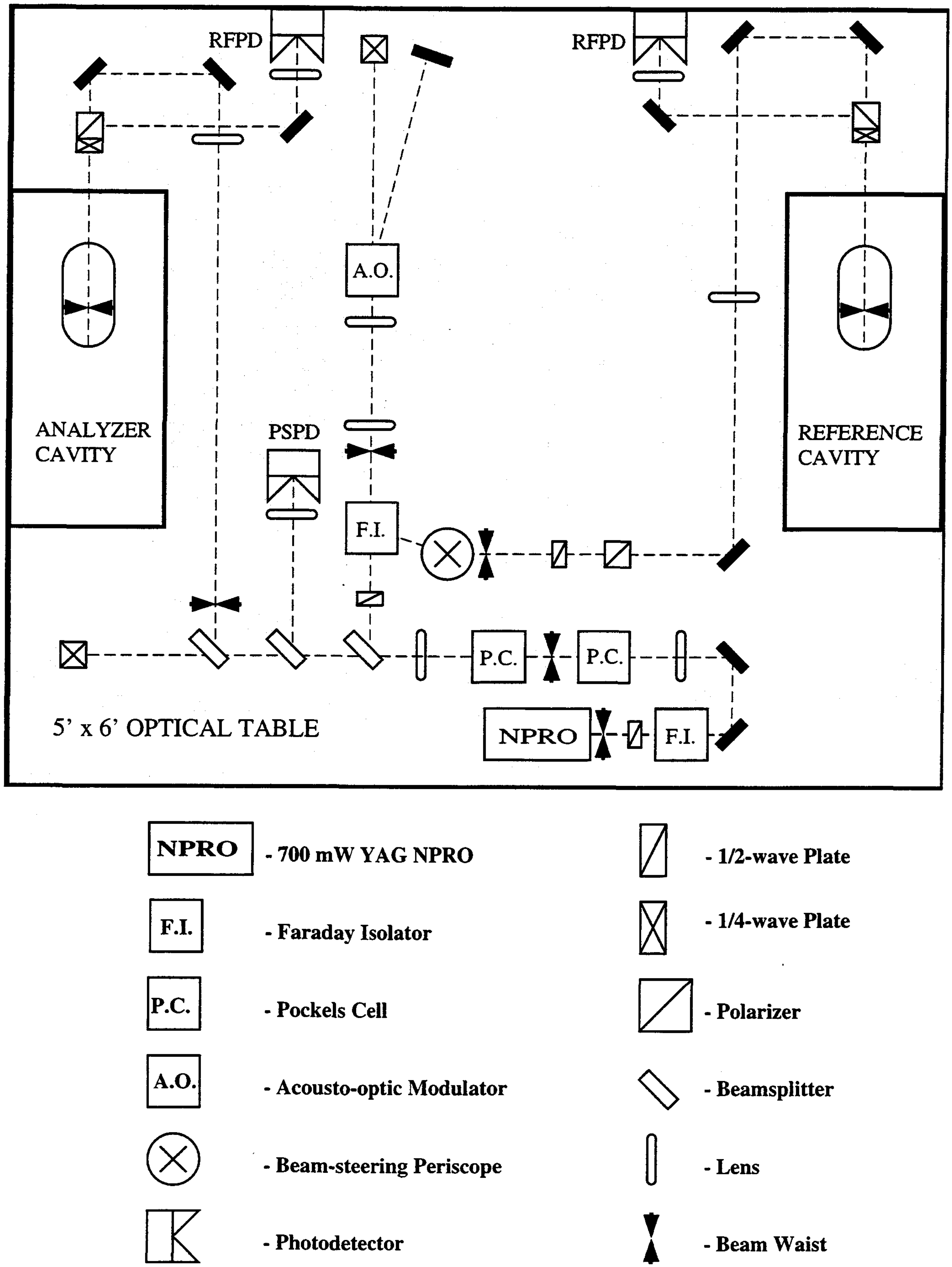


Fig. 11.

APPENDIX 1 SPECIFICATIONS

1. *Specifications for SLOW/FAST Controller*, **LIGO-E960043-01-D**
2. *Specifications for Power Sampling Photodetector*, **LIGO-E960042-00-D**
3. *Specifications for Power Stabilization Amplifier*, **LIGO-E960045-00-D**
4. *Specifications for Power Sampling PD Bias Supply*, **LIGO-E960048-00-D**

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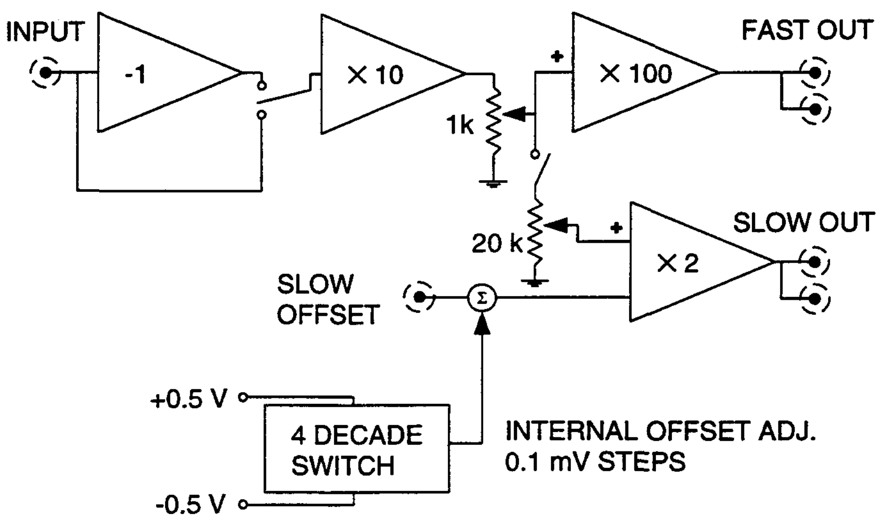
Specifications for SLOW/FAST Controller Intended for use with the NPRO-PSL

A. Abramovici, R. Savage, May 8, 1996

LIGO-E960043-01-D

1. General

- NIM module
- All controls on front panel
- Floating BNC connectors, unless otherwise stated



NOTE: "+" means "same-sign" connection

FIGURE 1. SLOW/FAST controller circuit schematic diagram.

2. Inputs

- **Signal Input**:
  - BNC connector on the front panel, labeled ***INPUT***
  - Input impedance: $Z_i \geq 1000\ \Omega$
  - Input polarity switch on front panel, labeled "+" for non-inverting and "-" for inverting.
- **Slow Path External Offset Input**:
  - BNC connector on the front panel, labeled ***SLOW OFFSET***

- **Slow Path Internal Offset**:
  - Range: ± 0.5 V
  - Four-decade (0.1 mV steps) switch on front panel, labeled ***SLOW OFFSET***

3. Outputs

- **Fast output**:
  - Two BNC connectors in parallel, one on front panel, one on back panel, labeled ***FAST OUT***
  - 3 dB bandwidth (without poles and zeros specified in section 5, below): ≥ 1 MHz
  - Range: ± 20 V nominal, ± 24 V max.
  - Output impedance: $Z_o \leq 10\ \Omega$
  - Input-referred noise: $\leq 10\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, $100\mathrm{Hz} \leq f \leq 100\mathrm{kHz}$
- **Slow output**:
  - Two BNC connectors in parallel, one on front panel, one on back panel, labeled ***SLOW OUT***
  - Range: ± 4V nominal, ± 6V max.
  - Output impedance: $Z_o \leq 10\ \Omega$
  - Input-referred noise: $\leq 10\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, $100\mathrm{Hz} \leq f \leq 100\mathrm{kHz}$

4. DC Gain

- **Fast path**:
  - Overall gain $1000 \pm 10\%$
  - First stage gain: $10 \pm 10\%$
  - Second stage gain: $100 \pm 10\%$
  - Gain control: 1 kΩ, ten-turn, lockable pot between first and second stage, mounted on front panel, labeled ***FAST GAIN***
- **Slow path**:
  - Overall gain $20 \pm 10\%$
  - First stage gain (common with fast path): $10 \pm 10\%$
  - Second stage gain: $2 \pm 10\%$
  - Gain control: 20 kΩ, ten-turn, lockable pot between first and second stage, mounted on front panel, labeled ***SLOW GAIN***

5. Poles and Zeros

- **Fast path**:
  - Two poles at 500Hz $\pm 10\%$
  - One pole at 1500Hz $\pm 10\%$
  - Three zeros at 30kHz $\pm 10\%$
  - Can be distributed between first stage and second stage amplifiers

- **Slow path**:
  - Two poles at $0.025\text{Hz} \pm 10\%$
  - Two zeros at $0.1\text{Hz} \pm 10\%$
  - Located in second stage (x 2) amplifier

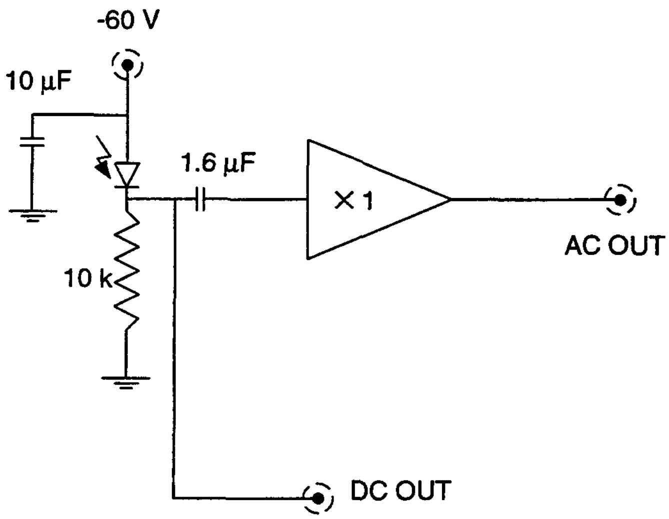
Specifications for Power Sampling Photodetector Intended for use with the NPRO-PSL

A. Abramovici, R. Savage, May 2, 1996

LIGO-E960042-00-D

1. General

- Die-cast aluminum RF-grade box of minimal size, labeled *Power Sampling PD, NPRO-PSL.*
- All circuitry and connectors shall be attached to the lid of the box. Standard 1/2" mounting post attached to the lid of the box via 1/4-20 or 8-32 screw.
- 1/2" dia. hole in the body of the box, centered on photodiode.
- Floating BNC connectors, unless otherwise stated
- Refer to the circuit diagram in Fig. 1.



Photodiode: YAG-200A by EG&G Canada

FIGURE 1. Circuit diagram for Power Sampling Photodetector

2. Inputs

- BNC connector for -60 V bias voltage, center conductor negative, labeled *-60 V IN.*
- Standard 3-pin LEMO connector for ±12 V input, labeled ±12 *V IN.*

3. DC Output

- BNC connector, labeled *DC OUT.*

4. AC Output

- BNC connector, labeled *AC OUT.*
- Impedance, $R_o \leq 10\ \Omega$
- Buffered:
  Gain=1
  3dB bandwidth 10 MHz
- No-light noise levels:
  $N \leq 30\ \mathrm{nV/Hz}^{1/2}$
  Line-related spikes $\leq 300\ \mathrm{nV}$ rms

Specifications for Power Stabilization Amplifier Intended for use with the NPRO-PSL

A. Abramovici, R. Savage, May 2, 1996

LIGO-E960045-00-D

1. General

- Single-width NIM module, labeled *PS AMP, NPRO-PSL*
- All controls on front panel
- Floating BNC connectors, unless otherwise stated

2. Input

- DC coupled
- BNC connector on front panel, labeled *PD IN*
- Input impedance, $R_i \geq 1000\ \Omega$
- DC offset zero correction using 10-turn linear pot accessible through front panel. Pot mid-range corresponds to 0.0 V offset correction.
- DC offset drift less than 10 μV p.t.p. between 15°C and 25°C, input-referred.
- Input-referred noise $\leq$ 30 nV/$\sqrt{\text{Hz}}$, 100 Hz-100 kHz

3. Output

- Two BNC connectors in parallel, one on front panel, one on back panel, both labeled *OUTPUT* or *OUT*
- Output resistance $R_0 \leq 10\ \Omega$
- Output range ± 10 V
- Line-related spikes ≤ 100 nV rms, input-referred

4. Gain

- DC gain $500 \pm 10\%$
- Gain adjustment range 5 to 500 by 10-turn logarithmic pot with lockable dial, labeled *GAIN*

5. Poles and Zeros

- Two poles at 1 kHz $\pm 10\%$
- Two zeros at 4 kHz $\pm 10\%$

Specifications for Power Sampling PD Bias Supply Intended for use with the NPRO-PSL

A. Abramovici, R. Savage, May 2, 1996

LIGO-E960048-00-D

1. General

- Single-width NIM module, labeled *PS PD BIAS, NPRO-PSL*

2. Output

- -60 V$\pm$10 %, 10 mA
- Two BNC connectors in parallel, one on front panel, one on back panel, both labeled $-60\ V\,OUT$
- Line-related spikes compatible with Power Sampling Photodetector output noise level specifications (refer to LIGO-E960042-00-D).

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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NPRO frequency stabilization

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1 ABSTRACT

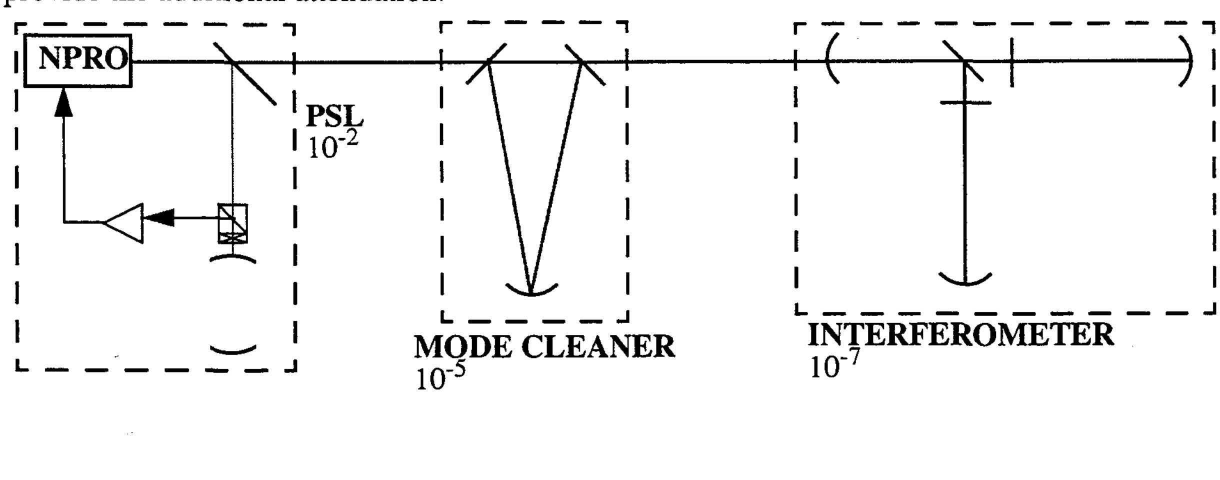
As a first step in the process in switching to Nd:YAG lasers in LIGO, frequency stabilization techniques were applied to a Lightwave model 126 Nd:YAG 1064 nm 700 mW laser. This has two main motivations. First is that the proposed 10 W laser under development for LIGO by Lightwave uses the Model 126 laser as a master oscillator in a MOPA (master oscillator/power amplifier) configuration, and as such will be the point at which frequency corrections are applied in the 10 W version. The second motivation is simply to develop a 1064 nm light source for various experiments while the 10 W version is still being developed, such as the PNI IR conversion.

In this document, a description of the system is outlined, the design of the servos is detailed, and a procedure for obtaining lock using a fixed length reference cavity is described. This system can readily provide stabilization to the level of 10 mHz/$\sqrt{Hz}$ from 10 Hz to ~10 kHz. Lock is also quite robust, with lock being kept for time periods of at least 24 hours on a regular basis.

2 CONCEPTUAL DESIGN

2.1. Outline of an interferometer

LIGO proposes to measure strains due to gravitational radiation on the order of $10^{-23}/\sqrt{Hz}$. An interferometer is to be used by essentially comparing the phase history of light down one arm of the interferometer with the phase history of the light that travelled down the second arm of the interferometer. If there is any mismatch to the lengths of the arms, it can be seen that phase noise, or equivalently, frequency noise, would be a source of noise in the signal, by the relation $\delta f \ll (\delta l)/l \cdot f \cdot (1 - CMRR)$, CMRR being the common mode rejection ratio. In order for LIGO to measure the proposed strains, frequency fluctuations will need to be kept below 10^{-7} Hz/$\sqrt{Hz}$in the interferometer in the bandwidth of interest, assuming a CMRR of 99%. Since the proposed Nd:YAG laser has a frequency noise level typically about 100 Hz/$\sqrt{Hz}$ at 100 Hz, it's obvious that some frequency stabilization will need to be done to the laser. This level of suppression is a bit beyond the abilities of a single control loop, so one way to do this is to provide suppression in stages. The first stage of this is called the PSL (Pre-stabilized laser). This supplies approximately 80 dB at 100 Hz. Next is the mode cleaner, after which the laser light should be about 10^{-5}Hz/$\sqrt{Hz}$. The common mode servo of the interferometer locks the laser light to the interferometer, and will provide the additional attenuation.



The above diagram gives a rough outline of how a LIGO-like system could be laid out. Not shown in the above diagram are feedback paths from the interferometer and the mode cleaner back to the PSL. The details of how the servo topology for frequency noise in LIGO will be laid out is yet to be finalized.

2.2. Requirements

For this first version of the NPRO PSL, refer to document "NPRO-PSL Design Requirements" (LIGO T960082-00-D) for requirements. Initial requirements of 1 mHz/$\sqrt{Hz}$ were relaxed while testing was going on to 10 mHz/$\sqrt{Hz}$ from approximately 10 Hz to 10 kHz. This calls for a servo gain of at least 46 dB at 10 kHz, and a gain of about 106 dB at 10 Hz. Also two feedaround paths were to be supplied, to allow direct frequency control to be applied from the mode cleaner and the interferometer. The reference cavity to be used would be a fixed length cavity made of two mirrors optically contacted to a ULE fused silica spacer. In order to have some ability to shift the frequency of the output beam from that of the reference cavity, a double-passed AOM would be used in the PSL stabilization path to shift the frequency of the light $2f_{AOM}$ +/- f_{Tuning}, where f_{Tuning} is +/- 5 MHz, determined by the requirement to keep the laser locked to both the reference and some external cavity.

3 SYSTEM LAYOUT

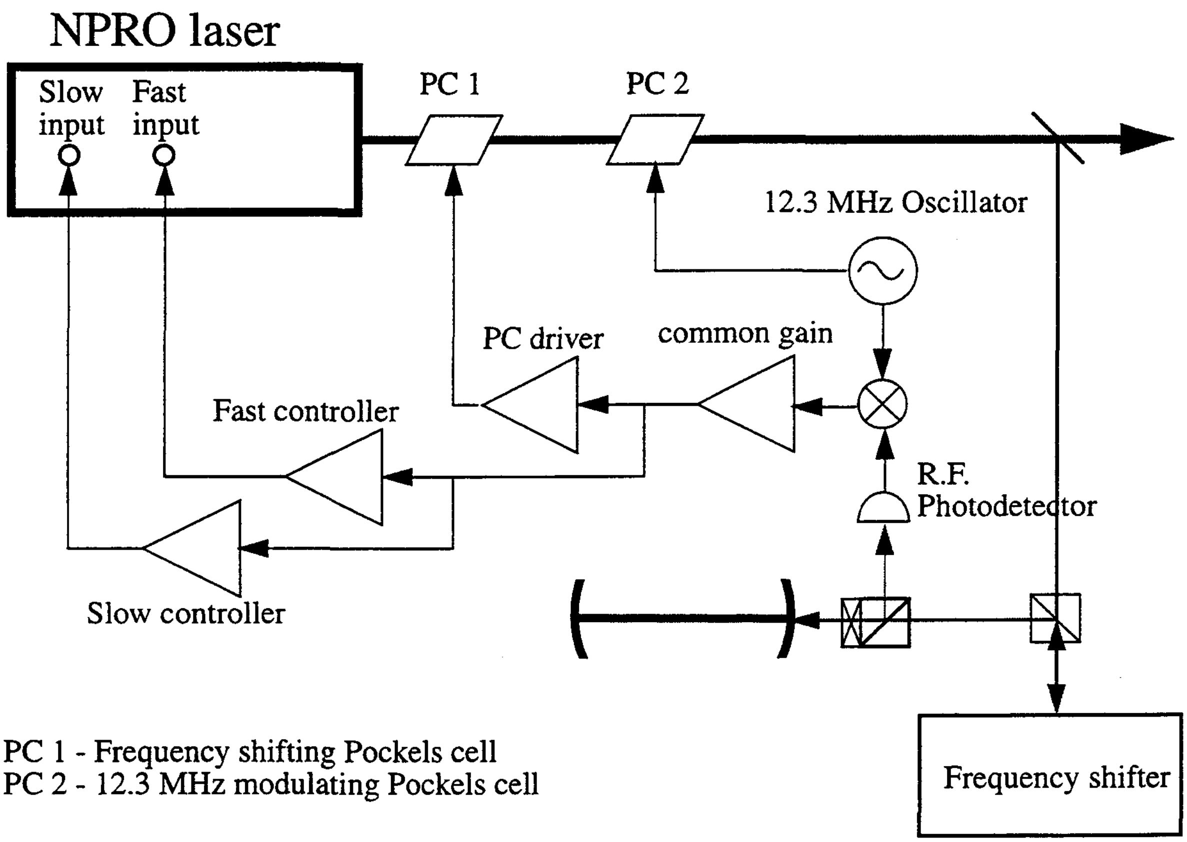
The proposed topology for frequency stabilization of the PSL is specified in the document, "NPRO-PSL Conceptual Design" (LIGO T960089-00-D).

The Model 126 NPRO laser comes with two frequency correction actuators built in. The "slow" controller consists of a thermoelectric cooler, which sets the temperature of the NPRO crystal. This has two effects, to change the physical size of the resonator cavity and to change the index of refraction of the crystal. Lightwave reports that the change Δn of the crystal has a much larger effect than the change in the size Δl. This input has a usable bandwidth of about 0.1 to 1 Hz. The gain is approximately 3-4 GHz/V, with a range of +/- 10 V. The "fast" controller consists of a piezo bonded to the resonator crystal. Voltage applied to it stresses the crystal, inducing changes in frequency. The bandwidth of this path is nominally limited by the internal resonances of the piezo, which begin around 200 kHz. The gain here is approximately 4 MHz/V, with a range of +/- 50 V. Both inputs give a positive change in frequency for a positive voltage. The free running frequency noise of the laser is approximately (2×10^4/f) Hz/$\sqrt{Hz}$ from 10 to 10 kHz.

The reference cavity is a ULE fused silica spacer, 20 cm in length, with mirrors optically contacted to each end. The mirror transmissions are 300 ppm, with losses < 30 ppm. This gives a finesse of ~ 10000, and a bandwidth of about 75 kHz. The temperature induced resonant frequency change is ~ 150 MHz/° C. The light is to be locked to this cavity using the Pound-Drever-Hall reflection locking technique, using sidebands at 12.3 MHz. The cavity is suspended in a vacuum chamber at 10^{-7} torr by two loops of wire from a 3 layer seismic isolation stack.

Since the cavity has no length adjustment, a double passed AOM is used to shift the frequency of the output laser light from that of the reference cavity. Double passing the 1st order diffracted beam output of the AOM, the light is shifted by twice the drive frequency of the AOM. This frequency is a nominal 80 MHz +/- 5 MHz. This gives a tuning range of +/- 10 MHz, which was chosen after analysis of data from the 40m interferometer and the 12m triangular mode cleaner.

The stabilization servo would need about 46 dB of gain at 10 kHz, but the fast piezos probably don't have a usable bandwidth much more than 20 kHz due to their resonances. This makes it necessary to utilize an external phase correcting Pockels cell to extend the bandwidth of the servo so it can be stable. The Pockels cell used is a New Focus model 4004 broadband Pockels cell, with a specified modulation depth of 15 mrad/V.



The diagram above lays out the general design of the NPRO PSL. The other Pockels cell in the diagram is the 12.3 MHz Pockels cell, a New Focus 4003 resonant Pockels cell. The 12.3 MHz oscillator and amplifier are existing modules. The photodiode is an existing RF photodetector, using a tuned tank circuit at 12.3 MHz, modified for 1064 nm with either a YAG444 or a 220A photodiode.

4 SERVO DESIGN

Servo design requires some modeling, into which physical parameters need to be put. Measurements were made of the various actuators to build the model.

4.1. Actuators and existing gains

4.1.1. Slow actuator

The slow actuator frequency response was measured by locking the laser to a Coherent optical spectrum analyzer in transmission. The slow input was driven and the transfer function from the slow input to the locking error signal was taken. The closed loop gain was divided out, giving the frequency response of the actuator. This is shown in Figure 1 (All figures are collected at the end of this document). A simple model for this response is a 3-pole roll off at 0.2 Hz, with a DC gain of 3 GHz/V.

4.1.2. Fast actuator

Nominally, the piezo of the fast actuator should have a relatively flat frequency response out to the mechanical resonances of the piezo. A measurement of this was made by locking the laser to the reference cavity with low gain and bandwidth (< 1 kHz). Above the servo bandwidth, then, the signal out of the demodulator is essentially an open loop measurement of the frequency noise. The fast piezo was driven above the unity gain of the servo, and a transfer function was measured from this input to the demodulator out. Figure 2 shows a 10-100 kHz span of this measurement. Included in the dynamics of this measurement is the cavity pole, which shows up at 35 kHz. Subtracting the cavity pole results in a flat response at least to 100 kHz. Of note are the features around 30 kHz, 60-70 kHz, and above 90 kHz. These are consistent with parallel, or parasitic resonances, most likely of the structure the piezo is mounted on. A measurement was made to higher frequencies, also. Piezo resonances were found around 250 kHz, above which the response was not coherent. The gain of the piezo was determined by driving the piezo open loop with a triangle wave generator. The amplitude was high enough to scan through the carrier and both sidebands. A photodiode monitored the transmitted light through the cavity, and an oscilloscope was used to determine the amount of voltage needed to scan from sideband to carrier, then carrier to the next sideband. Several measurements were averaged to give 4.1 MHz/V.

4.1.3. Pockels cell

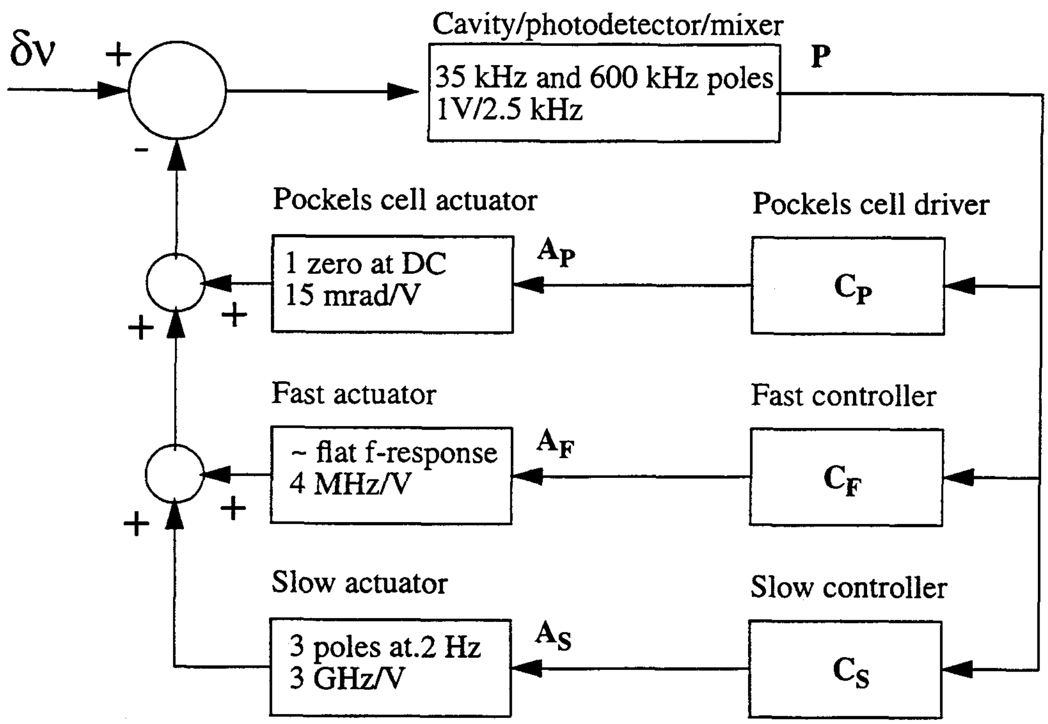
The Pockels cell response was measured in the same fashion. The laser was locked with low gain and bandwidth (~2 kHz). The Pockels cell was driven, and the transfer function from the Pockels cell to the demodulator output was measured. Figure 3 shows this transfer function, with the cavity pole, the demodulator gain, and the zero of the Pockels cell divided out. The measured gain of the Pockels cell is 19 mrad/V.

4.1.4. Demodulator gain

The "demodulator gain" refers to the voltage out of the mixer due to a frequency fluctuation about the point of resonance. This can be estimated using a relatively simple analytical model. The power incident on the photodiode which contains the signal proportional to frequency fluctuations goes as $Re\{E_0 \cdot (E_{+1} + E_{-1})^*\}$, where E_0, E_{+1}, and E_{-1} are the carrier and sideband fields reflected from the cavity. Using 85% photodiode efficiency, a known impedance of 8000 Ω in the tank circuit of the R.F. photodiodes, and a 6 dB insertion loss into the mixers, a demodulator gain of about 1 V/2.5 kHz is arrived at. In reality, the actual gain will probably be lower, due to imperfect modematching, etc. However, this number is sufficient to use in a model.

4.2. Controller design

A block diagram of the controller is shown below. Each of the actuator loops needs to be used in parallel with the other 2. The rule for parallel open loop gains is that the open loop looks like the frequency response of the particular loop which dominates in gain. In this case, we expect to see the slow loop dominate below .1 Hz, the fast loop to dominate up to about 20 kHz, and the Pockels cell to dominate out to the bandwidth of the servo.



4.2.1. Slow controller

The main purpose of the slow controller is to provide DC control of the laser. That is, for long term drifts due to variations in temperature of the laser, the reference cavity, etc., the slow actuator, with a possible tuning range of about 600 GHz, is used. Since the reference cavity has no length control, and a free spectral range of 750 MHz, DC fluctuations are most easily controlled using the slow actuator. This is most effectively done by using an integrator in the slow controller. For practical purposes, this controller needs a "switch" that turns the integrator off, which is done by moving the pole from DC to some finite frequency, in our case 0.05 Hz. This is useful to short the integrator if any offsets have been integrated, and allows for faster time responses of the slow controller in this mode. Since acquiring lock would also be very difficult with the integrator on, the shorted integrator is referred to as "acquisition mode". This loop should have a bandwidth of approximately 0.1 Hz, due to the poles at 0.2 Hz in the actuator.

The range of the slow controller would in principle need to be within one free spectral range of the cavity, or 750 MHz, which corresponds to about 200 mV in the slow actuator. Standard op-amps will have plenty voltage output to tune over many free spectral ranges, so the dynamic range of this controller would not be a problem.

At the upper end of the slow bandwidth, 0.1 Hz, we have no specific frequency noise requirement, but the requirement at 10 Hz of 10 mHz/$\sqrt{Hz}$ might suggest a level of 100 mHz/$\sqrt{Hz}$ at 0.1 Hz. Based on a conservative 1V/10 kHz mixer output, this corresponds to an input referred electronics noise of ~ 1μV/$\sqrt{Hz}$, which is pretty trivial.

4.2.2. Fast controller

The fast path will be responsible for the frequency noise suppression in the bandwidth of interest. The main design requirement is that the servo has enough gain, and has low enough noise. Given a 1/f free running noise spectrum, then the controller needs to be at least 1/f. A 2 pole controller was designed, mostly because it was simple enough to do. A third pole was added to help roll off the response at higher frequencies, in response to the presence of piezo resonances in the 200's of kHz. A zero was added to improve the phase of the fast loop at the point where control is handed over to the Pockels cell. So, the fast controller has poles at 10, 100, and 10000 Hz, and a zero at 500 Hz. The nominal gain at DC is about 10^6.

Given the free running frequency noise quoted in section 3.1, and assuming this is reasonably good down to .1 Hz, integrating this power gives about 2×10^6 Hz_{RMS} from .1 to 10000 Hz. Working back from the fast actuator, this corresponds to about 0.5 V_{RMS}, which is not a problem for controller or actuator.

The noise of this servo must be small, at least a factor of 10 below the frequency noise goal. Using 1 mHz/$\sqrt{Hz}$, and the demodulator gain, we specified an input referred noise of 300 nV/$\sqrt{Hz}$, which is also fairly simple, as long as the gain of this loop is kept in the early stages of the electronics.

4.2.3. Pockels cell driver

The main purpose of the Pockels cell path is to extend the bandwidth of the overall loop gain, so that there can be ~46 dB of gain at 10 kHz. There are several factors that motivate the shape of this loop. Drive voltages to a frequency correcting Pockels cell typically are rather high. In order to keep this number as low as possible, the loop is ac-coupled with 2 zeros at DC. This puts the phase of the loop +270 degrees. At the point where the Pockels cell loop gain equals the fast loop gain, however, stability considerations dictate that the difference in phase of the two loops needs to be less than 180 degrees. Since the fast loop has phase close to -180, several poles need to be incorporated in the Pockels cell path to bring the phase to an acceptable level. Zeros are also incorporated the controller to account for the cavity pole and the photodiode pole. To this end, the Pockels cell controller has two zeros at 0 Hz, one at 50kHz, and one at 1MHz. A pole is put at 1 kHz, and 3 more at 5 kHz. Gain is adjusted to cross the fast loop gain around 20 kHz.

As mentioned before, the two zeros in the Pockels cell path are included to reduce the amount of rms contribution from frequency noise out of the band dominated by the Pockels cell. A model of the loop was put together in Matlab, the transfer function was calculated from frequency noise to the voltage into the Pockels cell. Multiplied by the frequency noise of the laser, and integrated, the total rms to the Pockels cell is about 1-2 V_{RMS}. This allows the Pockels cell controller to be made using standard op-amps, which simplifies the problem somewhat.

Noise consideration are similar to the slow controller in that the bandwidth dominated by this controller is out of the specified frequency range for control.

4.2.4. Additional features

In addition to the poles and zeros and voltage requirements for each of the three loops above, other features of note are included in the design. First, a feedaround input, as required in the conceptual design document, is incorporated into the early stages of the amplifier. This is simply to be a unity gain buffer. Also, to simplify the amount of cabling, the mixer is included on board, along with notch filters for the modulation frequency and its first two harmonics. The slow path also includes a buffered input at the end of its path in order to sum an external DC voltage offset. As mentioned in the conceptual design document, this is necessary for lock acquisition. A DC bias is applied to the slow input in order to coarsely tune the laser to the resonant frequency of the reference cavity. Once the laser is close to the cavity frequency, lock can be acquired and the integrator in the slow path can be used to maintain the proper bias to the slow controller to keep the laser at that frequency. Also included are test inputs and outputs to measure transfer functions, and monitor outputs are on each of the servo path outputs. Since this is a 3 degree of freedom system, 3 gain controls are included. Since the Pockels cell path goes to high bandwidth where phase delays can have significant effect, the placement of the 3 gain stages are an overall gain stage, and one each in the slow and fast paths, leaving out any direct gain control in the Pockels cell path. Switches are included to switch off the slow controller, to switch between "acquisition" and "integration" mode in the slow controller, and to switch to a test input after the mixer output for diagnostic purposes.

A schematic of the controller along with a list of the front panel features and labels is included at the end of this document.

4.3. Modeling results and predictions

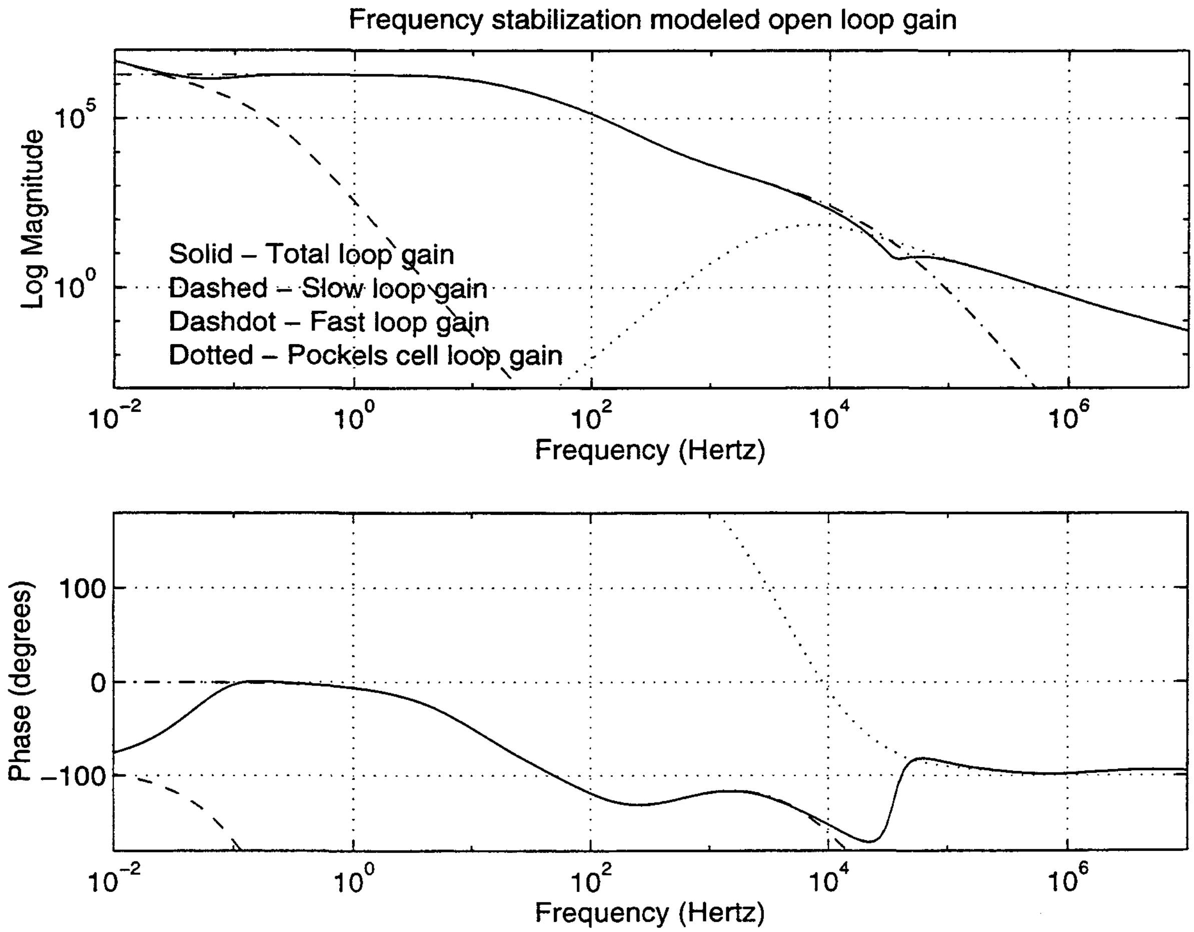
4.3.1. Loop gain and expected residual frequency noise

As mentioned in section 4.2.3, a model of this control loop was built in Matlab, using the measured parameters of the system and the proposed control electronics, as laid out in the diagram above. The paradigm consisted of *.m files which contained the frequency response of each of the blocks in the diagram in section 4.2. A master file called these transfer functions and multiplied them in the appropriate fashion to generate whatever transfer function was required. The resulting open loop gain is given by the following equation, and shown in the following figure. The C's, P's and A's are defined as in the block diagram in section 4.2. Calculating the residual frequency

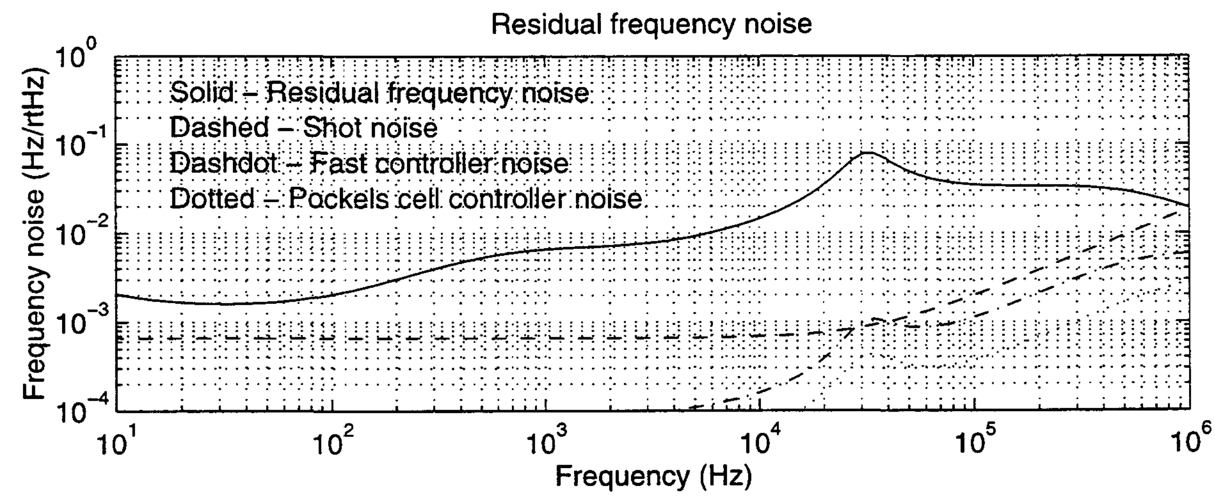
$$L_{OL} = P \cdot (C_S A_S + C_F A_F + C_P A_P)$$

noise requires the closed loop gain, shown below, multiplied by the open loop frequency noise spectrum. Based on this transfer function, and assuming a frequency noise spectrum like that

$$L_{CL} = \frac{1}{1 + L_{OL}}$$



stated in section 3.1, this results in a residual frequency noise spectrum shown in the following figure.



4.3.2. Limiting noise sources

4.3.2.1 Shot noise

The frequency detection method is a process dependent on sensitivity to optical power, in other words, it counts photons. A fundamental noise source with this sort of detection is shot noise, which essentially goes as $\sqrt{N}$, where N is the number of photons detected. Detailed calculations have derived formulas for the shot noise sensitivity of this detection method, given as

$$\frac{S}{N}(f) = \vartheta_{FSR}\sqrt{\frac{e}{\sigma}} \cdot \frac{\sqrt{3|E_+|^2 + E^2{}_{DC}}}{2\pi E_2 E_+} \cdot \frac{(1 - r_a r_b)^2}{T_a r_b} \cdot \sqrt{1 + \left(\frac{2\pi f}{\omega_c}\right)^2}$$

Definitions for the various parameters are found by referring to either "Shot Noise in a Recycled Unbalanced LIGO" by Torrey Lyons and Martin Regehr, or "Calculations for the Shot Noise in the Recycled 40m" by Malik Rahkmanov. Given the appropriate parameters for the optical configuration, the level of shot noise is shown on the previous figure.

4.3.2.2 Electronic noise

The designed electronics were modeled in Cadence to predict their transfer functions, and estimate their noise outputs. Cadence is a sophisticated program which takes into account real properties of op-amps, phase delays in circuits, etc. From the output referred noise predicted by the Cadence model, transfer functions were derived from the output of the controllers to the frequency error point to estimate the contribution to frequency noise due to noise in the electronics. The figure above containing the residual frequency noise also contains the level of noise contributions from both the fast and Pockels cell controllers.

5 PERFORMANCE

5.1. Measured transfer functions and noise

Figures 4 and 5 show measured transfer functions of the fast and pockels cell controllers. These all agree with the modeled transfer functions to reasonable levels of accuracy. Figures 6 to 8 show measured output referred noises of each of the controller electronics. These also agree remarkably well with the Cadence model prediction.

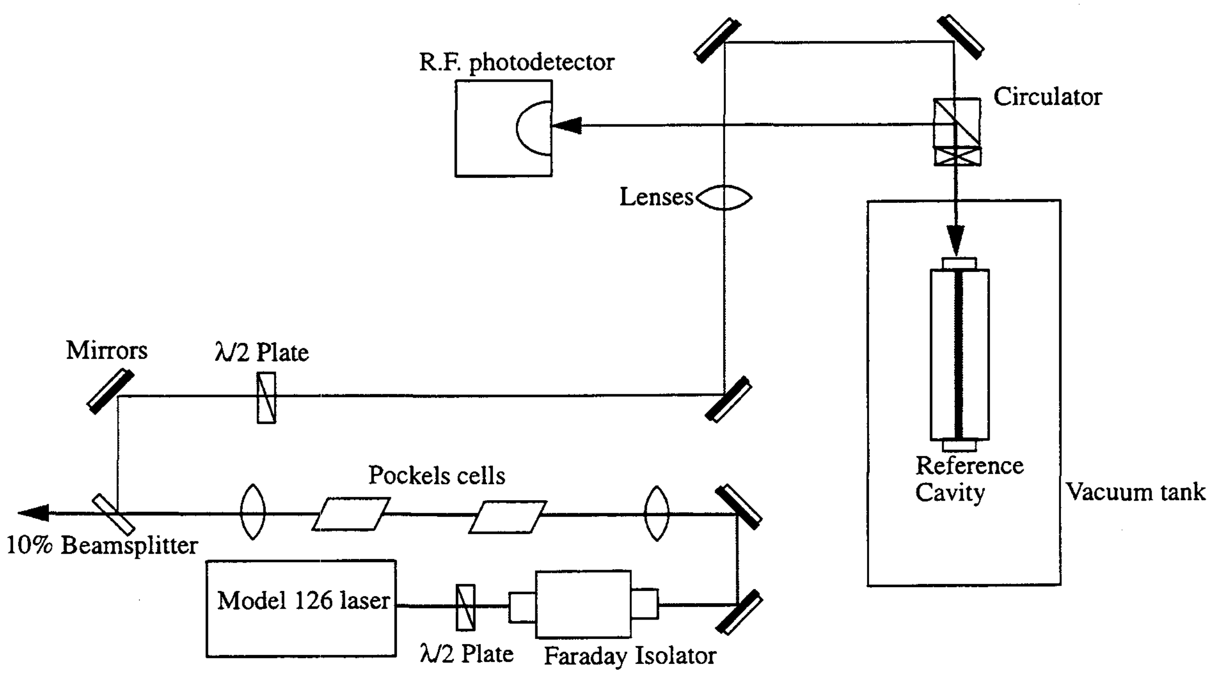
5.2. Locked laser measurements

Figure 9 shows an in-loop (and hence lower bound) measurement of the residual frequency noise. The following figures, 10 and 11, shows measurements of the open loop gain for this particular measurement, over different bandwidths. Of note is that the frequency noise requirements have mostly been met within the bandwidth of interest as measured inside the loop. Although the figure shows 10 mHz/$\sqrt{Hz}$ only to 7 kHz, obtaining this level at 10 kHz was not difficult, however, it entailed increasing the gain of the fast loop, which causes the bump at 30 kHz to grow. This is a result of the relative phase of the fast and Pockels cell paths at the crossover point, which gets worse at higher frequency. Agreement between this and the predicted residual frequency noise is very good. However, some problems show up in the measurement of the loop gain, most notably the amount of phase available at unity gain. The model prediction shows that there should be plenty of phase at unity gain, and bandwidth shouldn't be limited at all by this consideration. The measurement on the other hand indicates that the phase drops considerably in the 100 kHz band, and that phase margin goes to 0 at about 600 kHz. The fact that the phase is decreasing in the fashion that it does tends to suggest that phase delays are accumulating in the Pockels cell path. The measurement of the pockels cell controller supports this, and modeling phase delay produces a loop gain which agrees with the measurement.

6 OPERATION

6.1. Setup

The figure below lays out our optical table and elements.



The first λ/2 plate is used to rotate the polarization of the light from vertical to 45 degrees for insertion into the Faraday isolator (measured insertion of 93%). The light leaving the isolator is then polarized perpendicular to the table. The first lens is used to focus the light to a waist position between the two Pockels cells. The measured spot size at 5 cm from the laser is ~.2 mm, and the waist positioned between the Pockels cells is nominally.1 mm. The first Pockels cell is the broadband frequency correcting Pockels cell, and the second is used to impose the 12.3 MHz modulation. This was driven at ~ 6 V_{P-P}, resulting in a modulation of ~ Γ =.75. The next lens is used in conjunction with the 3rd lens for modematching. A 10% window is used to pick off a portion of the light for frequency stabilization. Since the laser is outputting about 600 mW, and we really only would like about 10 mW input to the cavity, the second λ/2 plate is used in conjunction with the circulator's polarizing beamsplitter to dump the rest of the light. This obviously is not optimal for use in an interferometer, however it suited this particular setup. The circulator is a polarizing beamsplitter with an optically contacted $\lambda/4$ plate. This causes the light reflected from the cavity to be reflected by the polarizing beamsplitter, not transmitted. This light is then detected by an R.F. photodetector, which has a tuned resonant circuit to maximally transmit power at 12.3 MHz. The vacuum tank was kept at 10^{-7} torr using a Vac-Ion pump. Inside the vacuum, the reference cavity was hung from small springs mounted on posts. Two small copper vanes were hung from the cavity close to two sets of 4 magnets in a quadrupolar configuration for eddy current damping of the two swinging modes of the suspended cavity. The supports for the cavity are mounted on an isolation system made up of 3 plates with RTV silicone springs between them. Not shown but also used was an infrared camera, placed at the far end of the vacuum tank in order to see the light transmitted when the cavity was on resonance. Also not shown is an optical spectrum analyzer, which has another 10% pick off just before the RF photodiode. Note that the frequency shifter was not incorporated into this layout, because time did not allow.

6.2. Alignment

Typical alignment procedure involved first passing the light through the Faraday isolator. This was done using an infrared photo card, and eyeballing the position of the beam approximately to the center of the F.I. apertures. The alignment was done by shifting the position and tilt of the F.I.. The next alignment was the first lens, which simply involved positioning the lens such that the beam passed through the center of the lens, by marking the position of the beam without the lens at the other end of the table, and bringing the position of the beam back to the same place once the lens was installed. Next, in order to align the beam through the 2 mm apertures of the Pockels cell, a negative lens was used to blow the beam up so it was approximately 2 cm in diameter on a beam block. The position of the front aperture for each Pockels cell was adjusted by finding where the beam clipped the aperture on each side, then centering the aperture in between these points. Then the positions of the rear apertures were dithered to minimize the distortion to the beam as viewed in the expanded spot. The next two lenses were also centered, and placed according to calculations to mode match into the cavity. Alignment into the cavity was performed first by roughly eyeballing the light to the center of the input cavity mirror, using the final two mirrors in the optical path. Then a function generator was used to dither the frequency of the laser over a large range in the slow actuator (by at least one free spectral range), while the camera which looked at the output of the cavity was monitored. Once modes began flashing in the cavity, adjustments were made based on the strength of the modes, to begin optimizing for lower order modes. Once a TEM_{00} mode was found, a slow DC offset was applied to the slow actuator to bring the laser close to the frequency of the 00 mode, and the function generator drove the fast actuator (the time scales of the slow actuator were irritatingly slow). Then, the alignment attempted to maximize the output of the 00 mode through the cavity. For reference, irises were placed in the optical path and centered on the beam for future alignment.

Some "electrical" alignment is also done. First, the phase of the local oscillator applied to the mixer needs to be set. Since the phase shifter has, at the smallest, 10 degree divisions, this was done by eye. The 00 mode was found, and the function generator used to dither the fast input of the NPRO. The output of the mixer was viewed on an oscilloscope set to trigger as the laser went through resonance. The phase was adjusted to maximize the symmetry of the demodulator output, verified by setting the phase to the "wrong" phase and confirming the symmetry in that output.

Also, the electronics comes with the ability to tune out any voltage offset out of the mixer. This was done by looking at the MIXROUT output through a SR560 and a gain of about 100, low passed at .03 Hz. The pot, located inside the NIM module, was tuned such that the DMM read about 1 mV, after the bias of the SR560 was tuned out, which seemed to be about as good as could be done.

6.3. Nominal settings

A set of parameters was developed as indications of the state of the system. Nominal values for these parameters were worked out to insure repeatability of results. These are listed in the table below.

Modulation voltage	2.5 V_{Peak}
Modulation depth	.75
Cavity input power	10 mW
Visibility	80-90%
Laser power	600 mW
Vacuum pressure	10^{-7} torr
RFPD V_{DC} (out of lock)	-130 mV
RFPD V_{DC} (locked)	-48 mV

Table 1: Nominal parameters for NPRO laser

6.4. Lock acquisition

The process used to acquire lock in these experiments was not automated. Gains in all loops are turned to 0, the slow loop is left open, and the integrator is switched off to keep from integrating up any offsets in the path. The slow actuator is ramped in the slow DC input using the Calibrators DC voltage supply until the 00 mode is found, usually by watching the camera which is looking at the transmitted cavity light. Once the mode is found, the gain in the fast path is turned up slightly. If the laser is very close to resonating, the laser will usually lock right away. If not, the slow actuator must be used to tune the laser closer to the right frequency, with the fast gain small, maybe about 0.1, and the common gain at minimum. The reason that the fast gain must be kept low is that when the laser needs to tune through the point where the sidebands are resonant, the servo has the wrong sign, and a large voltage builds up in the fast path as the slow DC tries to push against the fast gain of the servo. When the slow finally manages to exceed the ability of the fast loop to keep away from the sideband resonance, the fast voltage drops to zero and the laser frequency shifts very rapidly through the carrier and the other sideband, to the tuned point of the slow DC. However, with low fast gain, it's easy to tune via the slow DC close to resonance, then turning up the fast gain usually will lock the laser immediately. At this point, the fast gain needs to be increased to about 0.5 to 1.0 before the common gain can be turned up. This sets the crossover between the fast loop and Pockels cell at approximately the right place in the 20 kHz region. Then the common gain can be turned up to approximately 0.6 or 0.7. This brings the loop very close to the maximum gain possible, limited by the loss of phase margin at 600 kHz. If the MIXROUT output is being monitored on an oscilloscope, this is evident by the output voltage beginning to grow as the gain is increased. This is not due to a noisier laser, but rather unity gain oscillations at around 500 kHz. At this point, the slow loop is turned on, and the slow mode is switched from acquisition to integration. The gain of the slow loop can be turned up to about 0.3 or 0.4 before oscillations begin to develop.

Re-acquisition once lock is lost is a similar process. The first thing that needs to be done fairly quickly is the integrator must be switched off. Also the gains must be turned down in the same way as acquiring lock the first time. If the slow DC bias is still hooked up and supplying the DC voltage which brought the laser roughly to resonance, frequently all that's needed is to wait until the laser relaxes and returns to equilibrium. Loosing lock typically causes the laser to shift its frequency somewhat, and requires about a half a minute to relax. Once close to resonance, again, the fast gain is turned up, then the common gain. However, if the laser frequency set by the slow DC bias has drifted relative to the cavity sufficiently, the laser will not return to the point where the fast loop can acquire. At this point, the slow DC bias voltage must be scanned again to find the resonance. This typically is not far away, though, so radical shifts in voltage should not be required.

6.5. Problems

Below is a list of problems and other notes concerning frequency stabilization of the NPRO, both understood and not understood.

- When the common gain is turned up too high, although not high enough to lose lock, occasionally 2 spikes in the frequency spectrum show up around 3 and 5 kHz. The origin of this is unknown, however it's suspected that a stage in the pockels cell path may be saturating. The pockels cell path has very high gain, which peaks at about 4 kHz, and the first pass at these electronics had bad saturation problems in the pockels cell path (not on the output, however).
- Concerning the use of the power adjust input for power stabilization. There is a very strong coupling between the power adjust input and frequency noise. Figure 12 shows a transfer function between the power adjust input and frequency noise output. This measurement was made with the built in "noise eater" off, however with the noise eater on, this trace goes down maybe only 10 dB. It was made by driving the power adjust and looking at the voltage out of the demodulator. The cavity pole and the loop gain have been divided out, as well as the frequency to voltage gain of the demodulator. This coupling is both good and bad. The good is that stabilizing the power output of the laser diodes does help the frequency stabilization, which tends to suggest that a large amount of frequency noise comes from intensity fluctuations of the laser diodes. The bad is that stabilizing the laser light at some point far down the optical path may introduce noise into the laser diode in order to correct for artificial intensity fluctuations (i.e., fluctuations due to beam jitter through a mode cleaner, parasitic interferometers). This in turn will make the frequency stabilization worse.
- Changing the common gain of the servo while the integrator is on seems to occasionally cause problems, that is the slow path seems to want to begin oscillating. Not understood.

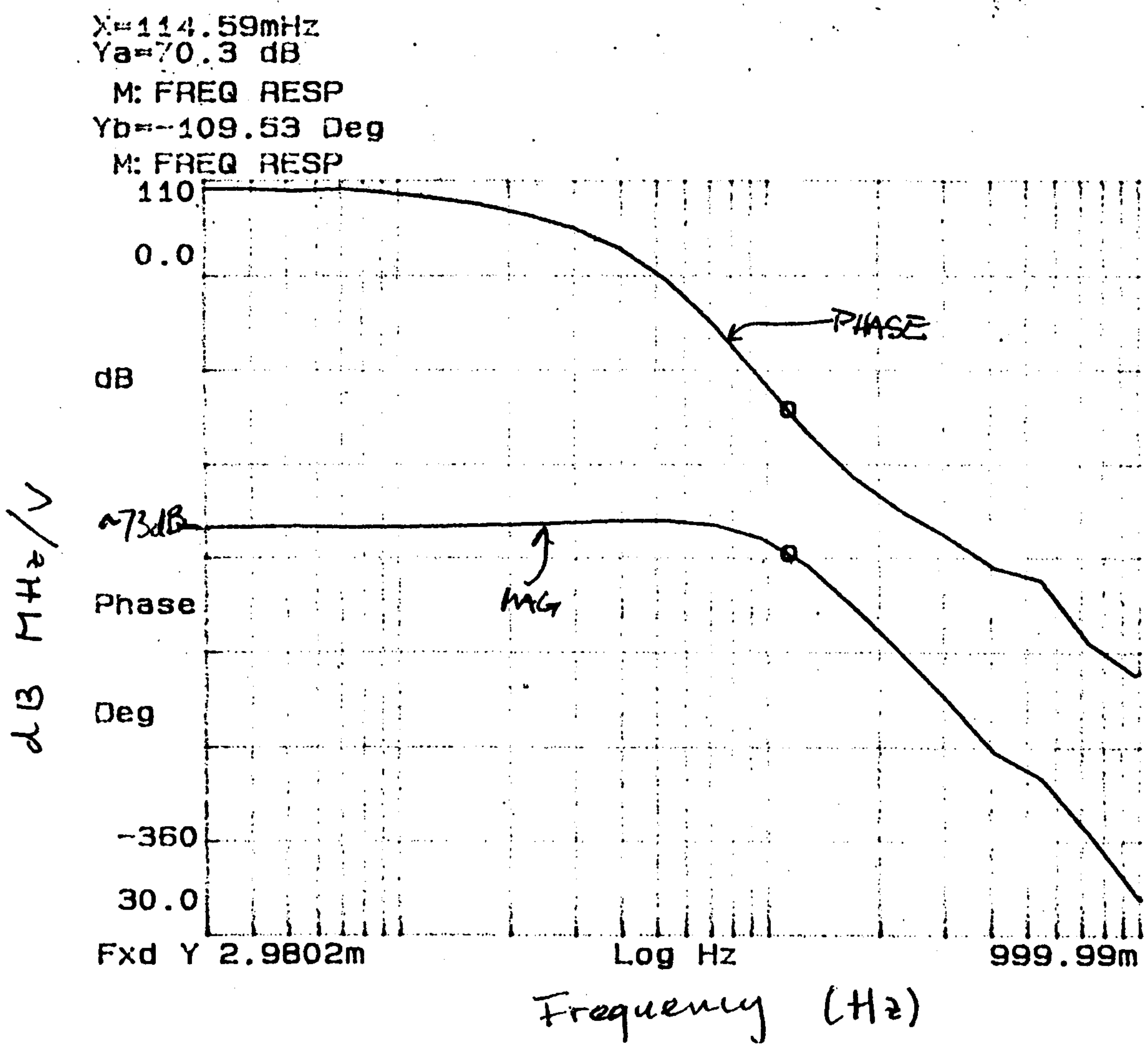
- The slow monitor output monitors the output of the slow controller before the slow DC bias is summed.
- Fast monitor offsets. The laser, once locked using the fast and Pockels cell, can be tuned using the slow DC bias until the DC offset out of the fast controller is nulled. Turning the slow controller on in acquisition mode will not typically change this, that is the slow controller will hold the DC laser frequency close enough to resonance such that the fast path will have no DC offset (over short time scales). However, turning the integrator on will typically shift the fast offset to a couple volts. The origin of this is uncertain, but could be consistent with mV offsets in the slow path. Changing the gain of the slow controller affects this offset, also. For long time scales, though, it's favorable to use the integrator, since it will keep this offset constant, whereas in acquisition mode, there isn't enough gain to adequately track the long term variations in the laser temperature and the cavity fluctuations.

7 FIGURES

29 MARCH 96 14:10

Response of "SLOW" NPRO input

FIGURE 1



73dB ~ $4 \cdot 10^3$

→ 4GHz/V

The magnitude for this plot is obtain by multiplying the measured one by:

x100 (since ÷100 monitor was actually measured)

x $\frac{300\ \text{MHz}}{86\ \text{V}}$ TROPEL tuning constant (measured).

Drive voltage to slow input

35 mV peak ÷ 2 ÷ 30 ≅ .6 mV peak.

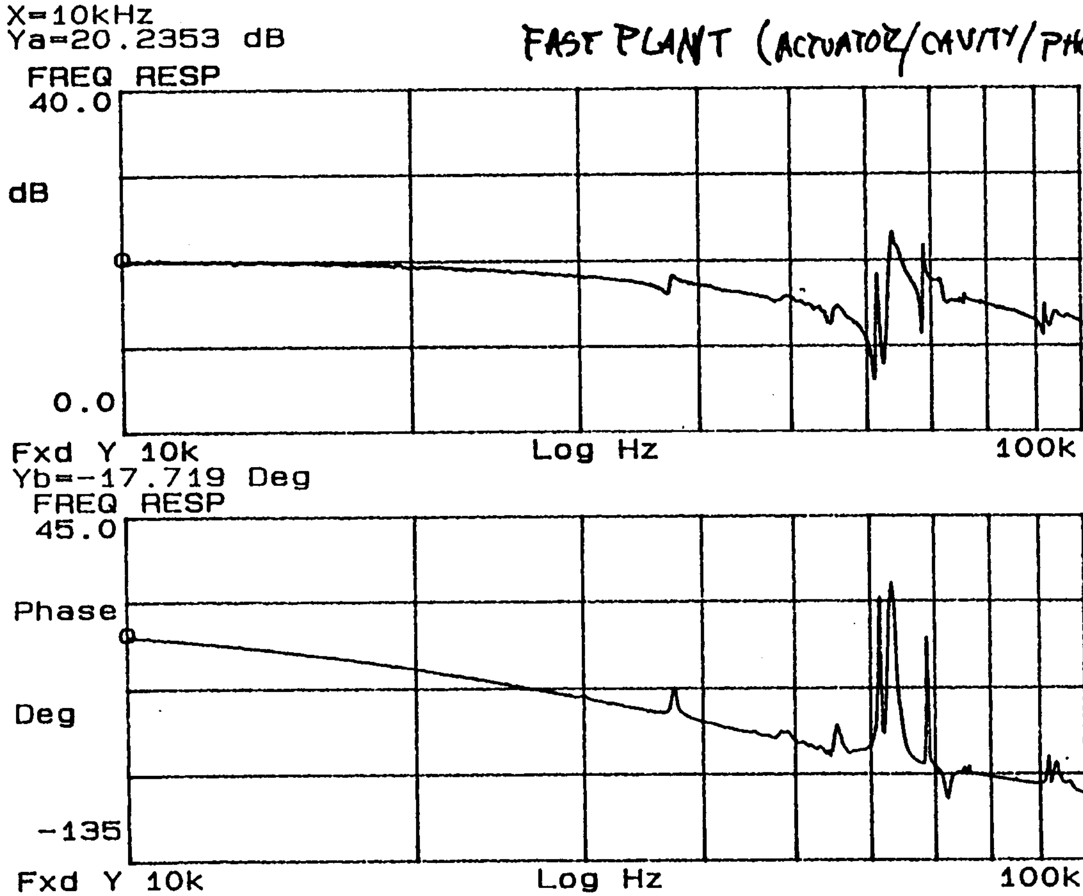
File: PSL/Slowin

10/16/96 16:00
JEM

"1016FPNT"

COHERENCE SAVED
AS 1016FPTC

FAST PLANT (ACTUATOR/CAVITY/PHOTODIODE)



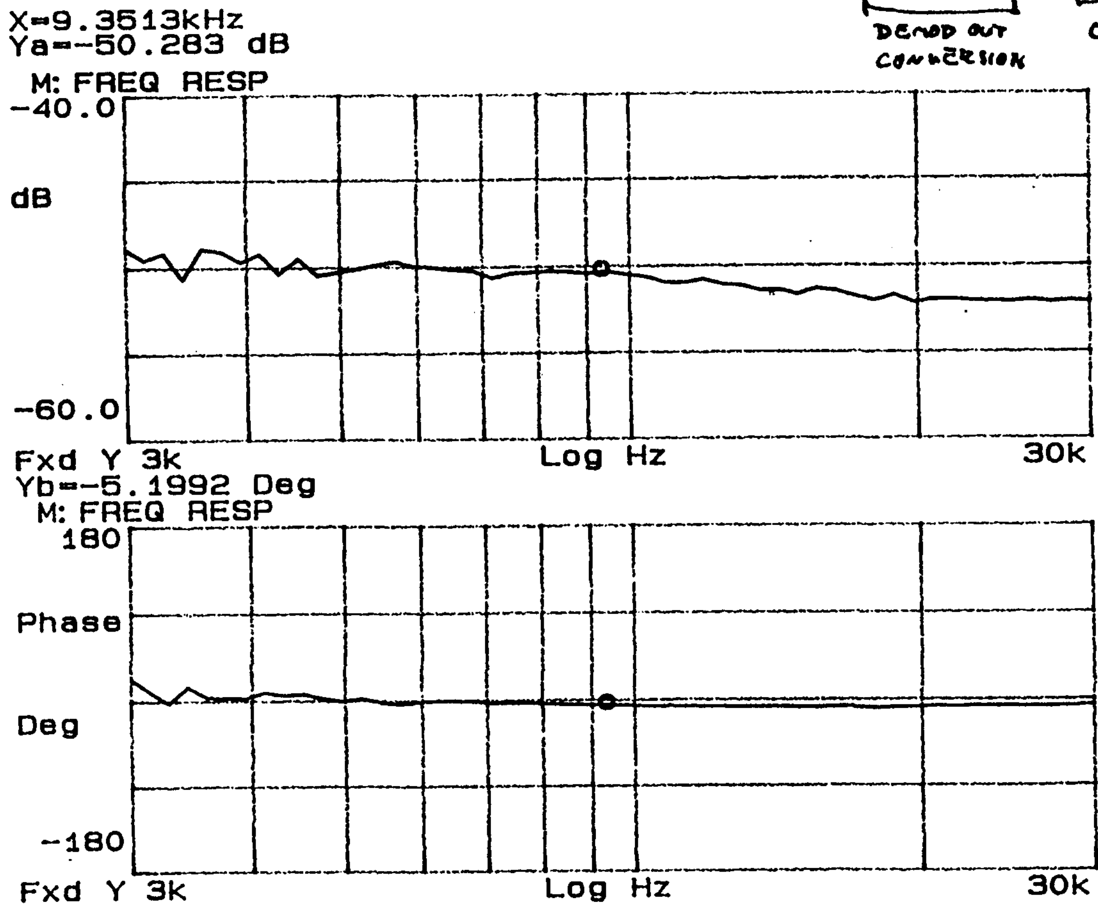
PROVIDED THAT THIS IS ESSENTIALLY AN OPEN LOOP MEASUREMENT, AND THAT WE EXPECT NO POLES/ZEROS < 10kHz, THIS GIVES THE DEMOD OUT V → FREQUENCY CONVERSION OF ~ 400kHz/V

FIGURE 2

12/17/96
JEM

POCKELS CELL ACTUATOR GAIN

$$\frac{V_{DEMOD\ OUT}}{V_{POCKEL\ CELL}}\ \text{TRANSFER FUNCTION} \times \underbrace{33.7\ kHz/V}_{\text{DEMOD OUT CONVERSION}} \times \underbrace{\frac{2\pi \times 35000}{s + 2\pi \times 35000}}_{\text{CAVITY POLE}} \times \underbrace{\frac{1}{i\omega}}_{\frac{1}{s}}$$



ROUGHLY −50dB = 3.2 mRAD/V

×2π = 20 mRad/V

@ 30 kHz, −52dB ⇒ 16 mRad/V

FIGURE 3

FAST CONTROLLER TRANSFER FUNCTION 1/30/97

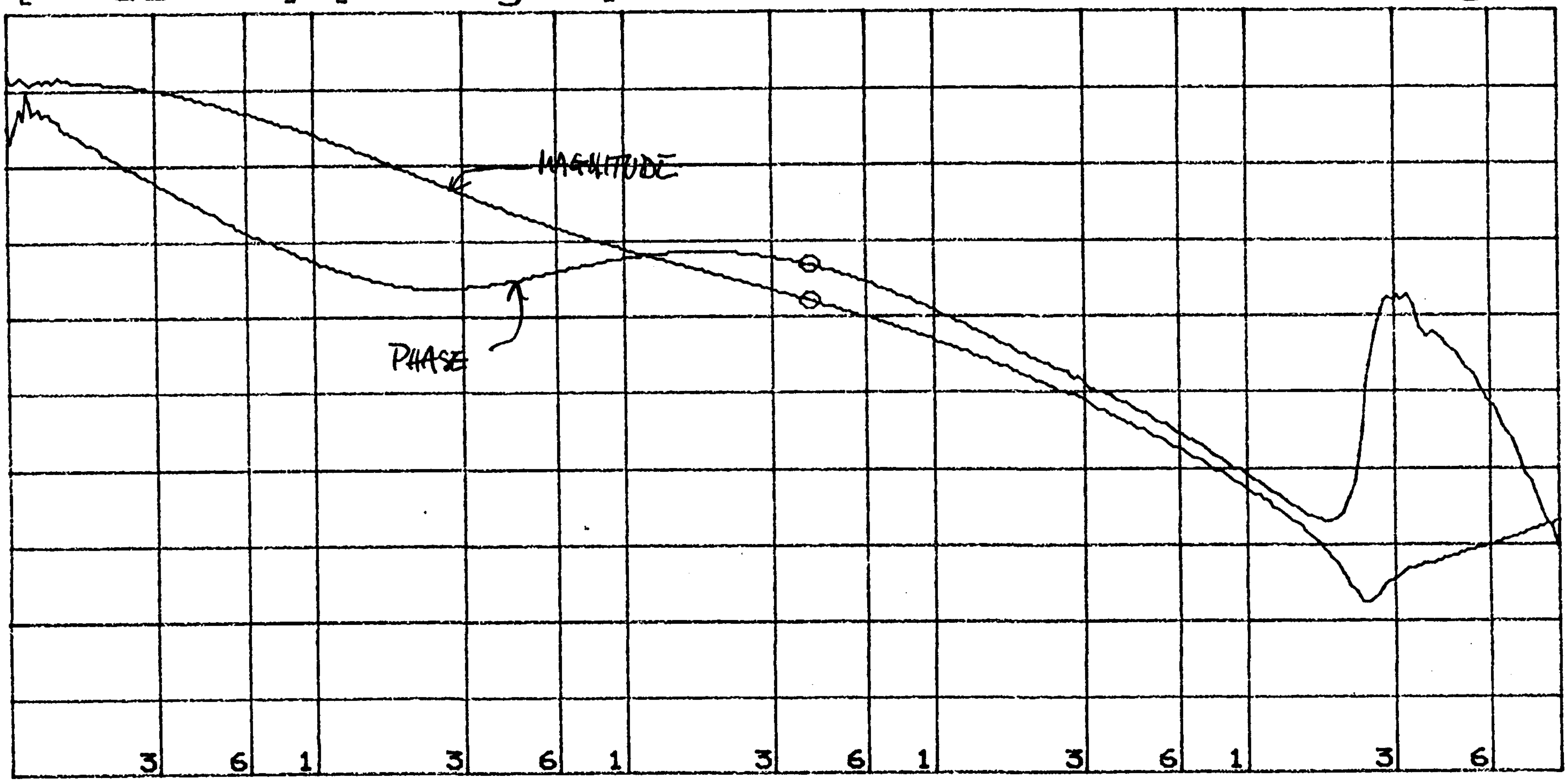
COMMON GAIN - 0.65 FAST GAIN - 1 JEM.

NETWORK

A: REF B: REF o MKR 3 981.072 Hz

80.00 180.0 T/R 4.25477 dB

[dB] [deg] θ 60.8732 deg



DIV 20.00 DIV 36.00 START 10.000 Hz

STOP 1 000 000.000 Hz

RBW: 10 Hz ST: 3.62 min RANGE: R=-10, T= 20dBm

FIGURE 4

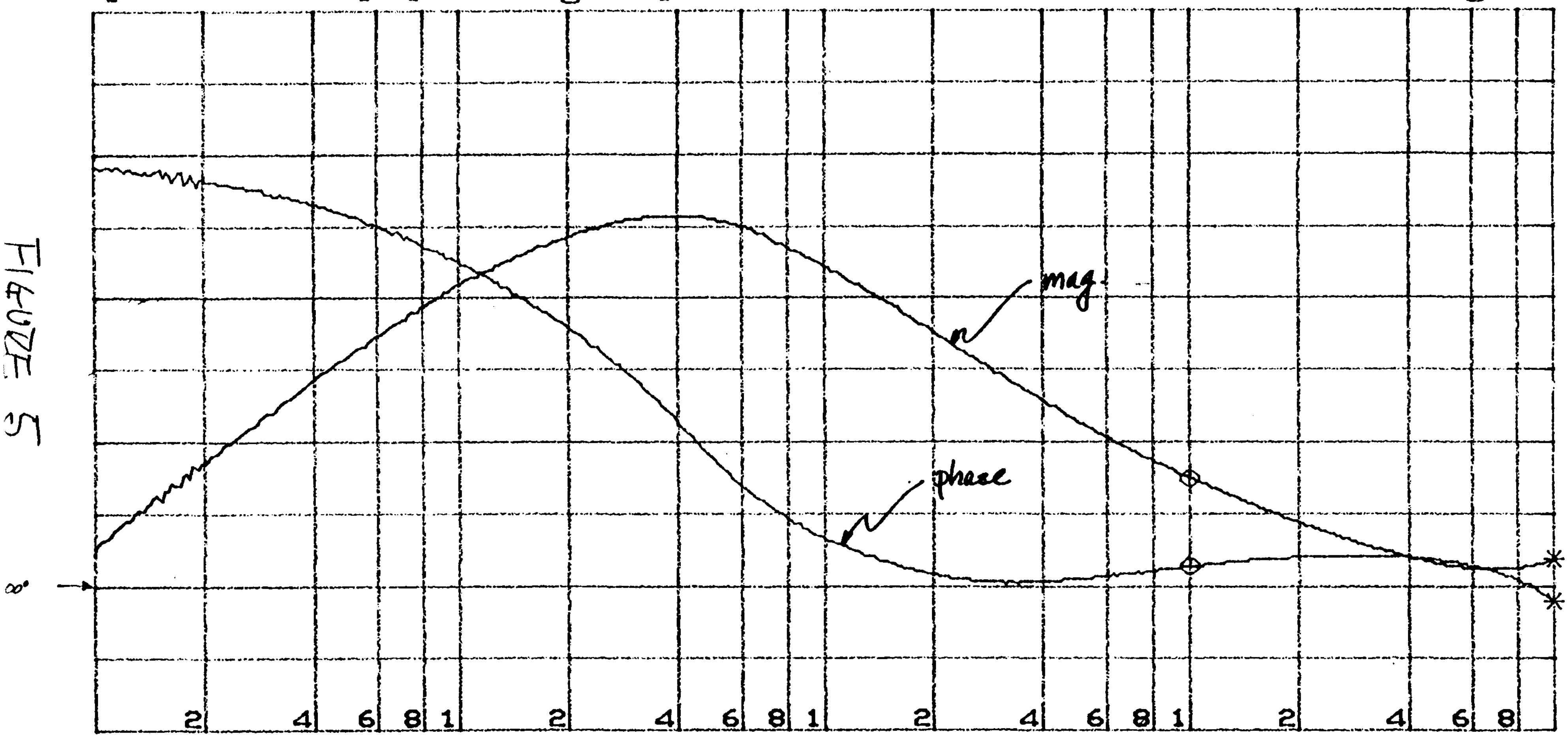
FREQ. STAB. SERVO ELECTRONICS. "INTI" TO "PC OUT"   21 JAN '97 RA.
1447

PLOT RE-TAKEN (THIS PLOT IS CORRECT.) WITH HIGH Z PROBE ON NWA "T" PORT.

NETWORK

A: REF	B: REF	* MKR	1 000 000.000	Hz
110.0	100.0	T/R	33.8060	dB
[dB]	[deg]	θ	−309.999	deg

FIGURE 5

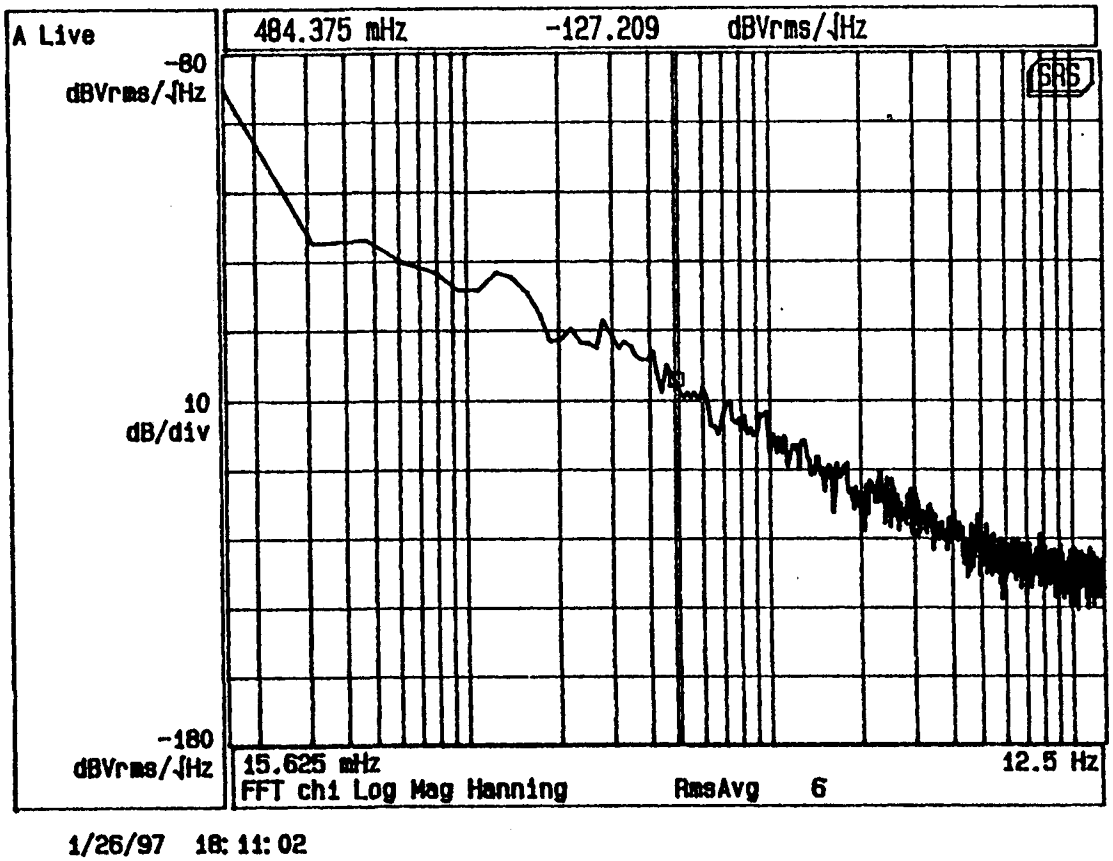


DIV	DIV	START	100.000	Hz
10.00	50.00	STOP	1 000 000.000	Hz

RBW: 100 Hz ST: 40.2 sec RANGE: R= 0, T= 20dBm

1/26/97 JEM

OUTPUT REFERRED NOISE OF THE SLOW CONTROLLER



INPUT 50Ω TERMINATED
COMMON GAIN 0.65
SLOW GAIN 0.35

FIGURE 6

OUTPUT REFERRED NOISE OF THE FAST CONTROLLER

INPUT 50Ω TERMINATED COMMON GAIN - 0.65 FAST GAIN - 1.0

1/26/97

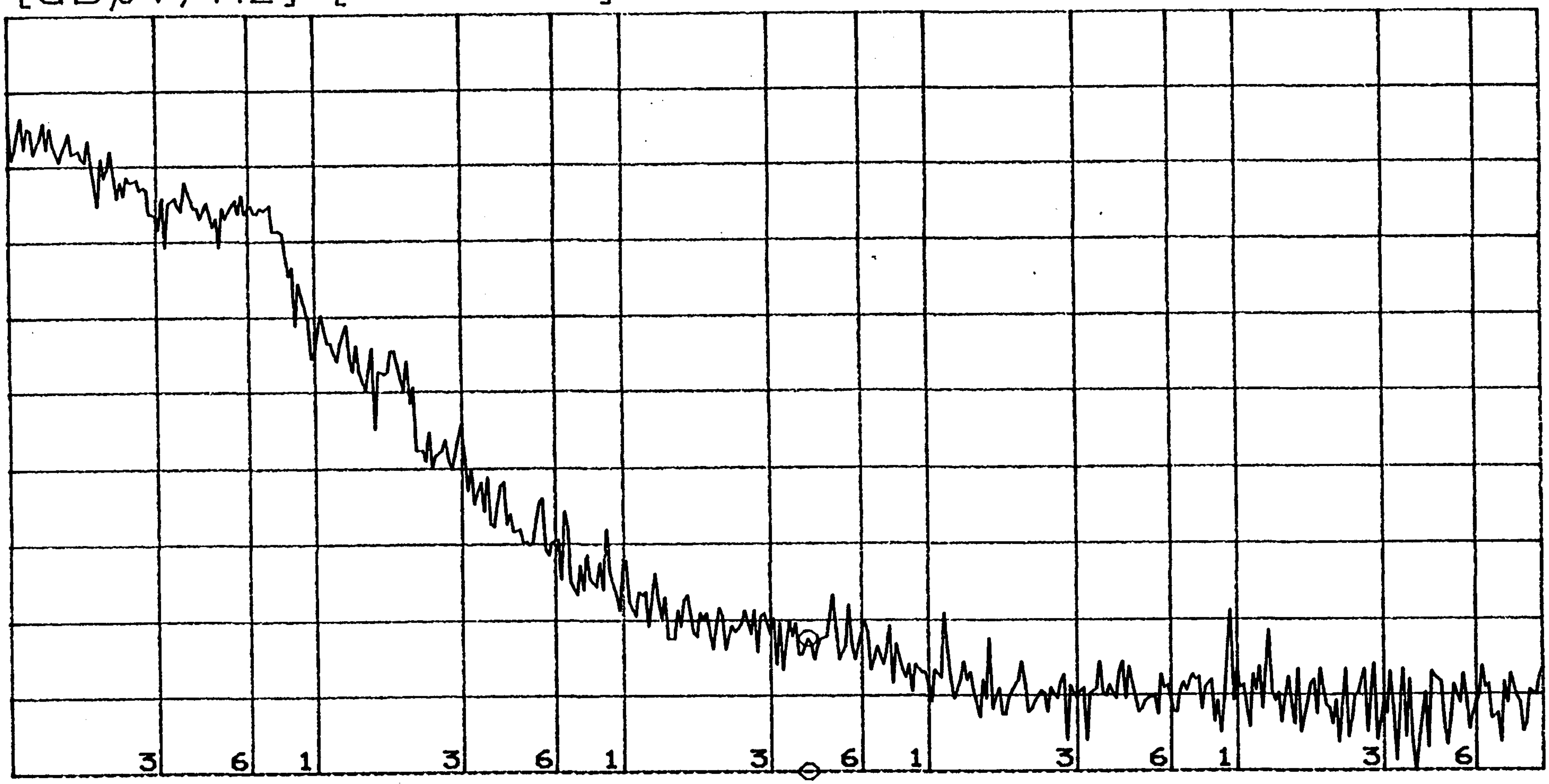
JEM

SPECTRUM

A: REF B: REF ○ MKR 3 981.072 Hz

60.00 −10.00 MAG −22.4445 dBμV/Hz

[dBμV/Hz] [ ] MAG



DIV DIV START 10.000 Hz

10.00 10.00 STOP 1 000 000.000 Hz

RBW: 30 Hz ST: 3.13 min RANGE: R=−20, T=−20dBm

FIGURE 7

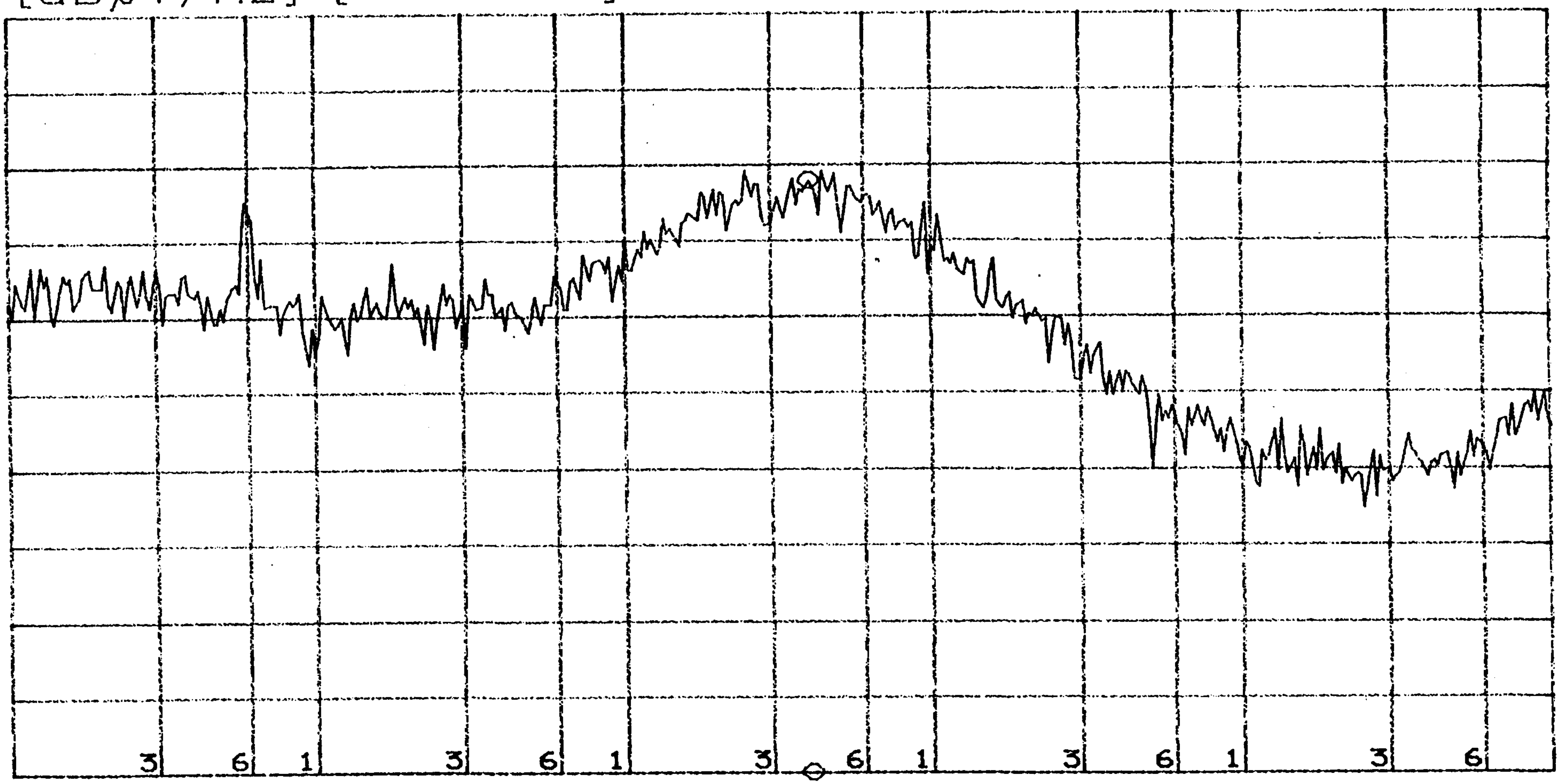
1/26/97
JEM

OUTPUT REFERRED NOISE OF THE POCKELS CELL CONTROLLER

INPUT 50Ω TERMINATED COMMON GAIN - 0.65

SPECTRUM

A: REF 60.00 [dBμV/Hz]
B: REF -10.00 [ ]
○ MKR 3 981.072 Hz
MAG 37.9227 dBμV/Hz
MAG



DIV 10.00 DIV 10.00 START 10.000 Hz
STOP 1 000 000.000 Hz
RBW: 30 Hz ST: 3.13 min RANGE: R=-20, T=-20dBm

FIGURE 8

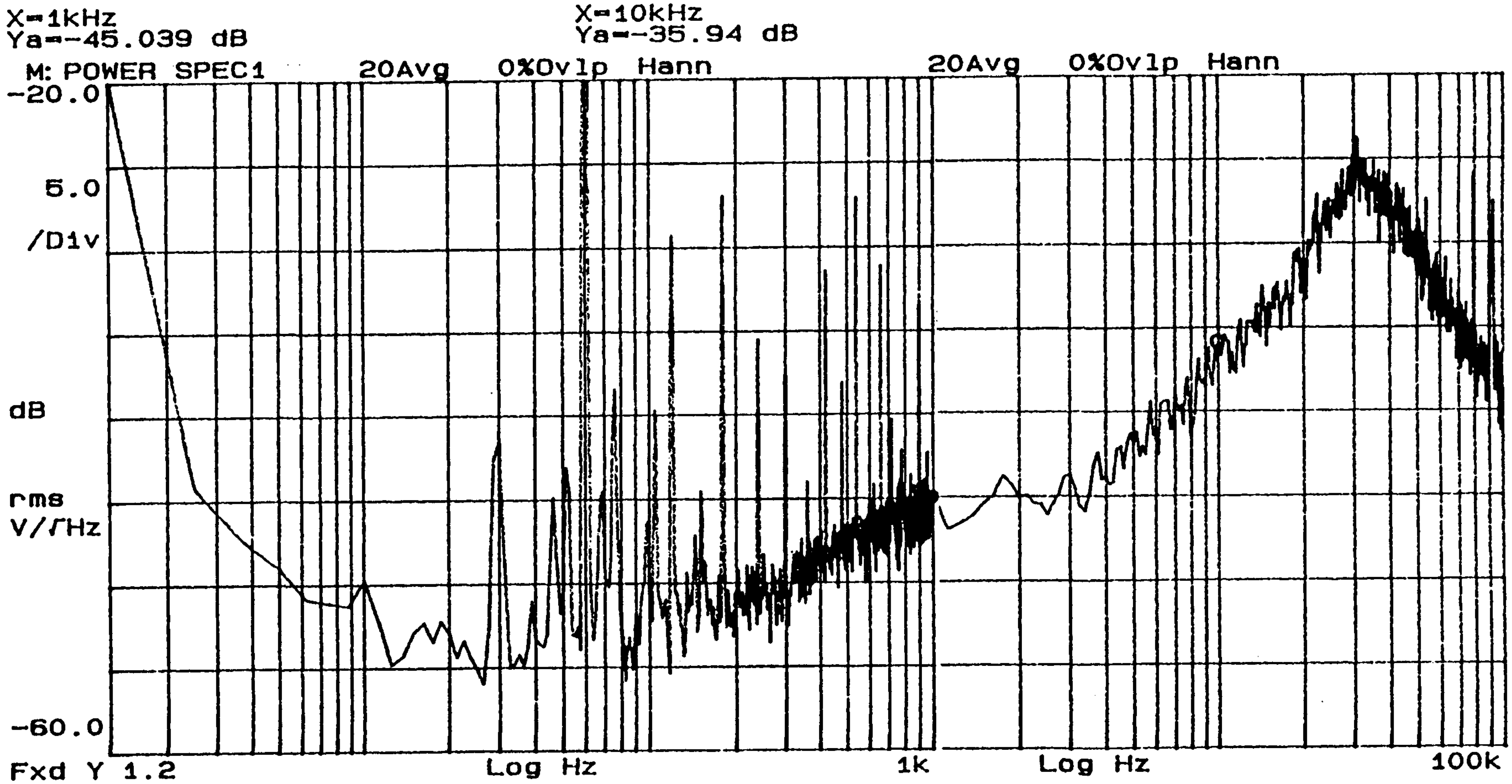
12/31/96
JEM

FREQUENCY NOISE MEASUREMENT (IN-LOOP)

SLOW 0.2
FAST 1.0
COMMON 0.8

USES 5.8 kHz/V

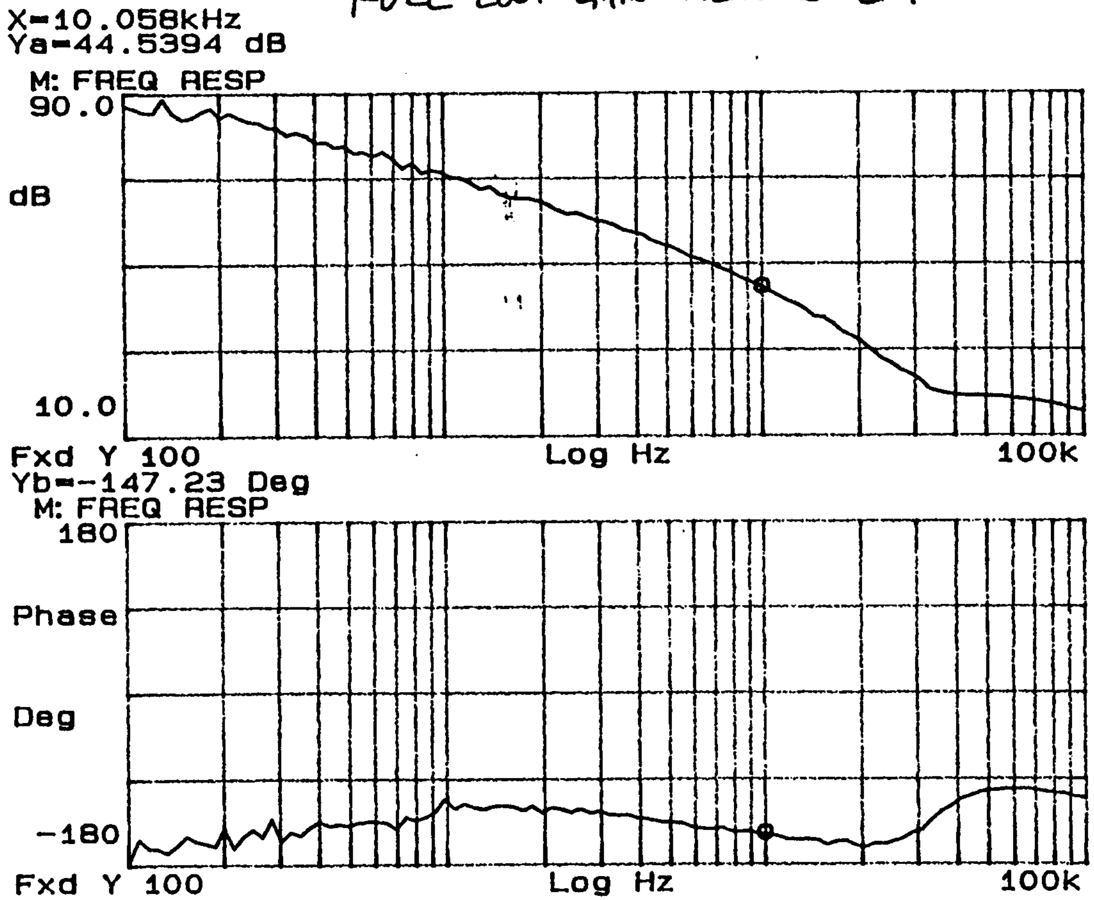
FIGURE 9



COMPOSITE OF ~~THE~~ 100 kHz &
1 kHz SPAN, FILES
1231P~~S~~H1 & 1231PSM1

12/31/96
JEM
"1231LG1"

FULL LOOP GAIN MEASUREMENT



SLOW-OFF
FAST - 1
COM - 0.8

12.3MHz - 6.06Vp-p
RFPD V_{DC} - -49.1mV
SLOW IN V_{DC} - -198.4mV
10mW TO THE CAVITY

FIGURE 10

FREQUENCY STABILIZATION LOOP GAIN MEAS.

S - 0.5
F - 10
H - 0.8
~10mW LIGHT TO CAVITY,
F~75, VISIBILITY ~83%

1/2/96 JEM

NETWORK Math
A: REF B: REF ○ MKR 441 570.447 Hz
50.00 180.0 MAG -158.841m DB
[DB] [°] θ 14.8382

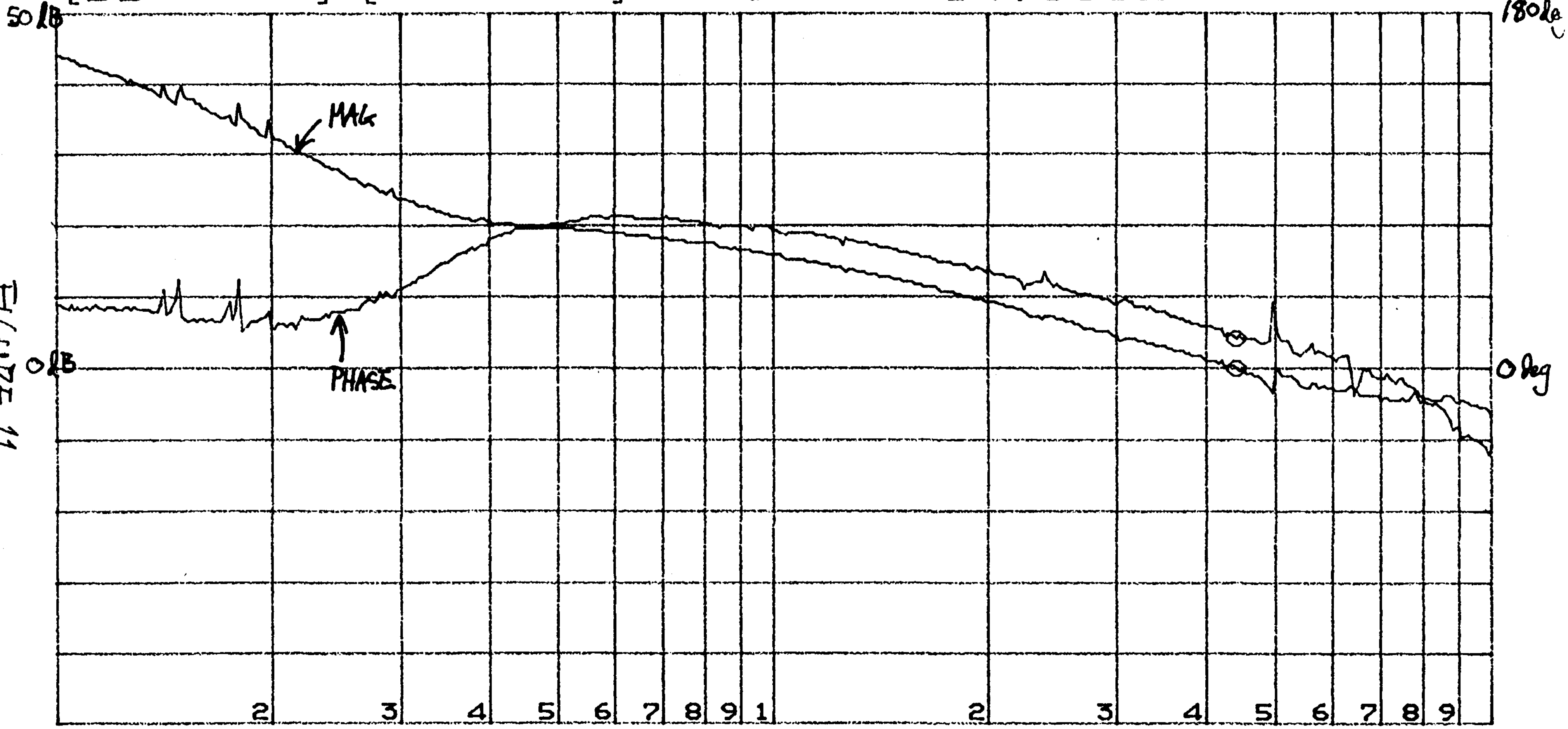


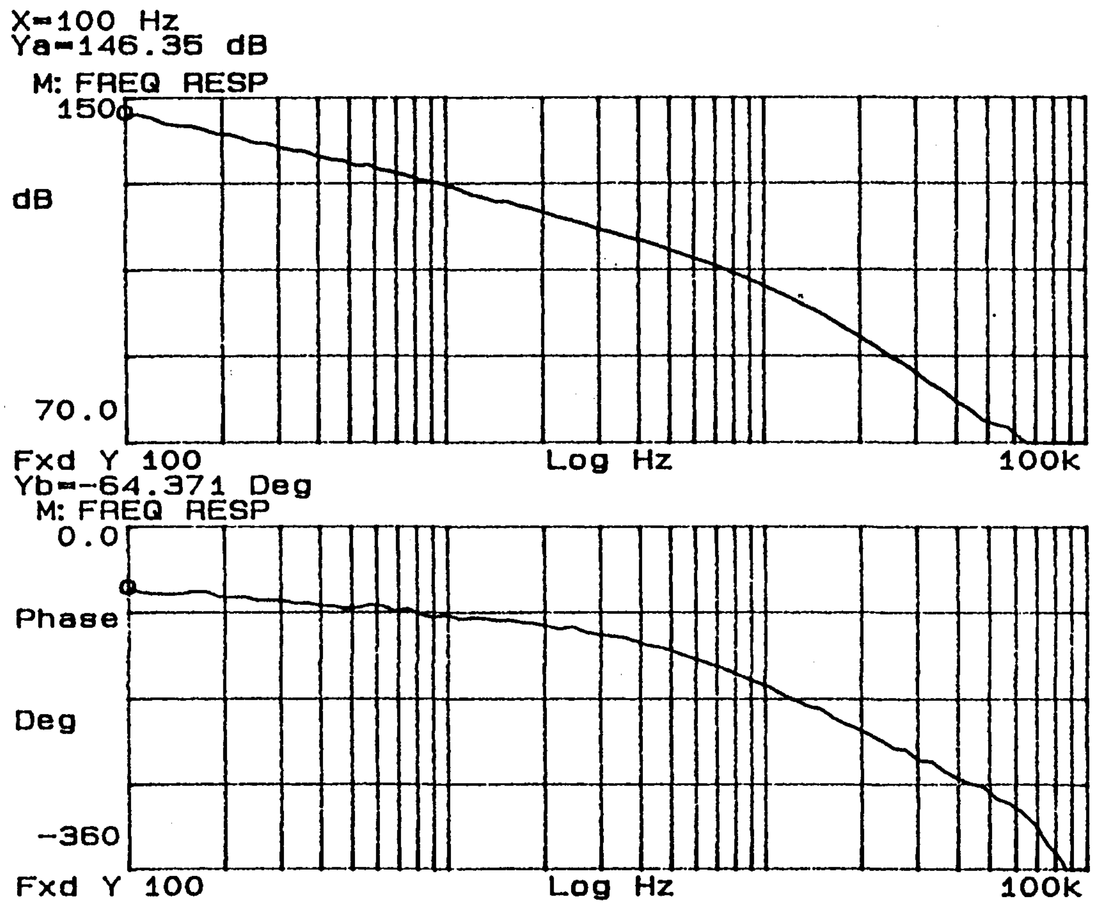
FIGURE 11

DIV DIV START 10 000.000 Hz
10.00 36.00 STOP 1 000 000.000 Hz
RBW: 30 Hz ST: 1.70 min RANGE: R= 0, T= 0dBm

1/5/97 JEM

FIGURE 12

'POWER ADJUST' TO FREQUENCY NOISE TRANSFER FUNCTION



NOISE EATER - OFF

COMM

LASER LOCKED,

COMMON GAIN - 0

FAST GAIN - 0

POCKELS CELL DISCONNECTED

INPUT - POWER ADJUST

OUTPUT - PCTI

THIS PLOT IS:

$$\frac{\text{PCTI}}{\text{POWER ADJUST}} \times \frac{5800\ \text{Hz}}{\text{V}} \times \frac{1}{\text{C.L.}} \times \frac{1}{\text{CAV. POLE}}$$

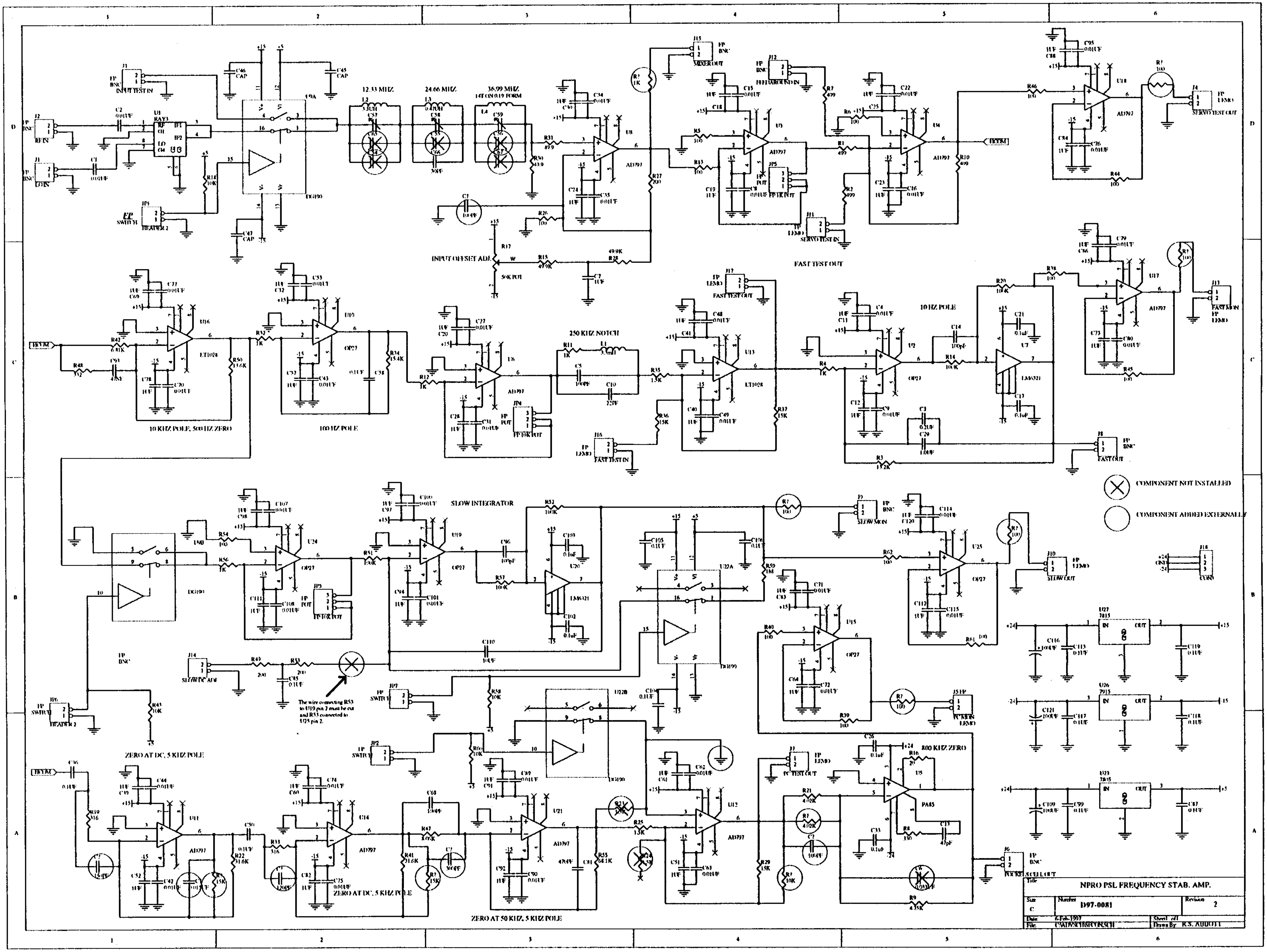
CLOSED LOOP GAIN.

$\frac{\text{PCTI}}{\text{PWR ADJ.}}$ ⇒ 13PRTF3

THIS PLOT ⇒ 13PRTF4

Front Panel Features For NPRO Servo Electronics.

1. **SLOWMON**: Buffered monitoring point for the output of the slow loop.
2. **FASTTO**: Output of fast loop test amplifier (U13).
3. **FASTTI**: Input to fast loop test amplifier (U13).
4. **SLOW ADJ**: Slow loop gain adjust pot.
5. **FAST ADJ**: Fast loop gain adjust pot.
6. **FASTOUT**: Output of the fast loop (U7).
7. **MIXROUT**: Output of the first stage after the mixer (U8), through a 1K resistor. This results in a gain of 5.2dB from that at the plane of the mixer itself.
8. **PCTO**: Pockels cell test output (U12).
9. **SLOW DC**: DC adjustment input for the slow loop. This input is used in initial locking to align laser frequency to the desired value in preparation for lock acquisition.
10. **FASTMON**: Buffered monitoring point for output of the fast loop.
11. **PCOUT**: Output of the pockels cell loop.
12. **FEEDIN**: Feed around input.
13. **MAINTI**: Used for overall closed loop transfer function measurement. Input to U4.
14. **PCMON**: Buffered monitoring point for output of the pockels cell loop.
15. **SLOWOUT**: Output of the slow loop (U25).
16. **MAINTO**: Output used in conjunction with MAINTI for closed loop transfer function verification. Output of U18.
17. **INTI**: Test input that when the RFSW is in the "ON" position, allows for injection of signals at the output of the mixer. Used for aligning the traps among other things.
18. **AQ/SLAQ**: Switch to go between integrator (SLAQ) mode and reduced gain mode (AQ) for the slow loop. Used during lock acquisition.
19. **CLOSE/SLOW LOOP**: Switch used to close the feedback path (CLOSE) for the slow loop electronics. The switch should be closed during normal locked operation. When the loop loses lock, the loop must be taken to the downward position to remove feedback to the slow actuator.
20. **ON/RFSW**: Switch used to select between INTI (ON) and normal mixer feedback path (U9A).
21. **INADJ**: Adjustment of the overall electronics gain or common gain. This will change the gain of all paths simultaneously.
22. **RF**: Input from the RF Photodiode.
23. **LO**: Local Oscillator input from reference phase shifter. Nominal level of 9 V P-P or 23 dBm.


12.33 MHZ
24.66 MHZ
36.99 MHZ
INPUT OFFSET ADJ.
FAST TEST OUT
10 KHZ POLE, 500 HZ ZERO
100 HZ POLE
250 KHZ NOTCH
10 HZ POLE
SLOW INTEGRATOR
COMPONENT NOT INSTALLED
COMPONENT ADDED EXTERNALLY
The wire connecting R53 to U19 pin 2 must be cut and R53 connected to U25 pin 2.
ZERO AT DC, 5 KHZ POLE
ZERO AT DC, 5 KHZ POLE
ZERO AT 50 KHZ, 5 KHZ POLE
800 KHZ ZERO
NPRO PSL FREQUENCY STAB. AMP.
D97-0081
Revision 2
Drawn By R.S. ABBOTT

Frequency stabilization for the NPRO Nd:YAG Lightwave Model 126 laser.
James Mason, LIGO, Caltech, 2/97

This directory contains a set of files for modeling the frequency stablization of the Model 126 laser. The files are for use in the Matlab environment, and use the "mu-tools" package to do analysis. Another requirement is the Matlab function file "vplotf.m". This is the function file "vplot.m" which is part of the "mu-tools" package, with a small modification to plot bode plots as functions of frequency, not radians. The steps for this are contained in the comments of the "vplot.m" file.

The control system is modeled by a block diagram like :

```
                  _________       _________
        + _      |         |     |         |
   ---->|_|---->|  cavpd  |---->|  hcom   |-----|
         ^-      |_________|     |_________|     |
         |        _________       _________      |
         |       |         |     |         |     |
         |<-----|slowact  |<-----|slowcon  |<----|
         |       |_________|     |_________|     |
         |        _________       _________      |
         |       |         |     |         |     |
         |<-----|fastact  |<-----|fastcon  |<----|
         |       |_________|     |_________|     |
         |        _________       _________      |
         |       |         |     |         |     |
         |<-----|pcact    |<-----|pcdriver|<----|
                 |_________|     |_________|
```

Each block is represented by a .m function file of the same name, which takes as an argument the number of points used to calculate the transfer function. The frequency responce is calculated from 10 mHz up to 10 MHz for all blocks. Each file also contains the option to plot it's individual transfer function by editing the file, which entails uncommenting the "vplotf" command, which is the last line of each file.

In order to close the loops and generate an open loop transfer function, the file "nproflg.m" was written. This is also a function file which takes as it's argument a number corresponding to a case setting which in turn determines which loops to close. The output is a bode plot.
The case numbers correspond to :

Case 1 : Slow loop
Case 2 : Fast loop
Case 3 : Pockels cell loop
Case 4 : Total open loop gain, along with each individual loop.
Case 5 : Slow and fast loops only

The file "rmspc.m" is a Matlab script file which calculates and stores into the Matlab workspace a number of useful transfer functions and variables (a function file stores none of it's internal variables in the workspace). It also outputs several plots relating to the voltage spectrum to the pockels cell, the rms integrated voltage to the pockels cell (the first purpose of the file, and hence it's name), and a plot containing the residual frequency noise, the contributions to noise due to output referred noise of the controller, and a shot noise calculation. The files associated and required for "rmspc.m" are :

"fastno.m" - Output referred noise of the fast controller
"pcellno.m" - Output referred noise of the pockels cell
"shotnoise.m" - DC level of shotnoise
"noisemodel.m" - Model for free running f-noise of the laser

```
function cpdf = cavpd(n)

% Model of the reference cavity/photodiode transfer function, based on
% Alex's notes.
% JEM 8/96

% Cavity pole at 35kHz, photodiode pole at 600kHz.
% Assuming 12MHz pd. circuit has Q = 10
% Corrections made, based on measurements.

num1 = 2*pi*35000;
num2 = 2*pi*6e5;
den1 = [1 2*pi*35000];
den2 = [1 2*pi*6e5];
[num,den] = series(num1,den1,num2,den2);

% Do conversion to volts, -> 1V/5.8kHz at DC

num = num*1/(5800);

% Generate frequency response.
w=2*pi*logspace(-3,7,n);

cpd = nd2sys(num,den);
cpdf = frsp(cpd,w);

%vplotf('bode_gl',[1 10^6 10^(-7) 10^(-5)],[1 10^6 -180 0],cpdf);
```

```
function fsactf = fastact(n)

% Matlab file to model the NPRO fast actuator.  By the NPRO document, this
% should be flat.  Mainly used for uniformity and gain adjustment.
% JEM 8/19/96

% Actuator based on open loop measurement of acutator/cavity/p.d, and a
% pole-zero fit by the HP3562A, assuming all but cavity poles belong here.

%fsact = zp2sys(-2*pi*[341.753+37343.1i 341.753-37343.1i ...
%                      252.874+53917.2i 252.874-53917.2i ...
%                      311.299+55247.7i 311.299-55247.7i ...
%                      361.104+61192.1i 361.104-61192.1i ...
%                      471.953+62268.4i 471.953-62268.4i ...
%                      161.817+68478.2i 161.817-68478.2i ...
%                      467.862+72132.1i 467.862-72132.1i], ...
%                 -2*pi*[319.741+37421.5i 319.741-37421.5i ...
%                      235.777+53912.0i 235.777-53912.0i ...
%                      336.158+55348.6i 336.158-55348.6i ...
%                      196.949+61433.2i 196.949-61433.2i ...
%                      713.145+63635.7i 713.145-63635.7i ...
%                      219.621+68648.0i 219.621-68648.0i ...
%                      497.368+72014.4i 497.368-72014.4i], ...
%                      3.5*10^6);

% A more useful and simpler model.

fsact = zp2sys(-2*pi*[],-2*pi*[],4.1*10^6);

% Find the frequency responce

w = 2*pi*logspace(-3,7,n);
fsactf = frsp(fsact,w);

%vplotf('bode_gl',[1000,10^5,10^5,10^7],[1000,10^5,-180,180],fsactf);
```

```
function fsconf = fastcon(n)

% Matlab file to generate mu-tools varying matrix for the fast piezo
% controller for the Nd-Yag NPRO psl.
% JEM 8/20/96
% Second controller design 12/96 JEM

% 2nd controller design
gain1 = (2*pi)^2*(10*100*10000)/(500)*4000;
fscon = zp2sys(-2*pi*[500],-2*pi*[100 10 10000],gain1);

% Generate frequency response
w = 2*pi*logspace(-3,7,n);
fsconf = frsp(fscon,w);

%vplotf('bode_gl',[100 10000000 10^(-5) 300],[100 10000000 -360 0],fsconf);
```

```
function fsno = fastno(n)

% Matlab file to generate a model of the output referred noise of the
% second fast controller.  This is done by generating the loop shape using
% poles and zeros and multiplying by the appropriate gain.  The magnitude
% is then extracted.
% JEM 1/97

% Noise shape generation
gain1 = (10*100*10000)/(500*20000*20000)*3*10^(-5);
fscon = zp2sys(-2*pi*[500 20000 20000],-2*pi*[100 10 10000],gain1);

% Generate frequency response
w = 2*pi*logspace(-3,7,n);
fsconf = frsp(fscon,w);

% Extract the magnigude of the noise from this transfer function
fsno = abs(fsconf(1:n,1));

% vplotf('bode_gl',[10 10^6 10^(-10) 10^(-4)],[10 10^6 -360 0],fsconf);
```

```
function comconf = hcom(n)

% Matlab file to generate the mu-tools varying matrix for the common
% gain stage.
% JEM 8/20/96
% Second controller design set this gain to 1.

comcon = zp2sys(-2*pi*[],-2*pi*[],1);

% Generate frequency response

w = 2*pi*logspace(-3,7,n);
comconf = frsp(comcon,w);

%vplotf('bode_g',comconf);
```

```
function  [f,fn] = noisemodel(n)

% Based on measurements which show rougly 1/f behavior in the 100 Hz to 10
% kHz band.

f = logspace(-3,7,n);

fn = 2*10^4 ./f;
```

```
function tlg = nproflg(case,n)

% Matlab function script to generate the loop gain plots of the various
% loops in the frequency stabilization for the Nd-Yag NPRO psl.
% JEM 8/21/96
%
% Syntax : nproflg(case,n)
%       case : indicates particular loop(s) to be closed.
%       n    : number of points to use in the calculation.
%

if case == 1            % Slow loop
    plant =cavpd(n);
    comcon = hcom(n);
    con = slowcon(n);
    act = slowact(n);

    slg = mmult(plant,comcon,con,act);
    vplotf('bode_gl',[.001 10^3 10^(-2) 10^8],[.001 10^3 -360 90],slg);

elseif case == 2        % Fast loop
    plant = cavpd(n);
    comcon = hcom(n);
    con = fastcon(n);
    act = fastact(n);

    flg = mmult(plant,comcon,con,act);
    vplotf('bode_gl',[10 10^6 10^(-3) 10^5],[10 10^6 -180 0],flg);

elseif case == 3        % Pockels cell
    plant = cavpd(n);
    comcon = hcom(n);
    conpc = pcdriver(n);
    act = pcact(n);

    pclg = mmult(plant,comcon,conpc,act);
    vplotf('bode_gl',[1000 10^7 .001 10],[1000 10^7 -180 180],pclg);

elseif case == 4        % Close all loops
    plant = cavpd(n);
    comcon = hcom(n);
    cons = slowcon(n);
    conf = fastcon(n);
    conpc = pcdriver(n);
    acts = slowact(n);
    actf = fastact(n);
    actpc = pcact(n);

    tlg = mmult(madd(mmult(cons,acts),mmult(conf,actf),mmult(conpc,actpc)), ...
            comcon,plant);
    slg = mmult(plant,comcon,cons,acts);
    flg = mmult(plant,comcon,conf,actf);
    plg = mmult(plant,comcon,conpc,actpc);

    vplotf('bode_gl',[.01 10^7 .001 10^7],[.01 10^7 -180 180],tlg,slg,'--',flg,'-.',plg,':')
;

elseif case == 5        % Close slow and fast loops only
    plant = cavpd(n);
    comcon = hcom(n);
    cons = slowcon(n);
    conf = fastcon(n);
    acts = slowact(n);
    actf = fastact(n);
```

```
    slcon = mmult(cons,acts);
    fscon = mmult(conf,actf);
    sfcon = madd(slcon,fscon);
    sflg = mmult(plant,comcon);
    slg = mmult(plant,comcon,cons,acts);
    flg = mmult(plant,comcon,conf,actf);

    vplotf('bode_gl',[.01 10^7 10^(-2) 10^8],[.01 10^7 -180 180],sflg,slg,'--',flg,'-.');

end
```

```
function pcactf = pcact(n)

% Matlab file to model the pockels cell acutator using mu-tools.  A
% gain of 15mrad/V is assumed.  A pole at high frequency has been added
% for calculatability (the pockels cell itself is just a zero).
% JEM 8/21/96

pcact = nd2sys(10^9/(2*pi)*[.015 0],[1 10^9]);

% Generate frequency response

w = 2*pi*logspace(-3,7,n);
pcactf = frsp(pcact,w);

%vplotf('bode_gl',[.1 1 .0001 .1],[.1 1 0 90],pcactf);
```

```
function pcdf = pcdriver(n)

% Matlab file to generate mu-tools varying matrix for the pockels cell
% controller for the Nd-YAG NPRO psl.
% JEM 8/96
% Second controller design 12/96 JEM
% Small modifications (zero at 1 MHz) 12/96 JEM

% An improved 2nd design
gain2 = (1000*5000*5000*5000)/(.01*.01*50000*1000000)*1.3*10^(-6);
pcd = zp2sys(-2*pi*[0.01 0.01 50000 1000000],-2*pi*[1000 5000 5000 5000],gain2);

% Calculate frequency response

w = 2*pi*logspace(-3,7,n);
pcdf = frsp(pcd,w);

% At high frequencies, phase delay can become significant.  This also
% is useful to match the measured controller transfer function

delay = exp(i*w/(2*pi*10^6));
delay = [delay' w'; n Inf];
pcdf = mmult(delay, pcdf);
% plot the bode plot.

%vplotf('bode_gl',[10 10^7 10^(-6) 10^4],[10 10^7 -180 180],pcdf,pcdf1)
```

```
function pcno = pcellno(n)

% Matlab file to generate a model of the output referred noise of the
% second fast controller.  This is done by generating the loop shape using
% poles and zeros and multiplying by the appropriate gain.  The magnitude
% is then extracted.
% JEM 1/97

% Noise shape generation
gain2 = (1000*5000*5000*5000)/(100*100*50000*800000)*5*10^(-7);
pcd = zp2sys(-2*pi*[1 10 100 100 50000 800000],-2*pi*[.3 3 1000 5000 5000 5000],gain2);

w = 2*pi*logspace(-3,7,n);
pcdf = frsp(pcd,w);

% Extract the magnitude of the noise from this transfer function
pcno = abs(pcdf(1:n,1));

%vplotf('bode_gl',[10 10^6 10^(-8) 10^(-2)],[10 10^6 -180 180],pcdf)
```

```
% Matlab script file to generate all sorts of useful and not so useful stuff.
%
% Once this file is run, many variables will be defined in the Matlab
% workspace, such as : all the blocks of the control system (actuators,
% controllers, etc.), various transfer functions for output referred noise,
% loop gains, etc., models of frequency noise, shot noise, and a few other
% surprises.
% JEM 12/96

plant = cavpd(200);
hc = hcom(200);
pcc = pcdriver(200);
pca = pcact(200);
fastc= fastcon(200);
fasta= fastact(200);
slowc = slowcon(200);
slowa = slowact(200);

% Form the total loop gain and the closed loop gain
tlg = mmult(madd(mmult(slowc,slowa),mmult(fastc,fasta),mmult(pcc,pca)), ...
                 hc,plant);
clg = minv(madd(tlg,1));

% Form the transfer function from frequency noise to p.c. voltage
pcv = mmult(plant,hc,pcc,clg);

% Form the transfer functions for output referred noise.
nop = mmult(pca,clg);
nof = mmult(fasta,clg);
nos = mmult(slowa,clg);

% Call noise model for output referred noise.

fsno = fastno(200);
pcno = pcellno(200);

% Create equivalent frequency noise from output referred noise

fastnoise = fsno .*abs(nof(1:200,1));
pcnoise = pcno .*abs(nop(1:200,1));

% Plot contributions of noise

%loglog(nof(1:200,2)/(2*pi),fastnoise,nof(1:200,2)/(2*pi),pcnoise);
%pause;

% Pull out the magnitude of the transfer function, generate frequency noise
% spectrum and multiply to get voltage noise to the p.c.

mtf = abs(pcv(1:200,1));
mcl = abs(clg(1:200,1));
[f,fn] = noisemodel(200);
vn = fn' .* mtf;
fnc = fn' .* mcl;

% Plot the voltage spectrum

subplot(1,1,1)
loglog(f, vn);
title('Voltage to pockels cell power spectrum');
xlabel('Frequency (Hz)');
ylabel('Volts/rtHz');
grid;
%print;
pause;
```

```
% Square the noise, integrate the power spectrum, square root to get
% Vrms to the pockels cell.

vn2 = vn .* vn;
vns = zeros(1,199);
f2 = zeros(1,199);
for i = 1:(length(vn2)-1)
    if i == 1
        vns(i) = (vn2(i+1)+vn2(i))/2*(f(i+1)-f(i));
        f2(i) = f(i+1);
    else
        vns(i) = (vn2(i+1)+vn2(i))/2*(f(i+1)-f(i)) + vns(i-1);
        f2(i) = f(i+1);
    end
end
Vrms = sqrt(vns);

semilogx(f2,Vrms);
title('Integrated RMS voltage to pockels cell');
xlabel('Frequency (Hz)');
ylabel('Volts (RMS)');
grid;

%gtext([num2str(Vrms(199)),' Volts RMS to the pockels cell.']);
%print;
pause;

% Calculate the DC shotnoise level for a given modulation depth, and
% generate the frequency response.

shotndc = shotnoise(.8);
shotn = shotndc * sqrt(1 + (f/35000).^2);

% Generate a plot with residual frequency noise, shot noise, and noise
% contributions from the controller
loglog(f,fnc,f,shotn,'--',f,fastnoise,'-.',f,pcnoise,':');
title('Residual frequency noise');
xlabel('Frequency (Hz)');
ylabel('Frequency noise (Hz/rtHz)');
axis([10 1000000 .0001 1])
text(.05,.9,'Solid - Residual frequency noise','Units','normalized')
text(.05,.8,'Dashed - Shot noise','Units','normalized')
text(.05,.7,'Dashdot - Fast controller noise','Units','normalized')
text(.05,.6,'Dotted - Pockels cell controller noise','Units','normalized')
grid
%print
```

```
function ups = shotnoise(gamma)

% Generate DC shot noise prediction for single cavity locking
% Uses Malik's calculation. If input parameter "gamma" is a vector
% of values, outputs a plot also of the DC shot noise level as a function
% of modulation depth gamma

% Optical parameters, transmissivities, losses, mode-matching fraction,
% input power
T = 300*10^(-6);
L = 30*10^(-6);
r = sqrt(1-T-L);
M = .8;
Pin = .010;

% Definitions used in calculation
g = L*r/(T+L);
G = g^2;
Ein = sqrt(Pin);
E0 = Ein*bessel(0,gamma);
E1 = Ein*bessel(1,gamma);
Rcav = M*G + (1-M)*(1-T-L);
Edc = E0*sqrt(Rcav);

% Other physical parameters needed, photodiode efficiency (A/W), free
% spectral range
e = 1.6*10^(-19);
sigma = .65;
vfsr = 3*10^8/(2*.2);

ups = sqrt(e/sigma)*sqrt(Edc.^2+2*E1.^2)./(E0.*E1)*vfsr*(T+L)^2/(2*pi*T*r);
if length(gamma) > 1
        plot(gamma,ups);
        title('DC shot noise prediction level');
        xlabel('Modulation depth (gamma)');
        ylabel('DC shot noise level (Hz/rtHz)');
        grid
end
```

```
function slactf = slowact(n)

% Matlab file to model the NPRO slow actuator.  Based on the matlab file
% generated by Alex A. in ~rick/Yag/Matlab/slowfit.m.
% JEM 8/19/96

slact = zp2sys(-2*pi*[],-2*pi*[0.2 0.2 0.2],3*10^9*(2*pi*.2)^3);

% Find the frequency responce

w = 2*pi*logspace(-3,7,n);
slactf = frsp(slact,w);

%vplotf('bode_gl',[.001,1,10^9,10^10],[.001,1,-360,0],slactf);
```

```
function slconf = slowcon(n)

% Matlab file to generate mu-tools varying matrix for the slow frequency
% controller for the Nd-Yag NPRO psl.
% JEM 8/20/96
% Second controller design JEM 12/96

% Two controllers are offered for both integrator mode and acquisition mode
slcon = zp2sys(-2*pi*[],-2*pi*[0],3);

%slcon = zp2sys(-2*pi*[],-2*pi*[.05],0.0025*2*pi*.05);

% Generate frequency response

w = 2*pi*logspace(-3,7,n);
slconf = frsp(slcon,w);

%vplotf('bode_gl',[.01 10 .01 100],[.01 10 -180 0],slconf);
```