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DOCUMENTATION OF THE NBS APD AND PIN CALIBRATION SYSTEMS FOR MEASURING PEAK POWER AND ENERGY OF LOW-LEVEL 1.064 μm LASER PULSES

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Page	Location	Incorrect Item	Correction
3	2.3, second line	November	October
3	3., second paragraph, third line	etched glass	ground-glass
4	4.,n.,2.	mΩ	MΩ
	4.,n.,3.	mΩ	MΩ
17	6.1.1,4., first line	1.5 mm	1 mm
25	6.3.4,2., second line	.(end of sentence)	for pulse rate.
	6.3.4,4., second line	.(end of sentence)	for cw input time interval.
27	6.3.9,3., second and third lines	from the LED pulsed beam	from the LED.
29	6.4.1,9., first and second lines	$3\ 10^5$ $3\ 10^5$	$3 \cdot 10^5$ $3 \cdot 10^5$
30	6.4.3,11., second line	200 ns	180 ns
36	6.7.2.,B.,1.	APD TS with aperture below.	APD TS with aperture attached (see 8. below).
37	G.,3.	AP	HP
43	Table 1, line (2)	147	47
44	Table 2, line (1)	104	106
47	H., third line	etched glass	ground-glass
49	G.,6.,a., and b.	mΩ	MΩ
50	H., line 2, fourth word	of	omit "of"
51	7., second paragraph, second line	with	within
57	7., right, second line	<200 ns	<180 ns
61	Source of uncertainty, item 3 down, first column	Precision beam-splitter attenuator	Precision beam-splitter attenuator (beam unpolarized)
61	Date, item 4 down, third column	4/82	8/85
63	8.3,3., first line	are	is
66	References, [1], third line	November	October
67	[8], third line	Paper 2097	25(2)

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DOCUMENTATION OF THE NBS APD AND PIN CALIBRATION SYSTEMS FOR MEASURING PEAK POWER AND ENERGY OF LOW-LEVEL 1.064 μm LASER PULSES

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Documentation of the NBS APD and PIN Calibration Systems for Measuring Peak Power and Energy of Low-Level 1.064 μm Laser Pulses

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National Bureau of Standards APD (avalanche) and PIN silicon photodiode transfer standards are documented for a calibration service to measure 1.064 μm laser pulses from $\sim 10^{-8}$ to $\sim 10^{-4}$ W peak power and $\sim 10^{-16}$ to $\sim 10^{-11}$ J energy. A modulated cw measurement system generating known low-level pulses is described. Calibration support equipment, systematic and random errors, and computer programs and calibration data are also described.

Key words: APD transfer standards; beamsplitter attenuator; calibration procedures; calibration service; low-level laser measurements; modulated cw measurement system; 1.064 μm laser pulse measurements; PIN transfer standards; pulse energy; pulse peak power

1. Introduction and Background

1.1 Introduction

This report describes documentation, maintenance, and operational procedures for the APD and PIN calibration systems. These systems consist of APD (avalanche) and PIN silicon photodiode transfer standards (TS) to measure peak power and energy, respectively, of fast, low-level 1.064 μm laser pulses. Similar systems were developed for the Air Force, Army, and Navy standards laboratories.

The culmination of this effort is a low-level calibration service of APD and PIN systems that are traceable to the national standards.

Disclaimer: Commercial equipment is identified to adequately specify procedures. This does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the equipment identified is necessarily the best available for the purpose.

1.2 Background

With the development of guidance receivers and range finders detecting low-level 1.064 μm laser pulses reflected from objects, the need arose for calibrating the peak power and energy of these pulses. Work was sponsored by the Calibration Coordination Group and NBS to develop transfer standards capable of measuring 1.064 μm, 10 to 30 ns laser pulses to 10^{-16} J and 10^{-8} W within about 20 to 25 percent uncertainty.

As an intermediate goal, a nanojoule transfer standard was developed. Commercial instruments already available were calibrated against an existing transfer standard in a precision beamsplitting system from 10^{-5} to 10^{-9} J cw and from 10^{-7} to 10^{-11} J Q-switched pulses. Results were independent of whether the energy was pulsed or cw. The instruments also integrated the ambient light. Therefore, room light and the solid angle for light entering the devices were reduced to low values. The remaining extraneous light was subtracted from the laser light measured. The instruments were also calibrated against each other.

For levels lower than the above, devices were built from commercial state-of-the-art APD and PIN silicon photodiodes, preamplifier, and amplifier components. An acousto-optically modulated cw measurement system was developed to generate nanosecond pulses and to calibrate the devices. The modulator fed a precision beamsplitter-attenuator system that generated cw and pulsed (~200 ns FDHM [full duration half maximum]) beams of known power and energy. APD and PIN transfer standards in the reflected beams of the beamsplitter attenuator were calibrated against a commercial or PIN transfer standard in a higher-level beam. Some were also calibrated in a precision beamsplitter-attenuator system using Q-switched pulses ~30 ns FDHM. These measurements showed that calibrations were independent of pulse duration.

Operating in the modulated cw measurement system, these APD and PIN transfer standards were determined capable of calibrating other devices to $\sim10^{-8}$ W peak power and $\sim10^{-16}$ J energy, respectively, in less subdued room light than the higher-level integrating devices described above. They are described in reference 1.

2. Description of the NBS APD and PIN Peak Power and Energy Calibration Service

2.1 APD Silicon Photodiode Transfer Standard Capability

APD 5-1 and APD 5-5 (first digit 5 = APD and second digit instrument identification).

Maximum collector area using aperture: 0.947 cm^2.

Calibrated range: $\sim10^{-7}$ to $\sim10^{-4}$ W for peak pulse power.

Minimum calibration region at NBS using the precision beamsplitter attenuator: $\sim10^{-8}$ W.

Power density range: determined by detector being calibrated.

2.2 PIN Silicon Photodiode Transfer Standard Capability

PIN 4-1 and PIN 4-3 (first digit 4 = PIN and second digit instrument identification).

Diode collection area: PIN 4-1 0.819 cm^2, PIN 4-3 1.002 cm^2.

Calibrated range: $\sim 10^{-14}$ to 10^{-11} J for pulse energy.

Minimum calibration region at NBS using the precision beamsplitter attenuator: $\sim 10^{-16}$ J.

Energy density range: determined by detector being calibrated and whether a collector is used.

These transfer standards are portable, so that personnel may make measurements at the customer's site.

2.3 Companion Publication on Transfer Standards

"A system for measuring energy and peak power of low-level 1.064 μm laser pulses," A. A. Sanders and A. L. Rasmussen, NBS Technical Note 1058, November 1982 (also listed as reference 1).

3. Design Philosophy Using APD and PIN Transfer Standards

To measure the low levels enumerated above, NBS chose to calibrate transfer standards assembled from commercial components because they are simpler to develop than absolute standards and components. NBS used available transfer standards calibrated by existing national standards, the Q- and C-series calorimeters, and precision beamsplitter attenuators. These were used to generate pulses of known and variable power and energy at the levels of interest. These pulses were used to calibrate the APD and PIN transfer standards. APD signals were amplified by a transimpedance preamplifier or a preamplifier on the same chip and by a wideband amplifier at the lower levels of calibration. PIN signals were amplified and integrated by a charge amplifier and by a linear amplifier. The peak voltages of the output of the APD and the PIN systems are proportional to the peak power and the energy of the pulses, respectively.

The APD has inherently small size and nonuniform responsivity. To overcome these problems, the largest APD available at 3 mm diameter was used with a focusing lens (collector) and etched glass diffuser in front of it. Still, the responsivity in volts/watt varied over the portion of the collector area designated for measurements. Consequently, the uniformity of the responsivity and the field of view were statistically determined. An ir-enhanced APD from the same manufacturer, which became available after the APD transfer standards were completed, can be used if the need occurs, because they are reported to be more uniform and higher in responsivity than the APD described in this report.

Since the APD systems designed have <100 MHz bandwidth, corrections to the peak voltage of the fastest pulses are necessary for dependable calibrations as a function of pulse duration. These corrections are calculated from the convolution of Gaussian pulses with the impulse response of the system.

The charge and linear amplifiers of the PIN system integrate the current and shape the pulse. A pulse emerges whose peak voltage is proportional to the energy in the original PIN pulse. Peak voltages of pulses are read out on an oscilloscope and/or a pulse height analyzer (PHA). The latter records the occurrence and amplitudes of pulses from which one can determine the average amplitude and stability of the laser output.

Because of the appreciable temperature coefficients of components, the APD and its preamplifier and the PIN were placed in a temperature-controlled environment. It consists of a thermally insulated box containing the components and a dc temperature controller circuit operating at some temperature around 30° to 35°C. The silicon photodiode lies in the center of a hole inside the box. A temperature meter outside or a ribbon thermometer indicates the inside temperature.

The dc bias is rectified 20 kHz and contributes little noise to the APD and PIN outputs.

4. APD and PIN Transfer Standard Calibration Support Equipment

a. Modulator power supply, IntraAction Corp. Model ME 40T, light modulator signal processor, S/N 2059.
b. Acousto-optic light modulator, IntraAction Corp. AOM 40 IR, S/N 1639.
c. Shutter system.
    1. Time generator.
    2. Dual preset controller, Computer Measurement Co., Model 913.
    3. Pulse driver circuit (PD-6).
d. Square-wave generator, Interstate F77 20 MHz log linear sweep generator, NBS 147582.
e. Relay switch.
f. Timer/counter, HP 5300A measuring system and HP5304A timer/counter, NBS 142535.
g. Electronic counter, HP 5245L, NBS 120743.
h. Oscilloscope, cw and pulsed beam operation monitor, Tektronix 535A, NBS 111933.
i. Red light indicator for showing pulsed beam operation.
j. DC voltage power supply, HP 6214A.
k. APD bias power supplies, Bertan Assoc. Inc., Model 602B-15N (APD 5-1) and Model 602B-15P (APD 5-5).
l. PIN bias power supplies, Bertan Assoc. Inc., Model 342.
m. Pulse generator, HP 8013A.
n. Oscilloscope readout, Tektronix 7904, NBS 145935.
    1. APD readout, dual trace amplifier, 7A24, 50 Ω.
    2. PIN 4-3 readout, dual trace amplifier, 7A12, 1 mΩ.
    3. PIN 4-1 readout, dual trace amplifier, 7A26, 1 mΩ, NBS 146251.
    4. Dual time base, 7B92A.
o. Digital voltmeter for bias voltage measurement, Dana 4600.
p. Pulse height analyzer readout, Tracor Northern TN-1706.

q. APD transfer standard shutter system.
  1. Pulse generator, Wavetek Model 142 HF VCG generator.
  2. Operation indicator switch.
  3. Pulse driver circuit (PD-5).
r. Amplifier SC-2 and light sensor for shutter timing measurement.
s. Pulser, Tennelec, TC 812.
t. Charge amplifier, Tennelec, TC 162, S/N 326 (PIN 4-1) and S/N 293 (PIN 4-3).
u. Linear (shaping) amplifier, Tennelec, TC 222, S/N 386 (PIN 4-1) and S/N 230 (PIN 4-3).
v. HP 462A wideband amplifier, S/N 551-01053.

5. APD and PIN Transfer Standard Calibration Support Equipment Operation

The seven diagrams below show how the calibration support equipment fit into the various systems used.

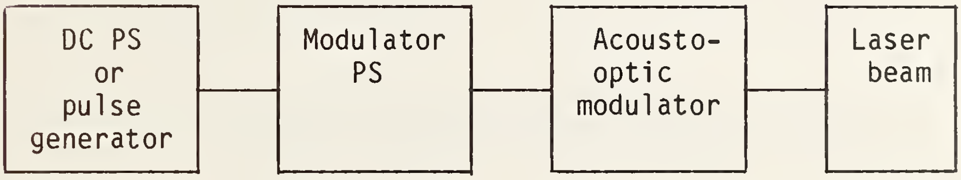

Diagram 1. Acousto-optic light modulator system.

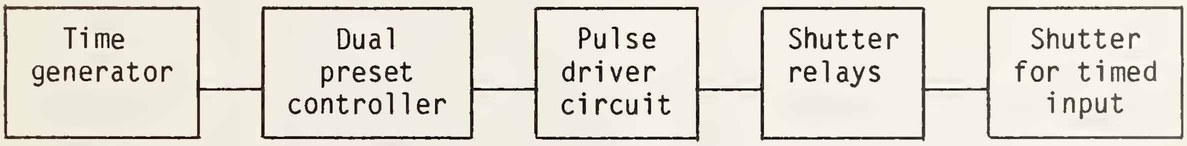

Diagram 2. Shutter system for timed input.

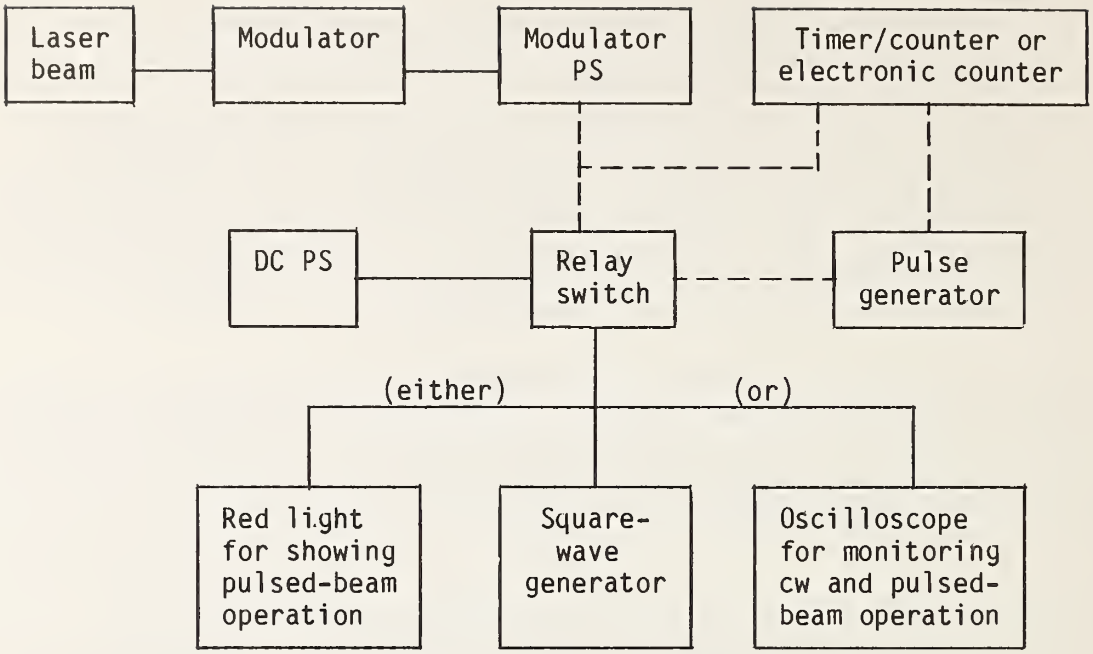

Diagram 3. Relay switch system for alternating between pulsed and cw laser beams at a specific duty cycle.

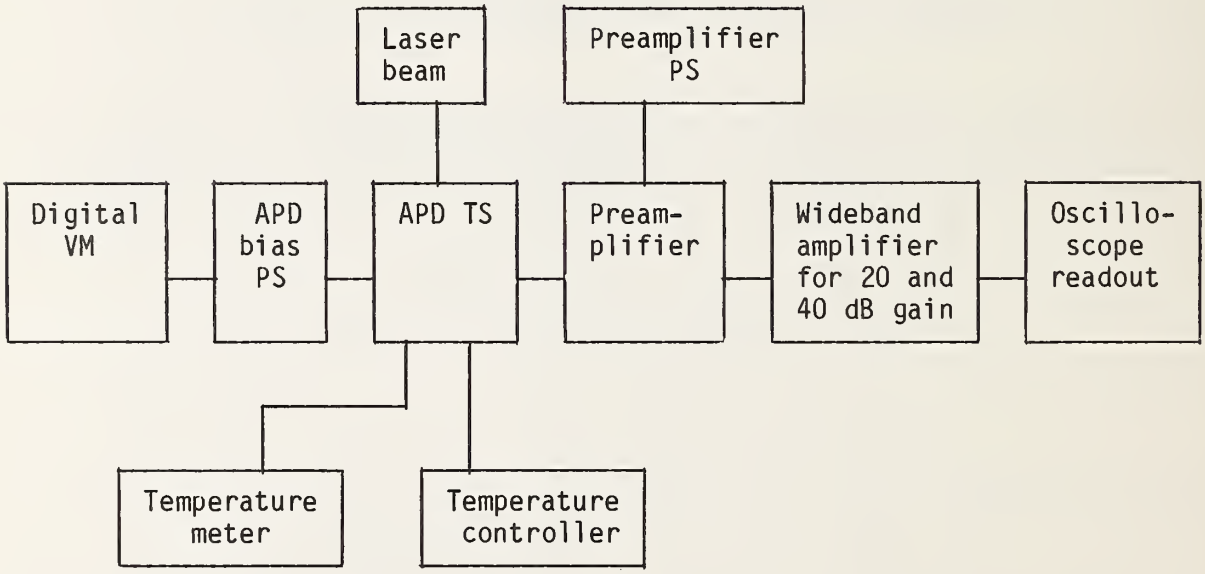

Diagram 4. APD TS system.

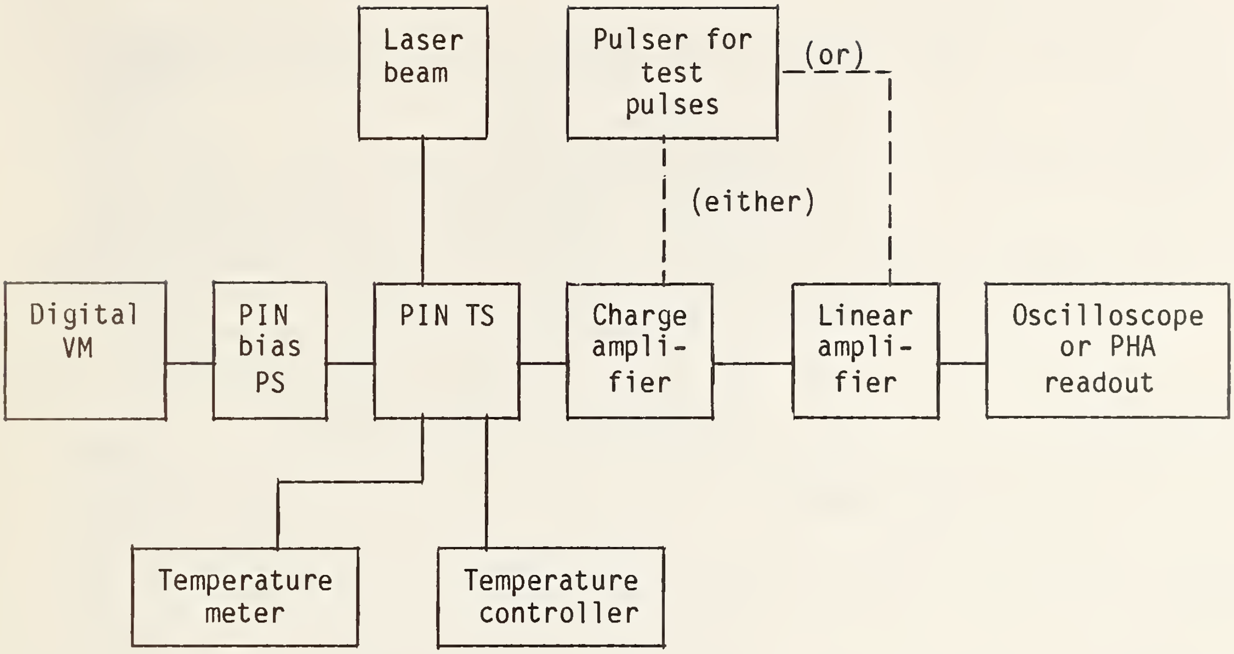

Diagram 5. PIN TS system.

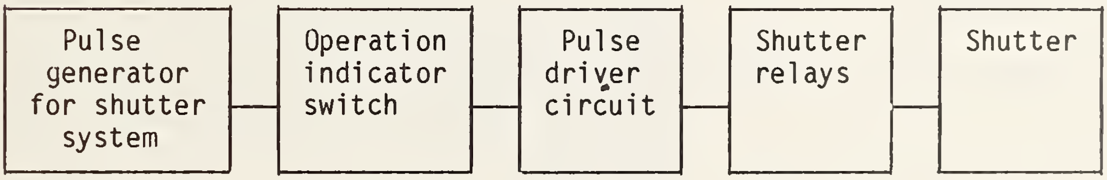

Diagram 6. APD TS shutter system.

Diagram 7. Amplifier and light sensor system for shutter timing measurement.

5.1 Modulator Power Supply

The modulator power supply (see diagrams 1 and 3) is set as follows:

Control	Setting or Connection
Carrier level 0 to 10	(1) APD and PIN about 0.5 to 6.0 (2) PIN only above 6.0 (first diffracted beam slightly distorted)
Video input	(1) Pulse generator at least +3 V peak for pulsed first diffracted beam. (2) DC PS +3 V for cw first diffracted beam (3) Analyzer connection of relay switch for alternating between 1 and 2.
RF output	Acousto-optic light modulator

5.2 Acousto-Optic Light Modulator

The acousto-optic light modulator (see diagrams 1 and 3) is set as follows:

Control	Setting or Connection
Input	RF output of modulator power supply
Left-right translator	Center beam in front and rear windows
Up-down translator	Center beam in front and rear windows
Vertical angle	Adjust two rear screws near output window for maximum first diffracted beam*
Horizontal angle	Rotate modulator in horizontal plane for maximum first diffracted beam*
	Modulator at beam focus region following the first lens

5.3 Shutter System for Timed Input

The shutter system (see diagram 2) is set as follows:

5.3.1 Time Generator

Control	Setting or Connection
Off/on	On
Start	Press to start time
Reset	Press to stop time
Time interval	1, x1 (one second)
- Output	Dual preset controller input

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*With an ir-to-visible converter and a black screen immediately in front of the nearest aperture, the beam is observed on the right of the main beam.

5.3.2 Dual Preset Controller

Control	Setting or Connection
Off/on	On
Input	Time generator - output
Red button	In opens shutter, Out closes shutter
Reset input	Press for zero time
Limit--pulse relay dial	Limit, 20 (shutter opens at 20 s)
Limit--recycle dial	Limit, 120 (shutter closes at 120 s)
Output	Pulse driver circuit

5.3.3 Pulse Driver Circuit (PD-6)

Control	Setting or Connection
Input	Dual preset controller output
Shutter manual Open/closed	Closed
Manual/automatic timer	Automatic timer
Output	Shutter relays

5.4 Square-Wave Generator

The square-wave generator (see diagram 3) is set as follows for APD calibrations:

Control	Setting or Connection
Sweep limit	About 4.93
Frequency multiplier	Var. sym x1 sym 0.01
Offset	Above the line
Waveform	Square
Mode	Continuous
Output P-P into 50 Ω	15 V
Output Z_0 = 50 Ω	2.0 V, oscilloscope input or red indicator light and square-wave input of relay switch
On/off	On with 2-hour warmup

5.5 Relay switch

Relay switch (see diagram 3) is set as follows for APD calibrations:

Control	Setting or Connection
+3 V dc	dc PS, +3 V
Input frequency with 50 Ω feedthrough termination	Pulse generator output (+) when used otherwise disconnected
Input square wave	Square-wave generator 50 Ω output
To analyzer	Video input of modulator power supply

5.6 Timer/Counter

The timer/counter (see diagrams 3 and 7) is set as follows:

Control	Setting or Connection
Com-Sep-Chk	Com
A input	(1) Analyzer connection of relay switch with pulse generator disconnected (2) Pulse generator output (3) SC2 amplifier gate output
B input	No connection
A input	X1, AC, and +
B input	X1, AC, and +
Function switch	(1) Above, 0.1 ms for cw duration (2) Above, auto for pulse rate (3) Above, 1 ms for shutter gate time
Auto	Pulse generator output for counting pulses
Level	(1) Lower + and upper - for cw cycle (2) Lower - and upper + for pulsed cycle

5.7 Electronic Counter

The electronic counter (see diagram 3) is set as follows:

Control	Setting or Connection
Signal input ac/dc	ac, pulse generator output for frequency
Sensitivity (V RMS)	0.1 (50 V max)
Time base	1 s
Function	Freq

5.8 Oscilloscope for Monitoring cw and Pulsed-Beam Operation

The oscilloscope (see diagram 3) is set as follows:

Control	Setting or Connection
Channel	A
at 1 MΩ input	Square-wave generator 50-Ω maximum output (up = pulsed, down = cw)
dc/ac	dc
Polarity	Normal (+)
Volts/cm	0.5
Time base	A
Stability/ triggering level	Triggering mode auto
Triggering mode/ trigger slope	Triggering mode auto
Horizontal display/ magnifier	A/off
Variable/time/cm	Off/5 ms (arbitrary)

5.9 Red Light Indicator for Showing Pulsed-Beam Operation

(See diagram 3.)

Control	Setting or Connection
Red light on/off	Square-wave generator 50 Ω maximum output (red light on = pulsed beam operation)

5.10 DC Voltage Power Supply

The dc power supply (see diagrams 1 and 3) is set as follows:

Control	Setting or Connection
Meter selection volts/amps	Volts
Adjust voltage/current	+ 3 V dc
Terminals +, -, ⏚	+ and -, (1) +3 V dc of relay switch (2) Video input of modulator power supply

5.11 APD Bias Power Supply

The negative bias power supply for APD 5-1 and the positive bias power supply for APD 5-5 (see diagram 4) are set as follows:

Control	Setting or Connection
Rear output (- PS)	APD 5-1 bias* and VM - 338.0 V
Rear output (+ PS)	APD 5-5 bias* and VM + 410.0 V
HV adjust	Do not adjust
Ten-turn pot	Pretested for correct polarity and voltage with the APD disconnected

5.12 PIN Bias Power Supply

The PIN bias power supply (see diagram 5) is set as follows:

Control	Setting or Connection
Positive/negative polarity	Negative (never changed)
Meter with magnifier	Not used
Switch 0, 0.5, and 1 kV	0 with switch handle removed
0 - 1000 V Ten-turn pot	Pot-rdg 1 + 80 VM-rdg -180.0 V
On/off	On
Rear J1 high voltage output	Neg bias of PIN diode and ungrounded VM terminals

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*Each APD has its own bias level.

5.13 Pulse Generator

The pulse generator (see diagrams 1 and 3) is set as follows:

Control	Setting or Connection
Rate Hz	(1) APD about 500 (2) PIN < 300,000 (3) Manual single pulse
Pulse period (s)	APD and PIN 0.1 ms - 10 ms PIN 1 μs - 0.1 ms
Pulse delay (s)	35 ns
Pulse width (s)	10 ns - 1 μs, APD 200 ns and PIN 100-200 ns
Amplitude (V) -	5 scale, 3-4 V
Amplitude (V) +	5 scale, 3-4 V
Offset (V) -	Off
Offset (V) +	Off
Output (-)	Time base of oscilloscope measuring pulses
Output (+)	(1) Video input of modulator power supply for pulsed first diffracted beam (2) Frequency input of relay switch (with 50 Ω feedthrough termination) for alternating between cw and pulsed first diffracted beam (3) Electronic counter ac input or timer/counter A input with auto for measuring pulse frequency

5.14 Oscilloscope for Readout

The readout oscilloscope with plug-ins (see diagrams 4 and 5) is set as follows:

(1) The 50 Ω dual-trace amplifier for APD readout (used with one mainframe only) on left vertical.

Control	Setting or Connection
Ch2 50 Ω	APD output/wideband amplifier
Polarity +Up/invert	(1) +Up without wideband amplifier following APD (2) Invert with wideband amplifier following APD
Position	Two large divisions for baseline if possible
Volts/div	0.005 to 0.5 V/division
Off/dc	(1) Off for baseline where it coincides with no input reading (2) DC for pulses
Trigger source/display mode	Ch2/Ch2

(2) The 1 MΩ dual-trace amplifier (the 12 unit) for PIN readout (used with one mainframe only) on right vertical.

Control	Setting or Connection
Ch1 1 MΩ, 24 pF	Linear amplifier readout of PIN 4-3
Polarity +Up/invert	+Up
Offset (same as position)	Two large divisions for baseline if possible
Volts/div	0.020 to 2 V/division
AC/GND/DC/DC and offset	(1) GND for baseline where it coincides with no input reading (2) DC for pulses
Display mode/ trigger mode	Ch1/Ch1

(3) The 1 MΩ dual-trace amplifier (the 26 unit) for PIN readout (used with one mainframe only) on left vertical.

Control	Setting or Connection
Ch2 1 MΩ, 24 pF	Linear amplifier readout of PIN 4-1
Polarity +Up/invert	+Up
Position	Two large divisions for baseline if possible
BW Full/20 MHz	Full
Volts/div	0.020 to 2 V/division
AC/GND/DC	(1) GND for baseline where it coincides with no input reading (2) DC for pulses
Trigger source/ display mode	Ch2/ch2

(4) The dual time base for APD and PIN readouts (used with one mainframe only) on right vertical.

Control	Setting or Connection
Main triggering mode/coupling/source	Norm/dc/ext or line
Slope/level Trig'd	Trig'd light on
Position	Horizontal adjustment
Dly'd sweep operation	Step 1. Dly'd time/div pulled out, rotated for delayed sweep rate, and pushed in. Step 2. Delayed sweep rate determined by Dly'd time/div switch, Time/div or Dly time switch, and Delay time mult dial setting. Runs after delay time control turned fully clockwise into detent. Cal in.
Term	Out 50 Ω
Main trig in	Pulse generator output (-)

5.15 Digital Voltmeter for Bias Voltage Measurements

The digital voltmeter for bias voltage measurement (see diagrams 4 and 5) is set as follows:

Control	Setting or Connection
Function switch	DCV
Range	1000 V
Input	Bias supply output connected to input and low terminals without ground

5.16 Pulse Height Analyzer for Readout

The pulse height analyzer (see diagram 5), used for a second readout in the PIN TS for the Air Force and the Navy, is set as follows:

Control	Setting or Connection
ULD	About 10,0
LLD	About 0,50
Zero	Preset about 0,50 (adjustment will change calibration)
Mode	PHA
Gate	Not used
Input	Bipolar output of linear amplifier and oscilloscope amplifier (if used)
Horizontal	Full
Preset	Cursor
Conversion gain	1024 (occasionally 2048)
Offset	Zero
Region enter/erace and cursor	The channel number (proportional to the peak voltage) is horizontal and the number of pulses in each channel is vertical on the display unit. The cursor can be made to stop on a channel from which you can read the channel number and the number of pulses in a channel. To integrate the number of pulses in a region, enter the lower and upper channel limits using the enter switch and the cursor. Erase the integration of the region using erase and the cursor < lower channel limit.
Vertical scale	100-1 M Vertical scale adjusted to find peak channel with greatest number of pulses.
Time base	9, ∞
Pen	Set
CAL XY and Ext	Not applicable
Clear data/time	Clear as needed
Add/subtract	Add (up position)
Acquire	Press to take data
Display unit	Adjust focus, intensity, horizontal expand and position, and vertical size and position as needed

5.17 APD Transfer Standard Shutter System

A shutter system (see diagram 6) for eliminating reflection from an APD TS during measurements in a lower-level beam of the precision beamsplitter attenuator is set as follows:

5.17.1 Pulse Generator for Shutter System

Control	Setting or Connection
PWR OFF/FREQ. Hz	X.01
Main dial	5
30 V P-P max	(above line), max
Freq ÷ 10 symmetry	Off
DC offset	Off
Output atten (dB)	-10
50 Ω out	Input of operation indicator switch

5.17.2 Operation Indicator Switch

Control	Setting or Connection
Input	50 Ω out of pulse generator
Off/on	On
Red light	On when shutter closed blocking APD TS
Output	Pulse driver circuit (PD-5)

5.17.3 Pulse Driver Circuit (PD-5)

Control	Setting or Connection
On/off	On
Shutter manual open/closed	Closed
Manual/automatic timer	Automatic timer
Output	Shutter relays

5.18 Amplifier and Light Sensor for Shutter Timing Measurement

(See diagram 7.)

1. The SC-2 amplifier is set as follows:

Control	Setting or Connection
Off/on	On
+ Gate output	Timer/counter, A input, 1 ms
Sensor	Light sensor
Zero set/±100 meter	Adjust to zero
Gain/±100 meter	Adjust gain to drive the timer/counter

2. Light sensor is set as follows:

Control	Setting or Connection
Input	Main beam of precision beamsplitter attenuator
Output	SC-2 amplifier, sensor

5.19 Pulser for Test Pulses

The pulser (see diagram 5) is set as follows:

Control	Setting or Connection
Pulse height	Clockwise increases height
Relay on/off	On
Cal	To calibrate pulse height
Pol +/-	Minus
A direct output 50 Ω	
B direct output/ext atten input	
Output	
5 V/0.4 ms	5 V/0.4 ms
1 V/2.0 ms	
Attenuation	Use with C output
$\sqrt{2}$, 2, 5	
10, 10, 10	
C output 50 Ω	Use with attenuation switches. Connect to the linear amplifier signal input minus. Connect to the test terminal of the charge amplifier. Connect the charge amplifier to the linear amplifier.

5.20 Charge Amplifier

The charge amplifier operation (see diagram 5) is described in section 6.

5.21 Linear (Shaping) Amplifier

The linear (shaping) amplifier operation (see diagram 5) is described in section 6.

5.22 Wideband Amplifier

The wideband amplifier operation (see diagram 4) is described in section 6.

6. Procedures for the Modulated cw Measurement System and for the Transfer Standards

The modulated cw Nd:YAG laser measurement system produces low-level cw and pulsed beams of known peak power and energy. See figure 6-1, low-level modulated cw measurement system. These beams provide the means for calibrating low-level transfer standards.

6.1 The Modulated cw Measurement System

6.1.1 Laser Alignment* and Operation Procedures

1. Align HeNe laser beam through the front and rear faces of the Nd:Yag rod alone.
2. Insert and align rear mirror with HeNe beam returning on itself through the rod.
3. Insert and align front mirror with HeNe beam returning back on itself through the rod.
4. Insert the cavity aperture, with about a 1.5 mm diameter hole, midway between the rod and rear mirror with HeNe beam passing through it.
5. Remove the HeNe laser.
6. Open water valves on each side of the water filter.
7. Open the outlet water valve and then the inlet water valve for cooling the distilled water pumped through the laser head.
8. Maintain distilled water level within a couple of centimeters of the top of the stainless steel tank inside the power supply cabinet.
9. Raise the wall power switch to the on position.
10. Turn on the laser console.
11. Turn the current dial to about 0.55.
12. In about 30 s, fire laser.
13. Adjust the laser current between 15 and 17 A depending on age of the flash lamp.
14. Set the power meter at the highest power scale.
15. Tune the laser for maximum output without the aperture by adjusting the rear and the front mirrors.
16. Insert the aperture between the rear mirror and the laser rod and adjust the position of the aperture with the micrometer adjustments for maximum laser output using an available detector.
17. Insert the collimator with the large knob side next to the laser output mirror.
18. Assuming the collimator has been preset, align the laser beam through the center of the collimator by adjusting the large knobs of the collimator.
19. The position of the laser beam may be changed slightly by adjusting the large knobs of the collimator while someone observes the orientation of the beam in the measurement system.
20. If the laser head and water tank feel cool, the laser may continue operation.
21. If the laser head and the water tank feel warm, the laser is turned off as described below.
22. If the laser is operating at a warm temperature, the water valve in the power supply cabinet may need replacement.

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*An available autocollimator may easily be used to also align the laser.

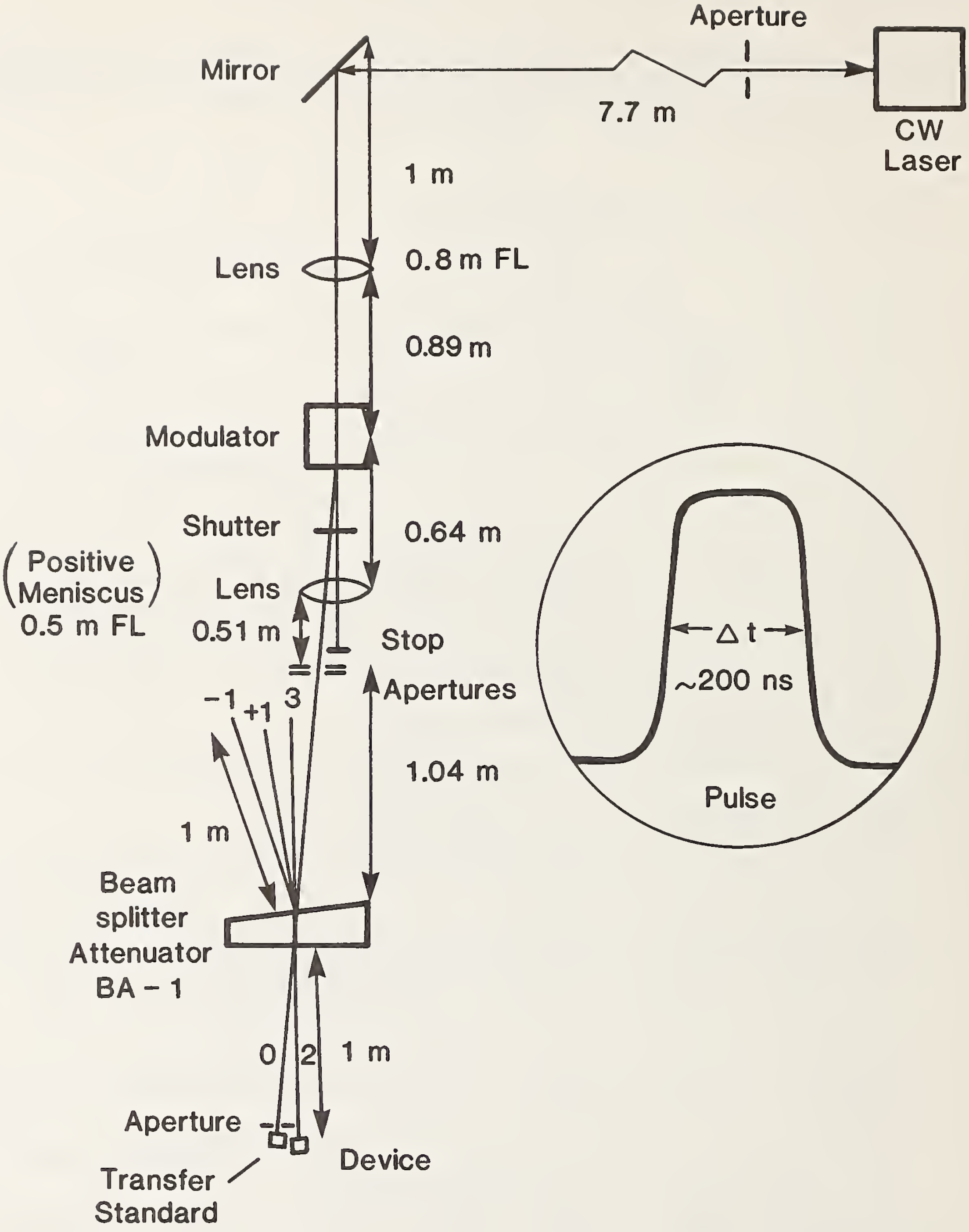

Figure 6-1. Low-level modulated cw measurement system.

23. If the laser output is unstable after 1 to 2 h at 15 to 17 A, the laser current may be increased to 17 to 19 A for relatively short periods.
24. The laser current may be increased from 19 to 22 A, but the laser output may actually decrease.
25. To turn off the laser, turn laser console dial to zero.
26. After 10 to 30 min cooling time, turn off the laser power supply switch on the console when the laser head is cool.
27. Close the inlet water valve and then the outlet water valve.
28. Lower the wall power switch to the off position.

6.1.2 Laser to the Modulator Alignment and Operation Procedures

1. Open the shutter between the rooms.
2. Adjust the first aperture to pass only the main portion of the beam.
3. Close the shutter between the rooms.
4. Open the C-series shutter.
5. Remove the C-series lens following the C-series shutter.
6. Insert the first mirror to direct the laser beam at a right angle to the left.
7. Open the shutter between the rooms.
8. Adjust the first mirror to direct the laser beam to the second and third mirrors that lower the height of the beam and convey the laser beam at a horizontal angle through the optical components that follow in the system.
9. Since the first mirror is removed whenever the C-series system is used, it may need slight adjustment of its micrometer knobs when put back into position or when the system is slightly out of alignment.
10. When the system is initially set up, the second and third mirrors are adjusted angularly to direct the beam into the first lens and rarely will need changing thereafter.
11. When the system is initially set up, the first lens is adjusted to direct the beam through the modulator and rarely will need changing thereafter.
12. When the system is initially set up, the modulator is permanently placed at a fixed distance from the first lens at the neck of the beam to yield fast rise and fall times of the modulator pulses.
13. Close the shutter between the rooms at the end of these procedures.

6.1.3 Modulator Alignment and Operation Procedures

1. Turn on the modulator power supply.
2. Connect the rf output of the modulator power supply to the acousto-optic light modulator.
3. Turn the carrier level of the modulator power supply to 6.
4. Turn on the dc power supply to +3 V.
5. Open the shutter between the rooms.
6. Connect the dc power supply to the video input of the modulator power supply to generate a cw first diffracted beam on the right of the main beam.
7. Remove the main beam absorber that follows the second lens.
8. Place a black absorbing surface in front of the aperture (iris) that follows the beam absorber.

9. Adjust the horizontal and vertical angles of the modulator for maximum brightness of the first diffracted beam on the right of the main beam (about 11 mrad separation).
10. Approximately center the beam in the modulator.
11. Replace and adjust the absorber that follows the second lens to absorb the main beam and to pass the first diffracted beam on the right.
12. Control the modulator output by adjusting the laser current and/or the modulator power supply carrier level.
13. Generate modulator pulses by applying pulses with amplitudes about 3 to 5 V from the pulse generator to the video input of the modulator power supply (carrier level input >2 V is "on" and <0.8 V is "off").
14. Pulses with carrier levels above six are distorted but may be used for energy measurements.
15. Determine the pulse duration [full duration half maximum (FDHM)] from oscilloscope-observed APD pulses synchronized by pulse generator pulses or from oscilloscope-observed pulse generator pulses corrected by substracting 10 ns.
16. Use 100 to 180 ns FDHM laser pulses for PIN transfer standard calibrations.
17. Use about 200 ns FDHM laser pulses for APD transfer standard calibrations.
18. The modulator may generate pulses from 1 to 10^7 pps.
19. Use laser pulse rates from ~100 to ~10^5-10^6 pps for PIN calibrations.
20. Use laser pulse rates about 500 pps for APD calibrations.
21. Use the cw first diffracted beam to align the system following the modulator and to align detectors with alignment mirror and iris or target in front.
22. Use the pulsed beam to align detectors more precisely.
23. Use the cw and pulsed beams to generate beams or pulses of known energy and peak power.

6.1.4 Procedures for Generating the Diameter and Collimation of the Beams at about 1 m Distance after Interacting with the Precision Beamsplitter Attenuator

1. To generate ~3 mm diameter, ~3 mrad divergence, laser beams at about 1 m distance after interacting with the precision beamsplitter attenuator, we inserted a second lens, the lens after the modulator, and calculated and/or measured the lens and beam properties.
2. The focal length and position of the second lens were calculated from the formula

$$\frac{1}{f_2} = \frac{1}{d_1} + \frac{1}{d_2}$$

where

f_2 = 0.51 m (FL of the second lens)

d_1 = 0.64 m (distance between the modulator and the second lens)

d_2 = 2.55 m (distance between the second lens and the detectors for calibration)

3. The diameter of the beam where the detectors are calibrated was calculated from the magnification formula and measurement of the diameter of the beam passing through the modulator as follows:

$$M = \frac{d_2}{d_1} D_M$$

where

M = ~3 mm (diameter of the beam at the detectors for calibration)
D_M = ~0.6-0.8 mm (diameter of the beam through the modulator)

4. The formulas for the diameter (D_M) of the beam through the modulator were compared to the measured value above

$$D_M = \frac{4}{\pi} \frac{\ell\lambda}{D_1} = 0.24 \text{ mm} \quad \text{(Gaussian beam)}$$

and

$$D_M = 2.44 \frac{\ell\lambda}{D_1} = 0.46 \text{ mm (Airy disk)}$$

where

ℓ = 0.89 m (measured FL of the first lens)
λ = 1.064 μm (wavelength of beam)
D_1 = 5 mm (diameter of the beam at the first lens)

5. Since calibrations of transfer standards with ~3 mm and ~6 mm diameter generated beams were similar, the ~3 mm beam was adopted for its convenience in aligning beams and in evaluating the uniformity of the responsivity of the transfer standard detectors.

6.1.5 Modulator to Detector Alignment and Operation Procedures

1. Generate a cw, first-order diffracted modulator beam (see 6.1.3, above).
2. Open the shutter that allows the modulator first-order beam to enter the precision beamsplitter attenuator system for specified times.
3. At a specific distance from the modulator, the second lens allows the beam to pass through it with the desired orientation of the beam in the precision beamsplitter attenuator system and rarely needs changing thereafter.
4. Orient the absorber following the second lens to absorb the main beam and to pass the first diffracted one on the right without striking the outside surface of the absorber.
5. Adjust the apertures to allow only the first diffracted beam to pass through them.
6. The precision beamsplitter wedge should have the thicker portion on the left of the incoming beam.

7. The beam should pass through approximately the center of the precision beamsplitter attenuator parallel to the top of the optical table at about 20 cm.
8. Slightly adjust the first mirror as needed to orient the beam through the center of the aperture in front of the Redw 3 transfer standard.
9. To align the precision beamsplitter attenuator, a mirror is permanently placed in the (m = 2) beam about 1.1 m from the beamsplitter.
10. A white card is temporarily placed in the (m = 3) beam about 1.1 m from the beamsplitter.
11. A white card with a hole is temporarily placed in the (m = 2) beam.
12. The (m =.2) beam and the reflected (m = 2) beam are aligned through the hole in the card.
13. The (m = 3) beam and the reflected (m = 2) beam are made to coincide on the card in the (m = 3) beam by adjusting the micrometers of the beamsplitter.
14. Repeat step 12.
15. Remove the card in the (m = 2) beam.
16. Repeat step 13.
17. Repeat the above steps until no further adjustments are needed.
18. The peak power or energy of each beam emerging from the beamsplitter depends upon the number of reflections and passes the original beam undergoes in the precision beamsplitter attenuator.
19. Place the detector in the beam to be used about 1 m from the beamsplitter.
20. Place absorbers in front of the beams not being used.

6.1.6 Procedures for Realignment of the Modulated cw Measurement System

1. Turn on the laser and other equipment as described elsewhere.
2. Quickly check the alignment of the beam into the apertures, the modulator and the stop to absorb the main beam.
3. If necessary, adjust the position of the first aperture to allow the main portion of the beam to pass.
4. If necessary, adjust the position of the first mirror to center the beam in the aperture in front of the Redw 3 transfer standard.
5. If necessary, adjust the other apertures and occasionally the horizontal and vertical angles and translators of the modulator to pass the beam and to generate the first diffracted beam on the right.
6. If necessary, adjust the stop to absorb the main beam and pass the first diffracted one on the right.
7. If necessary, align the beamsplitter attenuator as described in 6.1.5 steps 9 through 17 above.

6.1.7 Shutter Timing Measurement Procedures

1. Align the light sensor attached to the SC2 amplifier in the (m = 0) beam.
2. Attach the SC2 amplifier gate output to the timer/counter and read the shutter timing.

6.2 Redw 3 (TC15) Transfer Standard Alignment and Operation Procedures

1. Center the (m = 0) cw first diffracted beam in the entrance of Redw 3.

2. Absorb the three reflections from the window of Redw 3 in a high absorption black surface a few millimeters below the incoming beam and ~30 cm away.
3. Orient the center reflection just below the incoming beam.
4. Turn on Redw 3 TS and allow it to warm up 24 h before measurements.
5. Set the upper right hand switch to Power or Energy.
6. Set to the 0.1 J, the 1 J, or the 10 J and the laser, 100 s scales.
7. Temporarily turn the measurement selector switch to laser power, not timed.
8. Adjust the calorimeter baseline to give plus or minus zero readout.
9. Return the measurement selector switch to laser 100 s.
10. With its switch up, adjust the integrator baseline knob for no change in readout.
11. Limit the Redw 3 measurements on the 0.1 J, 1 J, and 10 J scales to 0.0100 to 0.1000, 0.100 to 1.000, and 1.00 to 10.00 readouts, respectively.
12. Set and clear the dual preset controller for 20 s on and 120 s off (see 5.3.2 above).
13. Start time generator.
14. Press the Redw 3 start measurement button at 18 s (1 or 2 s before shutter is to open).
15. At about 218 s, the red light by the restart meter button will go on and the meter can be read.
16. Press the Redw 3 restart meter button.
17. For the usual calibration sequence, make measurements without the video input of the modulator power supply, with the video input twice at the same carrier level, and without the video input.
18. Energy into Redw 3 is computed by subtracting the average readout without video input of the modulator power supply from each readout with the video input of the modulator supply and dividing the results by the calibration value.
19. cw power into Redw 3 is computed from the energy computed in step 18 divided by the input time.

6.3 APD Transfer Standard (APD TS) Procedures

6.3.1 APD TS Alignment and General Operating Procedures

1. Attach the alignment mirror and iris to the entrance of APD TS.
2. Attach the APD TS to the tilt table and the heavy-duty translating system in the (m = 2) or the (m = 3) cw first diffracted laser beam.
3. Align the APD TS with the (m = 2) or the (m = 3) cw laser beam in the center of the iris and reflected from the alignment mirror back on itself through a hole in a card in the beam and/or by superimposing the reflected (m = 2) beam on to the (m = 3) beam or the reflected (m = 3) beam on to the (m = 2) beam.
4. Align the APD TS precisely in the (m = 2) or the (m = 3) pulsed laser beam by observing the pulse height (oscilloscope 50 Ω amplifier plug-in unit) and varying the iris size.
5. To make APD TS calibrations, the relay switch (see 5.5) is connected to give alternately for about 10 s each equivalent levels of pulsed peak power and cw power of the laser beam into the system.
6. Adjust the pulse generator (see 5.13) for about 200 ns (FDHM) laser pulses, as observed by the APD TS, for peak power closely approximating cw power.

7. Set pulse rate ~500 pps for the pulsed energy to be negligible compared to the cw energy.
8. A square-wave generator operates the relay switch that alternately connects 3 V peak pulsed and 3 V dc signals for about 10 s each, or any other time selected, to the video input of the modulator power supply (see 5.4 and 5.5).
9. The order for the signals during a 100 s laser input is about 5 s pulsed input for the first and last 5 s and alternately 10 s cw and 10 s pulsed inputs.
10. APD TS measurements are made without the wideband amplifier (0 dB) and with the wideband amplifier (20 and 40 dB) attached to the output of the preamplifier (signal output connection).
11. APD measurements are from ~10^{-7} W to ~10^{-4} W peak power.

6.3.2 APD TS System Parts

1. APD TS.
2. Temperature controller and preamplifier power supply.
3. Bias power supply.
4. Wideband amplifier (20 dB and 40 dB gain).
5. Temperature meter.
6. Cables marked for connections.
7. Voltmeter with 0.1 percent accuracy or better (furnished by the user when the APD transfer standard is at the customer's site).
8. Alignment mirror and iris.
9. Aperture in a universal lens mount.

6.3.3 APD TS System Setup Procedures

1. Use cables as marked to make APD TS connections.
2. Before attaching the bias power supply to the APD TS, test it for correct output voltage and polarity as given on the APD TS.
3. The voltmeter to measure the bias power supply must be ungrounded.
4. Connect the temperature controller and preamplifier power supply to the APD TS.
5. Connect the bias power supply to the APD TS and the voltmeter.
6. Connect the APD TS signal output to the oscilloscope 50 Ω input.
7. When a signal needs amplification, attach the APD TS to the wideband amplifier at 20 or 40 dB.
8. Connect the output of the wideband amplifier to the oscilloscope 50 Ω input.
9. Connect the temperature meter to the APD TS.
10. Run the temperature controller and preamplifier power supply at least 1 h before making measurements.
11. Begin measurement after temperature meter is steady.
12. Gradually apply the bias power supply voltage to the APD TS and gradually return it to zero voltage when shutting equipment down.
13. Align the APD TS (see 6.3.1) in the (m = 2) or the (m = 3) beam of the precision beamsplitter attenuator.
14. In the modulated cw measurement system, place the tube, with the black paper aperture, in front of the APD TS without clipping the beam or moving the aligned APD TS.

15. In the modulated cw measurement system, set the pulse duration to 200 ns (FDHM) reading the APD TS output using the center four divisions of the oscilloscope read to one quarter division.

6.3.4 APD TS Calibration Procedures--cw Interval, Pulse Rate, and Background Measurements

1. Follow 6.3.5 steps 1 to 8 to preset pulse levels.
2. Connect the pulse generator to the timer/counter or the electronic counter (see 5.6 and 5.7).
3. Connect the dc PS at +3 V and the square wave generator 50 Ω output to the +3 V dc and input square wave connections of the relay switch, respectively (see 5.5).
4. Connect the analyzer cable of the relay switch to the timer/counter (see 5.6).
5. From previous peak power measurements, select the 0.1 J, the 1 J, or the 10 J and the laser, 100 s scales of Redw 3 for both background and APD TS measurements.
6. Open the shutter between the rooms.
7. With the dual preset controller at 20 s on and 120 s off, start the time generator (see 5.3).
8. Press the start measurement button of Redw 3 transfer standard at about 18 s.
9. Measure five cw input time intervals at the analyzer cable (see section 5.6).
10. Measure five pulse rates at the input frequency cable after setting the pulse rate to <500 pps (see 5.13).
11. Read Redw 3 when the ready light goes on at about 218 s.
12. Press the restart meter button of Redw 3 to clear the reading.
13. Repeat these measurements after 6.3.5 peak power measurements below.

6.3.5 APD TS Calibration Procedures--Peak Power Measurements

1. Block the entrance of Redw 3.
2. Attach the pulse generator to the video input of the modulator power supply.
3. Manually open the shutter.
4. To set the vertical deflection of the APD TS oscilloscope readout at a given level, adjust the carrier level of the modulator power supply between 0.5 to 6 and the laser current between 15 to 17 or 17 to 19 A; and if needed for very low levels, place and adjust the flat coated glass, variable attenuator in front of the iris following the second lens.
5. For no wideband amplifier (0 dB) following the preamplifier, use the 50 Ω unit plug-in unit oscillocope scales from 5 mV to 50 mV or 0.5 V per division in step 4.
6. For the 20 dB gain of the wideband amplifier, use the 50 Ω plug-in unit oscilloscope scales from 10 mV to 100 mV per division in step 4.
7. For the 40 dB gain of the wideband amplifier, use the 50 Ω plug-in unit oscillosope scales from 20 mV or 50 mV to 100 mV per division in step 4.
8. Adjust the pulse duration to 200 ns (FDHM).
9. Close the timed shutter following the modulator.

10. Close the shutter between rooms to allow modulator surfaces to cool for a few minutes.
11. Open the shutters between the rooms.
12. Remove the block in front of Redw 3.
13. Connect the analyzer cable of the relay switch to the video input of the modulator power supply.
14. Connect the pulse generator output to the input frequency connection of the relay switch with the 50 Ω termination attached.
15. Connect the square wave generator output to the square wave input of the relay switch and to the vertical input of channel A of the oscilloscope or to the red light indicator.
16. Use the positive output of the oscilloscope or the red light indicator to determine pulsed beam operation.
17. After pulsed beam operation for a few seconds, start the dual preset controller (see 5.3).
18. At about 18 s, press start measurement button of Redw 3.
19. Read the mean height of the middle of the APD TS pulses for the six periods between five cw inputs.
20. Read Redw 3 at about 218 s when the ready light goes on.
21. Press the restart meter button of Redw 3 to clear the reading.
22. Repeat these measurements a second time at the same input.
23. Record the temperature near the detector, the laser amperes, and the modulator carrier level.
24. Repeat 6.3.4 cw time interval, pulse rate and background measurements.

6.3.6 APD TS Calibration Computation

1. The calibration factor (K in V/W) using Redw 3 transfer standard is

$$K = \frac{AS1}{R/(C3\ T\ N3\ S)}$$

for oscilloscope readout where

AS1 = average voltage reading of APD TS where A is the average deflection reading and S1 is the volts/division setting of the oscilloscope.
R = Redw 3 reading less the average background reading
C3 = Redw 3 calibration (reading/J)
T = average duration of cw inputs (seconds)
N3 = number of T inputs
S = beamsplitter ratio

2. The calibration factor (K0 in V cm^2/W) using area L2 is

$$K0 = K\ L2.$$

3. The peak power (W) is

$$W = R/(C3\ T\ N3\ S).$$

4. The peak power density (WO in W/cm^2) is

$$WO = W/L2.$$

6.3.7 APD TS Uniformity Measurement Procedures

1. Attach the alignment mirror and iris to the collector of the APD TS.
2. Attach the APD TS to the tilt table and the heavy-duty or other translator.
3. Align the APD TS with the reflected beam from the alignment mirror returning on the path of the incoming beam.
4. Calibrate the APD TS in the center of the APD collector and in at least four other areas in the four cardinal directions next to the perimeter of about a central 1 cm^2 circular area to determine the uniformity of the responsivity.
5. Compute the average responsivity at the 95 percent confidence interval (CI) and use these data in the uncertainty statement of the calibration.

6.3.8 APD TS Field of View Measurement Procedures

1. Attach the alignment mirror and iris to the collector of the APD TS.
2. Align the APD TS with the reflected beam from the alignment mirror through the center of the attached iris at angles of reflection (θ_R) of 0, 5, 7.5, 10, 12.5, 15, 17.5, and 20 mrad in the four cardinal directions, and calibrate the APD TS at 0 mrad and at some of the angles in the four cardinal directions.
3. Compute the calibration for each angle selected.
4. Define beam divergence in mrad as

$$D = 2\theta_R + 3$$

   where the divergence of the beam in the system is approximately 3 mrad.
5. Prepare a table of the beam divergence (D) versus correction factor for the calibration, $(CF)_D = K_D/K$ where
   K_D = calibration at divergence D
   K = calibration at $\theta_R = 0$

6.3.9 APD TS Impulse Response Correction Procedures

1. Place the APD TS into operation at the bias voltage indicated on the instrument.
2. Attach the output of the APD TS to a 350 MHz to 500 MHz bandwidth, 50 Ω input impedance, oscilloscope plug-in unit.
3. Collimate a 300 ps duration, 0.9 μm LED pulsed beam with a converging lens and align the APD TS about a half meter from the LED pulsed beam.
4. Attenuate as needed the 300 ps, 0.9 μm LED pulsed beam with a variable transmission flat coated attenuator.

5. Feed the 300 ps, 0.9 μm LED pulsed beam into the APD TS in its linear region without the wideband amplifier (0 dB) and with the wideband amplifier (20 dB and 40 dB) attached.
6. Photograph the impulse response and ringing portions of the curve on the oscilloscope.
7. Read values at every subdivision from the impulse response curves.
8. Convolute from ~10 ns to ~100 ns duration, Gaussian and skewed Gaussian pulse data (1 V peak) and impulse response data (unity area) using the convolution computer program.
9. Compute and plot correction factors for peak voltage versus the observed pulse duration to get the original pulses for the 0 dB and the 20 dB and 40 dB gain settings of each APD TS.

6.3.10 Procedures for Measuring the Inequivalence of Pulsed and cw Power

1. Observe the height variation of pulses of the APD transfer standards as the laser pulses are stretched and compressed between 200 ns and 600 ns (average pulse height variation was within 2.5 percent).
2. Compare calibrations using (1) pulsed peak power measurements and (2) cw power measurements (calibrations using (1) and (2) were within 1 percent of each other).
3. We concluded (1) that the pulse height, if it could be measured to cw, would not vary significantly and (2) that the pulsed peak power and the cw power inequivalence has a 2.5 percent uncertainty.

6.3.11 APD Transfer Standard Optics

1. The sequence of the optics in the APD transfer standards from the outside to the inside are aperture, collector lens, diffuser, and silicon avalanche photodiode (APD).
2. The aperture is about 1.1 cm diameter.
3. The lens is a B270 crown glass, biconvex lens that has about a 2.5 cm diameter and a 2.5 cm focal length and a 1.064 μm antireflection coating.
4. The lens is about 2.13 cm from the diffuser and about 2.54 cm from the APD.
5. The diffuser is about 0.16 cm thick Suprasil-1 glass with the front surface ground with a 400 grit abrasive (about $40 \cdot 10^{-4}$ cm size).
6. The APD is about 0.3 cm diameter and about 0.07 cm^2 area, and is hermetically sealed behind a flat glass window.
7. APD 5-5 has an APD with a hybrid preamplifier in a single modified 12 lead TO-8 package.

6.4 PIN Transfer Standard (PIN TS) Procedures

6.4.1 PIN TS Alignment and General Operation Procedures

1. Attach the alignment mirror and iris to the entrance of the PIN TS.
2. Attach the PIN TS to the tilt table and the heavy-duty or other translating system in the (m = 2) or the (m = 3) cw first diffracted laser beam.
3. Align the PIN TS with the (m = 2) or the (m = 3) cw laser beam in the center of the iris and reflected back on itself through a hole in a card in the beam or with the superposition of either the (m = 2) and

the reflected (m = 3) beam from the PIN TS mirror or the (m = 3) and the reflected (m = 2) beam from the PIN TS mirror.

4. Align the PIN TS precisely in the (m = 2) or the (m = 3) pulsed laser beam by observing the pulse height on an oscilloscope with a megohm amplifier plug-in unit and varying the iris size.
5. Place the tube, with a black paper aperture, in front of the PIN TS without clipping the beam or moving the aligned PIN TS.
6. Compute laser energy/pulse from the total energy in a beam divided by the number of pulses.
7. Use Redw 3 in the (m = 0) beam or a PIN TS in the (m = 2) beam as a reference standard.
8. Use pulses from 100 to 180 ns duration (FDHM) (laser pulses <100 ns are unsteady and above 200 ns may be distorted in the linear amplifier).
9. Use about 10^5 to 3 10^5 pps with the reference Redw 3 TS and 10^3 pps maximum with the reference PIN TS (the 3 10^5 pps limit is necessary with a pulse height analyzer readout).
10. Integrate and amplify PIN pulses with the charge amplifier and the linear amplifier at the specified external and internal settings.
11. Calibrate the average joules per pulse versus the average peak voltage per pulse.
12. Calibrations are independent of pulse duration to 200 ns.
13. Determine pulse duration (FDHM) from APD TS or by subtracting 10 ns from pulse generator pulses.
14. Adjust the carrier level of the modulator power supply and the laser current to control pulse energy.
15. The PIN TS measures ~10^{-14} J to ~10^{-11} J/pulse.

6.4.2 PIN TS System Parts

1. PIN transfer standard.
2. Temperature controller power supply.
3. Temperature meter.
4. Charge amplifier.
5. Portable NIM BIN with power supply for NIM BIN components.
6. Linear amplifier NIM BIN component.
7. Pulser NIM BIN component.
8. Bias power supply NIM BIN component.
9. Voltmeter with 0.1 percent or better accuracy (furnished by the user when the PIN TS is at the customer's site).

6.4.3 PIN TS System Setup Procedures

1. Use cables as marked to make PIN TS connections.
2. Connect the bias power supply by itself to an ungrounded voltmeter and gradually increase output to -180 V.
3. If it is functioning properly, connect the bias power supply to the PIN TS and to the ungrounded voltmeter.
4. Connect the charge amplifier directly to the signal output terminal of the PIN TS using a double male type N connector and to the back of the linear amplifier.
5. Connect the temperature controller to the PIN TS.
6. Connect the temperature meter to the PIN TS.

7. Turn on the temperature controller and other equipment for at least one hour before measurements.
8. Check the readout of the temperature meter to know the temperature controller is functioning.
9. Gradually apply bias voltage and gradually return it to zero voltage when shutting equipment down.
10. Align the PIN TS (see 6.4.1, steps 1 through 5).
11. From ~10^{-14} J/pulse to ~10^{-11} J/pulse, use pulse durations (FDHM) from 100 ns to 200 ns with the longest pulses used with the Redw 3 TS.
12. Set and measure the pulse duration (FDHM) by an APD TS or by subtracting 10 ns from measurements of pulse generator pulses.
13. The linear amplifier is set internally at time constant (TC) 2 μs, multiplier X 0.2, and delay out.
14. The linear amplifier is set externally at
    BLR ASYM 1
    RATE OUT
    Bipolar positive peak
    Coarse gain 5 and fine gain 0.500 (set by turning potentiometer counterclockwise)
    Coarse gain 10, 50, 100, and 200 (when calibrated or needed) and fine gain 1.000 (set by turning potentiometer clockwise)
15. Use oscilloscope as follows
    Bandwidth: >200 MHz
    Input: 1 MΩ
    Sweep: 0.2 μs
    Vertical deflection: 5 to 100 mV/div to 2V/div
    Baseline: 2 divisions
    Pulse height: 3 to 5 divisions
16. Other PIN transfer standards than the ones described here have been calibrated with a pulse height analyzer (PHA) readout (600 Ω input) and an oscilloscope readout (1 MΩ input) in parallel (see 5.16).
17. The PHA readout may be read alone with the same calibration as when read in parallel with the oscilloscope, but the oscilloscope readout must be read in parallel.
18. The PHA readout gives both accurate averages and individual measurements of pulse height.

6.4.4 PIN TS Calibration Procedures--Preparation Procedures and Pulse Rate and Background Measurements

1. Select a pulse rate from 10^5 to $3 \cdot 10^5$ pps of the pulse generator when using the Redw 3 TS as a reference standard.
2. Select a pulse rate of $<10^3$ pps of the pulse generator when using a PIN TS as a reference standard.
3. Set and measure the FDHM pulse duration between 100 and 200 ns by an APD TS or by subtracting 10 ns from measurements of pulse generator pulses.
4. Align the PIN TS with the (m = 2) or (m = 3) cw laser beam in the center of the iris and reflected from the alignment mirror back on itself through a hole in a card in the beam or with the superposition of either the (m = 2) and the reflected (m = 3) from the PIN TS mirror or the (m = 3) and the reflected (m = 2) beam from the PIN TS mirror.

5. Place the tube, with a black paper aperture, in front of the PIN TS without clipping the beam or moving the aligned PIN TS.
6. When a PIN TS is used in the (m = 2) beam as a reference standard, use the procedures of steps 4 and 5 above except orient the PIN TS at a slight angle from the incoming beam and open and close the (m = 2) beam shutter to verify that no reflected (m = 2) beam enters a detector in the (m = 3) beam.
7. With the pulse generator attached to the video input of the modulator power supply, adjust the carrier level (0.5 to about 9) and the laser current (15 to 17 A or 17 to 19 A for relatively short periods) to get the desired pulse amplitudes.
8. Select the pulse amplitude of the PIN TS from 20 mV/division to 2 V/division, a two division baseline, and a three to five division peak of the oscilloscope megohm amplifier plug-in unit (see 5.14).
9. Connect the pulse generator to the electronic counter or the timer/counter.
10. Press the stop button of the time generator, close the timed shutter, and clear the dual preset controller to zero readout.
11. Close the shutter between rooms for a few minutes to cool the modulator surfaces after being heated by the laser beam.
12. Set the dual preset controller to open the shutter at 20 s and close it at 120 s.
13. Press the start button of the time generator if the Redw 3 TS is used as a reference standard, otherwise, perform step 16 only.
14. Open the shutter between rooms.
15. Press the start meter button of Redw 3 at 18 s.
16. Measure the pulse rate.
17. Read the Redw 3 meter when the ready light goes on at about 218 s.
18. Press the restart meter button of Redw 3.
19. Go to 6.4.5 energy measurements, stop, or start at step 7 again.

6.4.5 PIN TS Calibration Procedures--Energy Measurements

1. Perform PIN TS calibration procedures (see 6.4.4) before proceeding with these steps.
2. Attach the pulse generator to the video input of the modulator power supply.
3. Reset the dual preset controller.
4. Press the start button of the time generator.
5. Press the start meter button of Redw 3 at 18 s if Redw 3 is used as a reference standard, otherwise omit steps 5, 7, and 8.
6. Read each PIN TS peak every 10 s during the 100 s the timed shutter is open.
7. Read the Redw 3 meter when the ready light goes on at about 218 s.
8. Press the restart meter button of Redw 3.
9. Repeat steps 3 through 8 a second time, otherwise go to step 10.
10. Record the temperature near the transfer standard, the laser amperes, and the modulator carrier level.
11. Repeat 6.4.4 steps 12 through 17.

6.4.6 PIN TS Calibration Computation

1. Calibrations J1 (J/V) and K1 (J/V cm^2) for oscilloscope readout and J2 (J/PHA reading) and K2 (J/PHA reading cm^2) for PHA readout of a PIN TS in the ($m = 2$) or ($m = 3$) beam using a Redw 3 TS in the ($m = 0$) beam are

$$J1 = \frac{R}{C3\ S\ F\ T\ AS1},\ J/V$$

$$K1 = J1/L2,\ J/V\ cm^2$$

$$J2 = \frac{R}{C3\ S\ F\ T\ P1},\ J/PHA\ reading$$

$$K2 = J2/L2,\ J/PHA\ reading\ cm^2$$

where
J = R/(C3 S F T), joules/pulse
R = Redw 3 reading minus the average background reading
C3 = Redw 3 calibration, reading/joule
S = beamsplitter ratio
F = average pulse rate
T = input time, 100 s
AS1 = average pulse height of A divisions times the volts per division S1 of the oscilloscope
P1 = av PHA reading of the pulses
L2 = apertured area of the PIN TS

2. Calibration J3 (J/V) and K3 (J/V cm^2) for oscilloscope readout and J4 (J/PHA reading) and K4 (J/PHA reading cm^2) for PHA readout of a PIN TS in the ($m = 3$) beam using another PIN TS in the ($m = 2$) beam as a reference standard are

$$J3 = \frac{C2\ BS2}{S\ AS1},\ J/V$$

$$K3 = J3/L2,\ J/V\ cm^2$$

$$J4 = \frac{C2\ BS2}{S\ P1},\ J/PHA\ reading$$

$$K4 = J4/L2,\ J/PHA\ reading\ cm^2$$

where
C2 = calibration, J/V of PIN TS as a reference standard
BS2 = average pulse height of the reference PIN TS of B divisions times the volts per division S2 of the oscilloscope

6.4.7 PIN TS Uniformity Measurement Procedures

1. Attach the alignment mirror and iris to the PIN TS.
2. Attach the PIN TS to the tilt table and the heavy-duty or other translator.
3. Align the PIN TS with the reflected beam from the alignment mirror returning on the path of the incoming beam.
4. Calibrate the PIN TS in the center and in at least four different areas next to the edge of the aperture of the PIN diode to determine the uniformity of the responsivity over the approximately 1 cm^2 PIN area.
5. Compute the average responsivity at the 95 percent confidence interval and use these data in the uncertainty statement of the calibration.

6.4.8 PIN TS Scan Procedures for Uniformity Measurement

1. Use a cw Nd:YAG laser source with very stable output.
2. Attenuate the beam with a coated glass attenuator that is raised or lowered to vary the attenuation.
3. Attenuate the beam with the (m = 2) beam of a wedge.
4. Change the beam direction 90 deg with a wedge.
5. Attenuate the beam with a coated glass attenuator that is rotated to change attenuation.
6. Focus the beam on the detector with a 1 m FL lens.
7. Position the beam with a horizontal and a vertical scanning mirror.
8. Attach the PIN TS detector output to a 50 Ω plug-in of an oscilloscope.
9. Scan the whole detector with a less than 1 mm diameter, ultrastable laser beam with 12 or more horizontal sweeps.
10. Photograph the scan image on the oscilloscope.
11. Use the detector with the most uniform scan image as a PIN TS.

6.5 Temperature Controllers for APD and PIN Transfer Standards

1. The temperature controllers for the APD and PIN transfer standards operate on dc power to reduce noise.
2. The temperature controllers maintain the transfer standards at a temperature in the 30°C to the 35°C range using an IC temperature transducer.
3. A milliammeter or other readout instrument indicates the relative temperature of the transfer standard.
4. The temperature controller is operated about one hour before the transfer standard to which it is attached is used.
5. Figure 6.5-1 shows the dc temperature controller circuit.

6.6 Procedures for Calibration of Customer's Instrument at NBS

1. The APD or PIN transfer standard is aligned in the (m = 2) beam of the precision beamsplitter attenuator (BA-1) with a tube in front for reducing the field of view.
2. The customer's instrument is aligned in the (m = 3) beam of BA-1 with a tube in front of the instrument.
3. A pulse rate $<10^3$ is used.

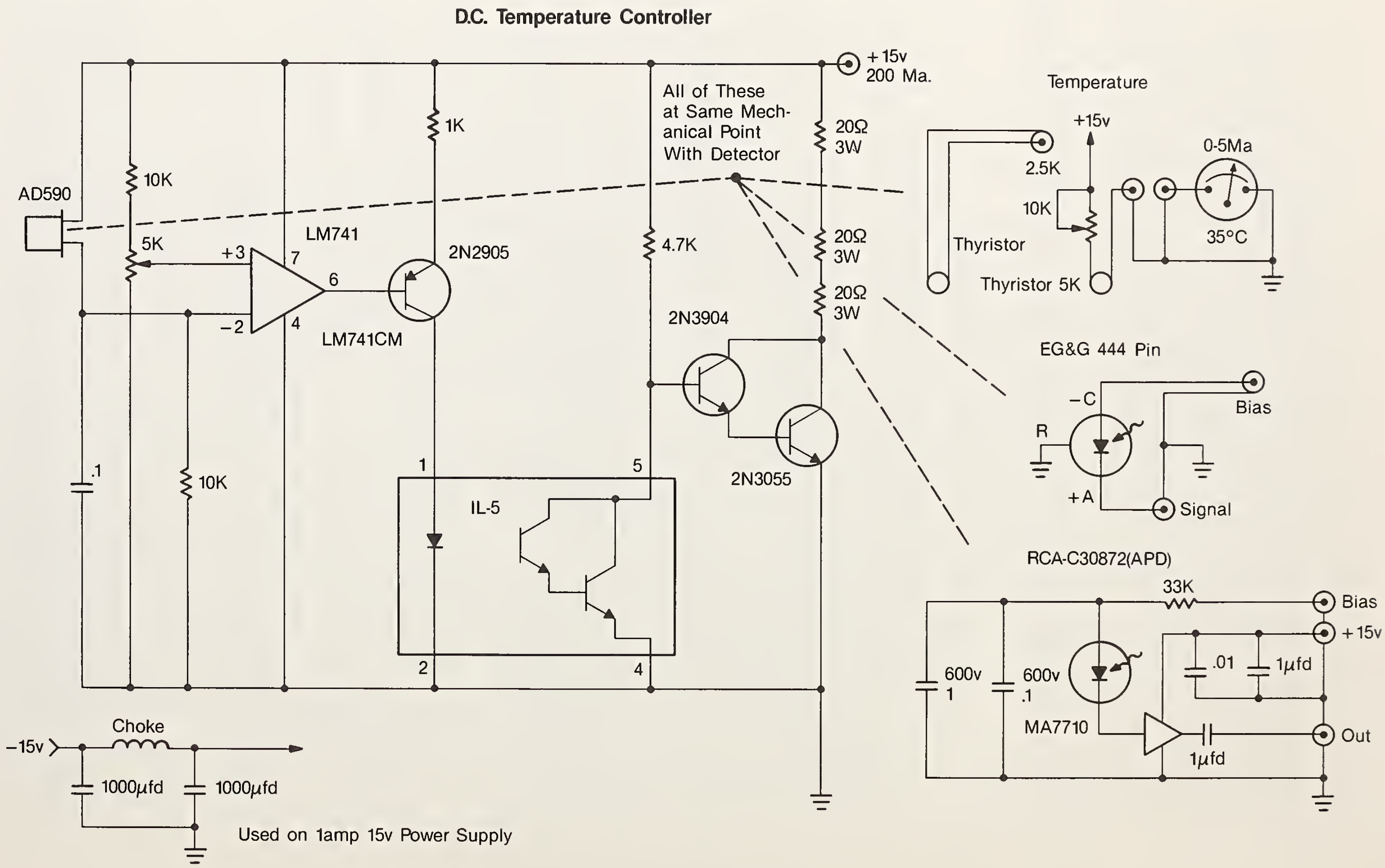

Figure 6.5-1. DC temperature controller circuit.

4. A shutter in the (m = 2) beam of BA-1 is used to eliminate a small amount of reflection from the APD TS when the customer's instrument is read.
5. During a 100 s input, the APD and the customer's instrument are alternately read for 10 s each.
6. The APD TS is read when the shutter in the (m = 2) beam is open and the customer's instrument when the shutter is closed.
7. The PIN TS is used with the shutter in the (m = 2) beam open, and it is aligned without a reflection into the customer's instrument.
8. The PIN TS and the customer's instrument are read every 10 s for a 100 s input.
9. For APD TS measurements, the peak power density (W/L2) into the customer's instrument is

$$W/L2 = \frac{V/K}{29.7\ L2}$$

where
W/L2 = peak power density in W/cm^2 into the customer's instrument
V = average oscilloscope readout in V
K = APD TS calibration in V/W
29.7 = beamsplitter attenuation ratio
L2 = area of the customer's instrument in cm^2

10. For PIN TS measurements, the energy density (E/L2) into the customer's instrument is

$$E/L2 = \frac{V\ J3}{29.7\ L2}$$

where
E/L2 = energy density in J/cm^2 into the customer's instrument
V = average oscilloscope readout in V
J3 = PIN TS calibration in J/V
29.7 = beamsplitter attenuation ratio
L2 = area of the customer's instrument in cm^2

11. Calibration of the customer's instrument may be performed in any beam except ($m > 4$) of the precision beamsplitter attenuator, using an APD TS, a PIN TS, or a Redw 3 TS and using the appropriate equations.
12. If the customer's instrument is calibrated at pulse durations around 100 to 200 ns and is to be used at pulse durations around 10 to 20 ns, then the instrument must have sufficient bandwidth for calibrations to apply at 10 to 20 ns.

6.7 APD TS Measurement Instructions for the Customer's Site

6.7.1 General Instructions

1. When you receive our transfer standard system, please carefully read the enclosed operating instructions. Note the way the equipment is packed so that you can repack it that way.
2. After completing measurements, please send the transfer standard system with all original parts to NBS.
   a. Send by UPS Blue Label.

   b. Sender must prepay shipping charges. You cannot send UPS collect.
   c. Ship to:
      U.S. Department of Commerce - NBS
      Alvin L. Rasmussen, 724.02
      325 Broadway
      Boulder, CO 80303

3. Before shipping back to NBS, be sure that the instrument is packed in the manner it was sent.
4. Please call Alvin L. Rasmussen at NBS at 303-497-5367 (FTS 320-5367) and advise when the instrument will be or was shipped.

6.7.2 APD Transfer Standard Operating Instructions

A. Warning to stay within the limits of the APD TS

   1. This system is for pulsed peak power between about 10^{-1} and 10^2 μW.
   2. Stay within the ranges in the table of the APD TS system.
   3. Exceeding these limits can burn out components in the APD TS and cost considerable expense and time to repair and recalibrate.
   4. Disassembling the APD TS can ruin its calibration.
   5. Operate the APD TS in a darkened room to prevent instrument damage and erroneous measurements.

B. System Parts

   1. APD TS with aperture below.
   2. APD TS temperature controller and preamplifier power supply.
   3. Temperature meter.
   4. P for positive and N for negative bias power supply.
   5. Wideband amplifier.
   6. Marked cables.
   7. Alignment mirror and iris.
   8. Aperture in a universal lens mount.
   9. Ungrounded precision voltmeter (provided by the user).

C. Bias Power Supply Check

   1. Attach B- VM cable to rear of the bias power supply and to the ungrounded precision voltmeter.
   2. Turn on the bias power supply, gradually turn the 10-turn potentiometer clockwise to read exactly the bias voltage on the voltmeter, gradually return potentiometer to 0 V, and turn off the power supply.
   3. If the voltmeter read the bias voltage, proceed to the next step.

D. Setup

   1. Attach the APD temperature controller and the preamplifier power supply to the APD TS.
   2. Attach the temperature meter to the APD TS.
   3. Attach the bias power supply to the APD TS and to the ungrounded precision voltmeter.
   4. Attach the signal (output) of the APD TS to an oscilloscope 50 Ω plug-in unit with a BW of 350 to 500 MHz.
   5. Attach the 20 dB or 40 dB input of the wideband amplifier to the APD TS and the output to the oscilloscope (see step 4) when lower peak power levels are to be measured.
   6. Yellow wires from APD 5-1 TS and APD 5-5 TS are attached to a wheatstone bridge set at low sensitivity to minimize heating from

the bridge current. Resistance readings of about 691 and 684 Ω, respectively, indicate proper temperature of each APD and its preamplifier.

E. Operation
  1. Turn on the temperature controller and the preamplifier power supply, run them for at least one hour, and check the temperature meter or ribbon thermometer for a steady reading.
  2. Turn on the bias power supply, gradually turn the 10-turn potentiometer clockwise to read exactly the bias voltage on the voltmeter, and gradually return it to zero and off when shutting down the equipment.
  3. Align the APD TS.
     a. Blow dust off the APD collector surface with a squeeze-type air blower ONLY (other types such as those in spray cans may spray liquid and damage the surface).
     b. Reattach the aperture, the alignment mirror and the iris.
     c. Align the APD TS in a visible light or 1.064 µm beam with the beam returning on itself, or
     d. Align the APD TS without the alignment mirror and the iris by positioning the APD diode for maximum pulses at one gain and range in the calibration table. See APD 5-5 calibration table for the difference in calibration using maximum pulses.
  4. Make APD TS measurements.
     a. Set a baseline of two divisions and a pulse height of three to five divisions.
     b. Refer to the table for gain, calibration, range and uncertainty.
     c. Read the peak voltage and the observed pulse duration (FDHM) to one quarter division each.
     d. Find the corrected peak voltage by multiplying the observed values by the correction factors in the figures.
     e. Divide the corrected peak voltage by the calibration (corrected for beam divergence when given) in the table to get the power density (W/cm^2).
     f. Acquire sufficient data for significant statistical information.

F. Shutdown.
  1. Gradually turn the ten-turn potentiometer of the bias power supply counterclockwise to zero and turn off the power supply.
  2. Turn off the temperature controller and preamplifier power supply.
  3. Reattach the alignment mirror to the APD TS to protect the collector.

G. APD Transfer Standard Equipment
  1. APD bias power supplies, Bertan Assoc. Inc., Model 602B-15N (APD 5-1) and Model 602B-15P (APD 5-5).
  2. Digital voltmeter for bias voltage measurement, Dana 4600 (used at NBS).
  3. AP 462A wideband amplifier, S/N 551-01053.
  4. Oscilloscope readout, Tektronix 7904, NBS 145935 (used at NBS).
     a. APD readout, dual trace amplifier, 7A24, 50 Ω.
     b. Dual time base, 7B92A.

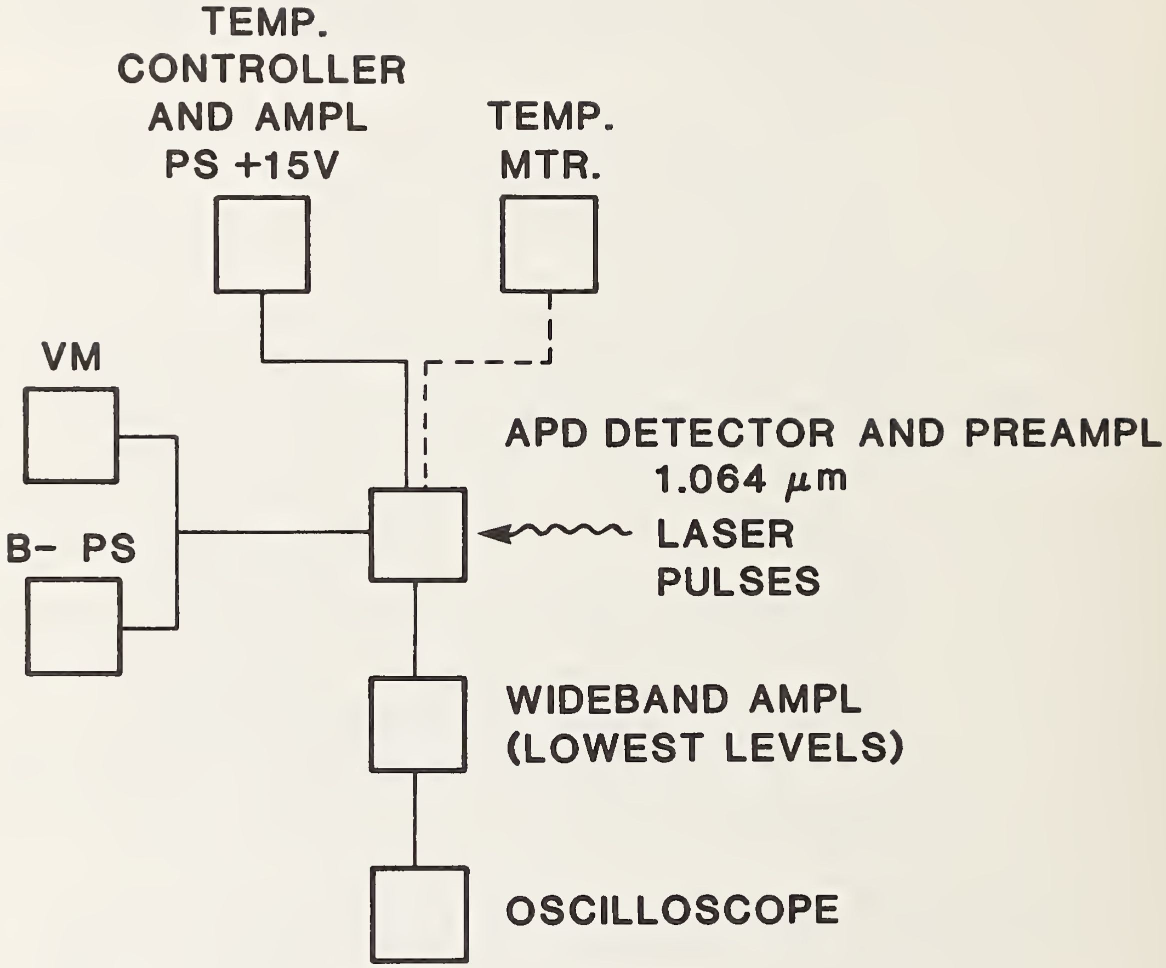

Figure 6.7-1. APD transfer standard system.

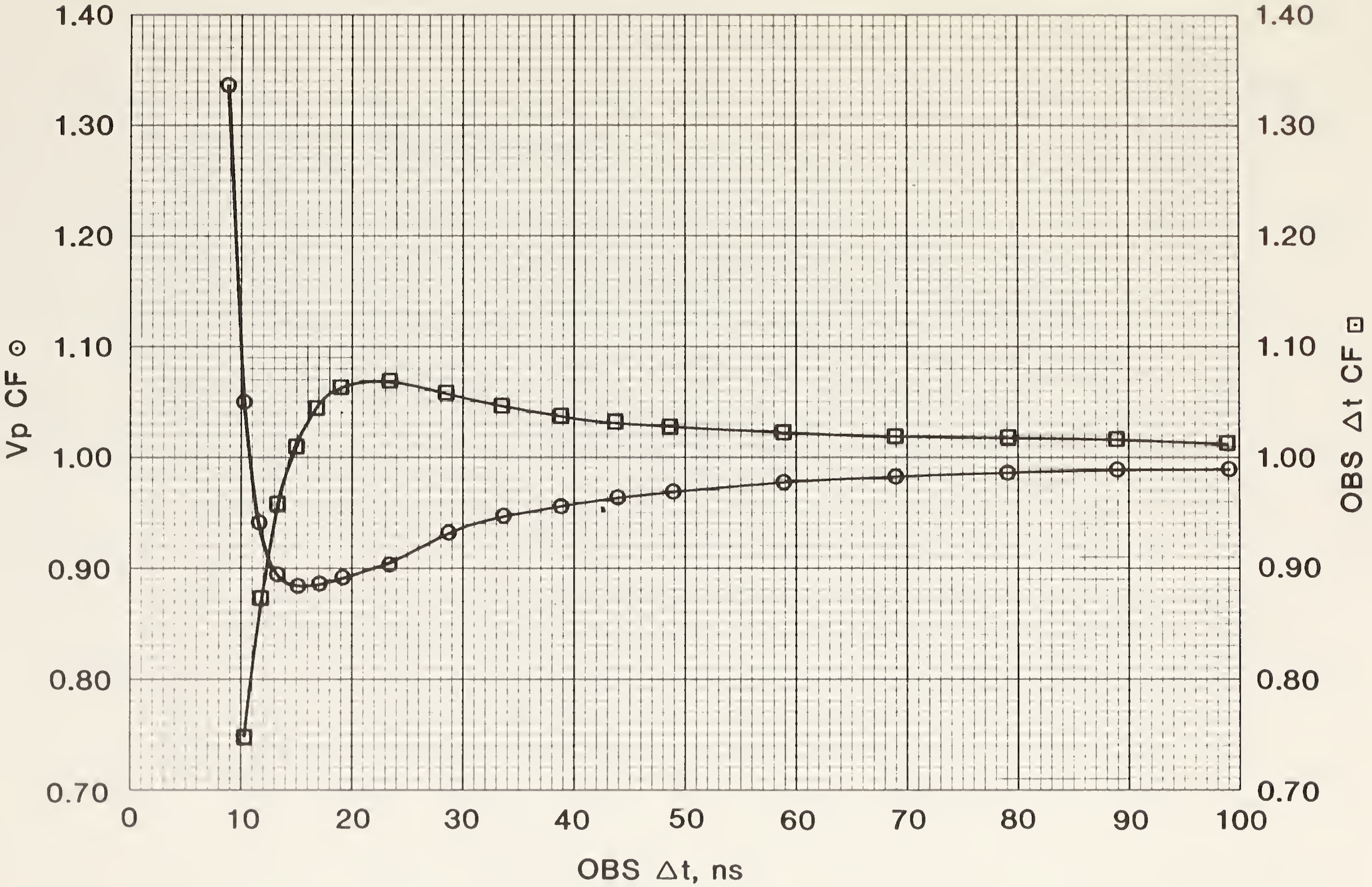

Figure 6.7-2. APD 5-1 correction factors (without HP amplifier) for peak voltage (Vp CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

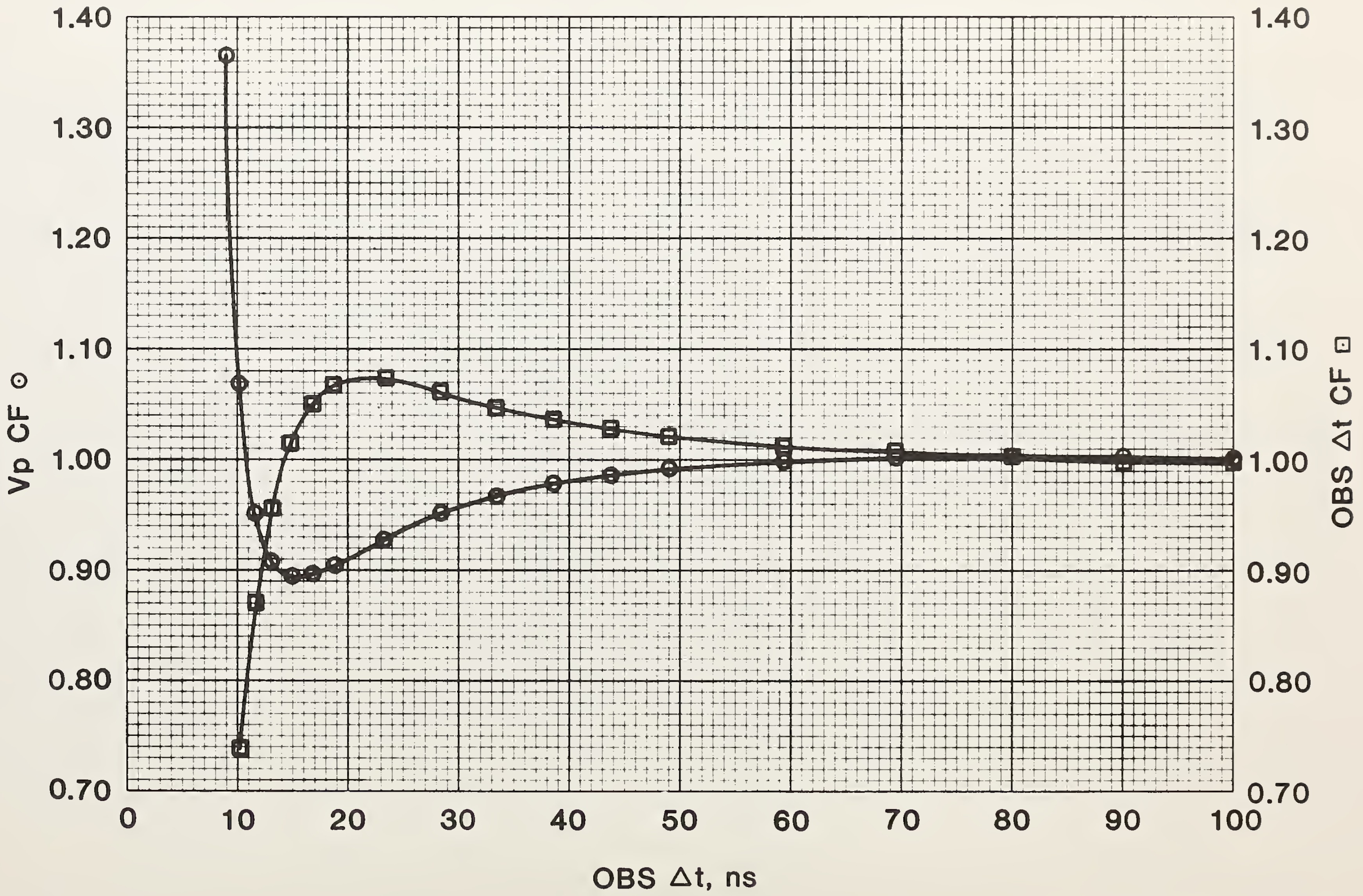

Figure 6.7-3. APD 5-1 correction factors (with HP 462A amplifier 20 dB and 40 dB) for peak voltage (Vp CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

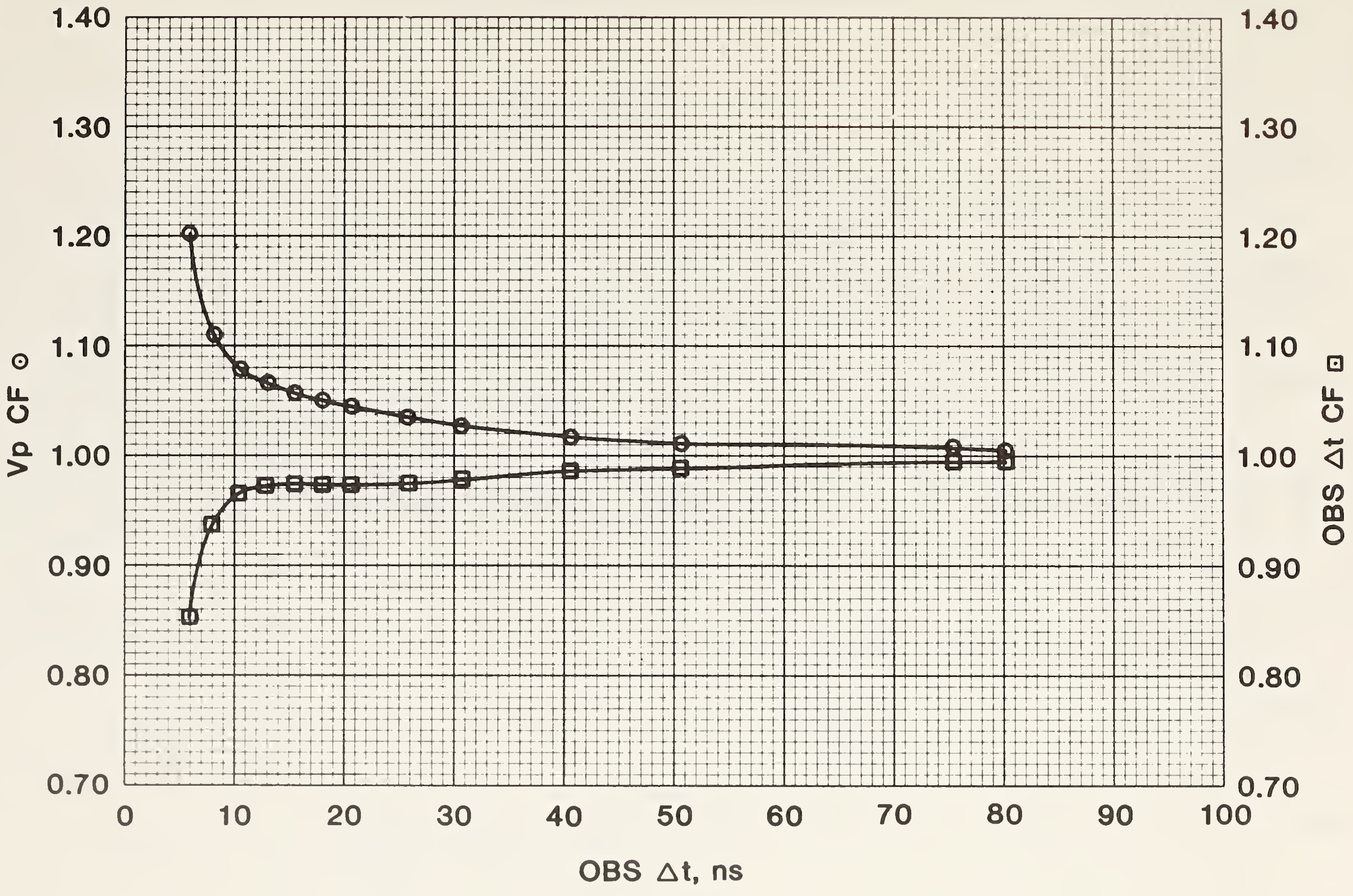

Figure 6.7-4. APD 5-5 correction factors (<u>without</u> HP amplifier) for peak voltage (Vp CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

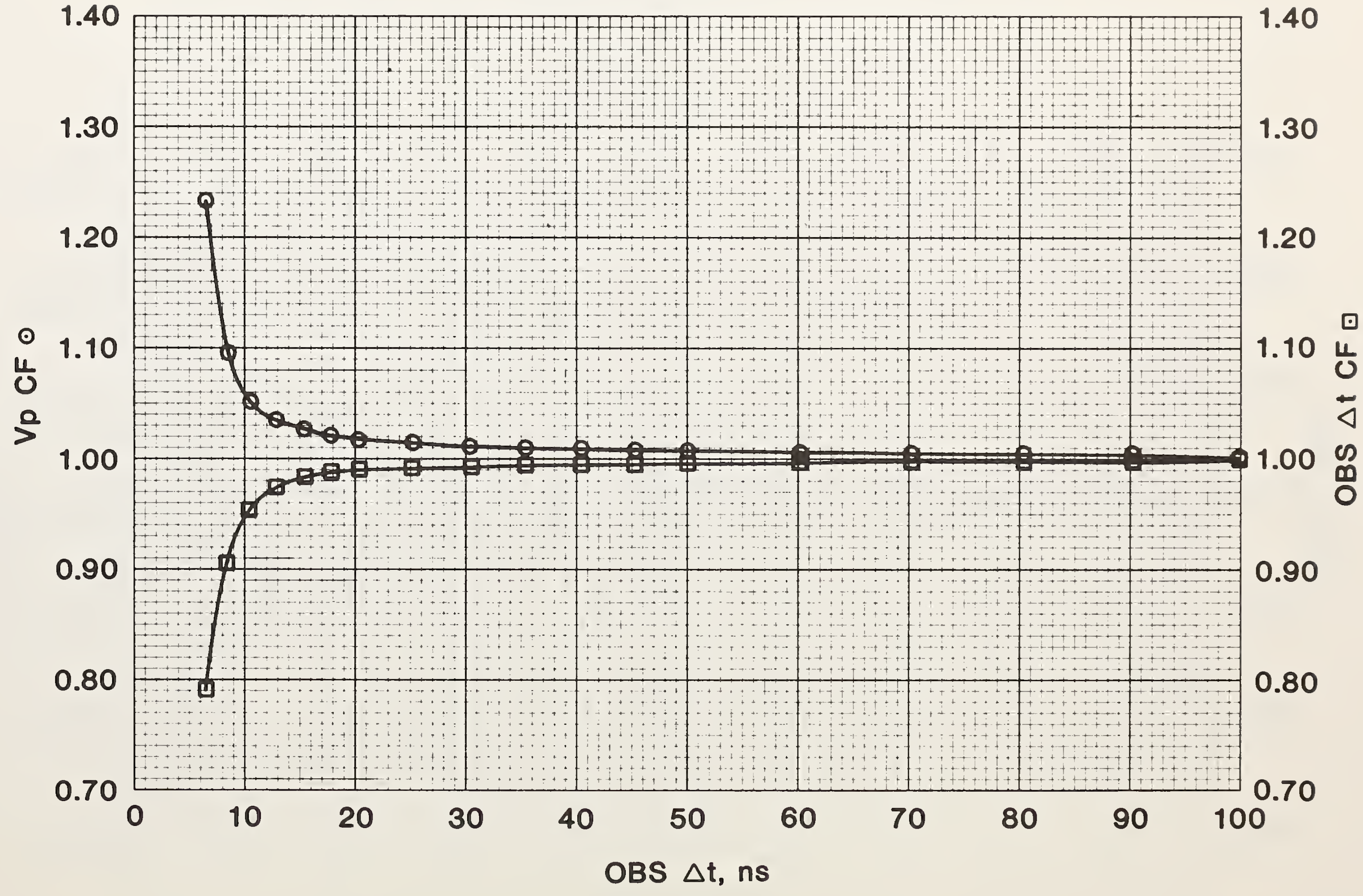

Figure 6.7-5. APD 5-5 correction factors (with HP 462A amplifier 20 dB and 40 dB) for peak voltage (Vp CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

Table 1. APD 5-1 system calibration.*

	Calibration $V \cdot cm^2/W$ * ** †	Number of calibrations n	Uncertainty in the average of the measurements at 95% CI %	Total estimated uncertainty at 95% CI %	Power range $\mu W/cm^2$ **	Readout range V
(1)†	9.8×10^3	81	0.4	10.9	2.0 -156	0.019-1.52
(2)†	8.9×10^4	147	0.6	13.4	0.44-5.1	0.040-0.43
(3)†	8.7×10^5	32	0.6	13.4	0.22-0.53	0.19 -0.45

* Calibration period 45 months.

** Aperture area 0.947 cm^2. Field of view at least 25 mrad.

† TX 7904 oscilloscope, Ch 2, 7A24 50 Ω plug-in:
(1) plus polarity.
(2) invert polarity, HP 462A amplifier 20 dB.
(3) invert polarity, HP 462A amplifier 40 dB.

Table 2. APD 5-5 system calibration.*

	Calibration $V \cdot cm^2/W$ * ** †	Number of calibrations n	Uncertainty in the average of the measurements at 95% CI %	Total estimated uncertainty at 95% CI %	Power range $\mu W/cm^2$ **	Readout range V
(1)†	5.6×10^3	104	0.5	10.5	3.3 -40	0.019-0.23
(2)†	5.1×10^4	81	0.5	13.6	0.73-8.1	0.04 -0.41
(3)†	4.9×10^5	60	0.7	13.6	0.16-0.99	0.08 -0.49

* Calibration period 43 months.

** Aperture area 0.947 cm^2. Field of view at least 15 mrad. Aligned with beam reflected on itself. If aligned by adjusting detector for maximum output, multiply calibration by 1.05 and add 1.2 percent estimated uncertainty.

† TX 7904 oscilloscope, Ch 2, 7A24 50 Ω plug-in:
(1) plus polarity.
(2) invert polarity, HP 462A amplifier 20 dB.
(3) invert polarity, HP 462A amplifier 40 dB.

Table 3. Error budget APD 5-1 system.

Source of error	Uncertainty %*
Redw 3 transfer standard	1.9
Beamsplitter attenuator	2.5
Equivalence of pulsed and cw power	2.5
Oscilloscope readout	3.0
Amplitude response of HP 462A amplifier	2.5
Precision, uniformity, and field of view	1.0
Total error budget	
(1) Without HP 462A amplifier	10.9
(2) With HP 462A amplifier at 20 and 40 dB	13.4

*At the 95 percent CI.

Table 4. Error budget APD 5-5 system.

Source of error	Uncertainty %*
Redw 3 transfer standard	1.9
Beamsplitter attenuator	
(1) Without HP 462A amplifier	1.9
(2) With HP 462A amplifier at 20 and 40 dB	2.5
Equivalence of pulsed and cw power	2.5
Oscilloscope readout	3.0
Amplitude response of HP 462A amplifier	2.5
Precision, uniformity, and field of view	1.1
If aligned for maximum output, use a 1.05 correction factor and add to error budget	1.2
Total error budget	
(1) Without HP 462A amplifier	10.4
(2) With HP 462A amplifier at 20 and 40 dB	13.5

*At the 95 percent CI.

H. APD System Description

The APD has inherently small size and nonuniform responsivity. To overcome these problems, the largest APD available at 3 mm diameter was used with a focusing lens (collector) and etched glass diffuser in front of it. Still, the responsivity in volts/watt varied over the portion of the collector area apertured. Consequently, the uniformity of the responsivity and the field of view were statistically determined.*

Since the APD systems designed have <100 MHz bandwidth, corrections to the peak voltage of the fastest pulses are necessary for dependable calibrations as a function of pulse duration. These corrections are calculated from the convolution of Gaussian pulses with the impulse response of the system.

Because of the temperature coefficients of components, the APD and its preamplifier were placed in a temperature-controlled environment. It consists of a thermally insulated box containing the components and a dc temperature controller circuit operating around 30° to 35°C. The silicon photodiode lies in the center of a hole inside the box. A temperature meter and a ribbon thermometer next to the APD indicates the inside temperature.

The dc bias is rectified 20 kHz and contributes little noise to the APD output.

6.8 PIN TS Measurement Instructions for the Customer's Site

6.8.1 General Instructions

1. When you receive our transfer standard system, please carefully read the enclosed operating instructions. Note the way the equipment is packed so that you can repack it that way.
2. After completing measurements, please send the transfer standard system with all original parts to NBS.
   a. Send by UPS Blue Label.
   b. Sender must prepay shipping charges. You cannot send UPS collect.
   c. Ship to:
      U.S. Department of Commerce - NBS
      Alvin L. Rasmussen, 724.02
      325 Broadway
      Boulder, CO 80303
3. Before shipping back to NBS, be sure that the instrument is packed in the manner it was sent.
4. Please call Alvin L. Rasmussen at NBS at 303-497-5367 (FTS 320-5367) and advise when the instrument will be or was shipped.

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*An ir-enhanced APD from the manufacturer, which became available after the APD transfer standards were completed, can be used if the need occurs, because they are reported to be more uniform and higher in responsivity than the APD described here.

6.8.2 PIN Transfer Standard Operating Instructions

A. **Warning to stay within the limits of the PIN TS.**
   1. **This system is for pulsed energies between 10 to 10^4 fJ/cm^2.**
   2. **Stay within the gains and ranges in the table of the PIN TS system.**
   3. **Operate the PIN TS in a darkened room to prevent instrument damage and erroneous measurements.**

B. System Parts
   1. PIN transfer standard.
   2. PIN temperature controller power supply.
   3. Temperature meter.
   4. Charge amplifier.
   5. Charge amplifier cable.
   6. NIMBIN with linear amplifier, pulser, and bias power supply.
   7. Five marked cables.
   8. Alignment mirror, iris, and two lens mount sleeves.
   9. Ungrounded precision voltmeter (provided by the user).

C. Bias Power Supply Check
   1. Attach the HV--NEG BIAS cable to rear of the bias power supply and to the ungrounded precision voltmeter.
   2. Turn on the bias power supply, gradually turn the 10-turn potentiometer clockwise to read -180.0 V on the voltmeter, gradually return potentiometer to 0 V, and turn off the power supply.
   3. If the voltmeter read -180.0 V, proceed to the next step.

D. Setup
   1. Attach the +15--+15 cable to the PIN TS and the PIN temperature controller power supply.
   2. Attach the TEMP MTR--TEMP MTR cable to the PIN TS and the temperature meter.
   3. Attach the charge amplifier cable to the rear of the linear amplifier and to the charge amplifier using the pair of screws on the device.
   4. Attach the charge amplifier directly to the signal (output) terminal of the PIN TS using the double male connector.
   5. Attach the T connector to the NEG BIAS terminal of the PIN TS.
   6. Attach the HV--NEG BIAS cable to the rear of the bias power supply and to the NEG BIAS terminal of the PIN TS.
   7. Attach the B- --VM cable to the NEG BIAS terminal of the PIN TS and the ungrounded precision voltmeter.
   8. Attach the linear amplifier--SCOPE cable to the bipolar output of the linear amplifier and to an oscilloscope meghom plug-in unit with BW > 200 MHz and 0.2 μs sweep.
   9. Set the linear amplifier at BLR: ASYM.1, RATE OUT and the gain at one of the ranges of the calibration table (see step 10).
   10. Set the fine gain at 0.500 by turning the potentiometer counter clockwise and at 1.000 by turning the potentiometer clockwise.

E. Operation
   1. Turn on the temperature controller power supply, run it for at least one hour, and check the temperature meter for a steady reading.
   2. Turn on the NIMBIN and run it for at least one hour.

3. Turn on the bias power supply, gradually turn the potentiometer clockwise to read -180.0 V, and gradually return it to zero and off when shutting down the equipment.
4. Align the PIN TS.
    a. Blow dust off the PIN collector surface with a squeeze-type air blower ONLY (other types may spray liquid and damage the surface).
    b. Reattach the two lens mount sleeve, the alignment mirror, and the iris.
    c. Align the PIN TS in a visible or 1.064 μm beam with the beam almost returning on itself, or
    d. Align the PIN TS without the two lens mount sleeves, the alignment mirror, and the iris by positioning the PIN diode for maximum pulses at one gain pair and range of the calibration table.
5. Make PIN TS measurements.
    a. Set a baseline at two divisions and a positive pulse height from three to five divisions.
    b. Refer to the table for gain, calibration, range and uncertainty.
    c. Read the pulse height to one quarter division and determine the peak voltage.
    d. To determine energy multiply the peak voltage by the calibration.
    e. Acquire sufficient data for significant statistical information.
    f. If the area of the beam is less than the area of the PIN TS, either multiply the calibration by the area of the PIN TS for a new calibration in J/V, or multiply the calibration by the area of the PIN TS divided by the area of the beam for a new calibration in J/V cm^2.

F. Shutdown.
   1. Gradually turn the ten-turn potentiometer of the bias power supply counterclockwise to zero and turn off the power supply.
   2. Turn off the NIMBIN.
   3. Turn off the temperature controller.
   4. Reattach the two lens mount sleeves and the alignment mirror to the PIN TS to protect the diode.

G. PIN Transfer Standard Equipment
   1. PIN bias power supply, Bertan Assoc. Inc., Model 342.
   2. Digital voltmeter for bias voltage measurement, Dana 4600 (used at NBS).
   3. Charge amplifier, Tennelec, TC 162, S/N 326 (PIN 4-1) and S/N 293 (PIN 4-3).
   4. Linear (shaping) amplifier, Tennelec, TC 222, S/N 386 (PIN 4-1) and S/N 230 (PIN 4-3).
   5. Pulser, Tennelec, TC 812.
   6. Oscilloscope readout, Tektronix 7904, NBS 145935 (used at NBS).
       a. PIN 4-3 readout, dual trace amplifier, 7A12, 1 mΩ.
       b. PIN 4-1 readout, dual trace amplifier, 7A26, 1 mΩ NBS 146251.
       c. Dual time base, 7B92A.

H. PIN System Description

The charge and linear amplifiers of the PIN system integrate the current and shape of the pulse. A pulse emerges whose peak voltage is proportional to the energy in the original PIN pulse. Peak voltages of pulses are read out on an oscilloscope and/or a pulse height analyzer (PHA). The latter records the occurrence and amplitudes of pulses from which one can determine the average amplitude and the stability of the laser output.

Because of the temperature coefficients of components, the PIN was placed in a temperature-controlled environment. It consists of a thermally insulated box containing the components and a dc temperature controller circuit operating around 30° to 35°C. The silicon photodiode lies in the center of a hole inside the box. A temperature meter indicates the inside temperature.

The dc bias is rectified 20 kHz and contributes little noise to the PIN output.

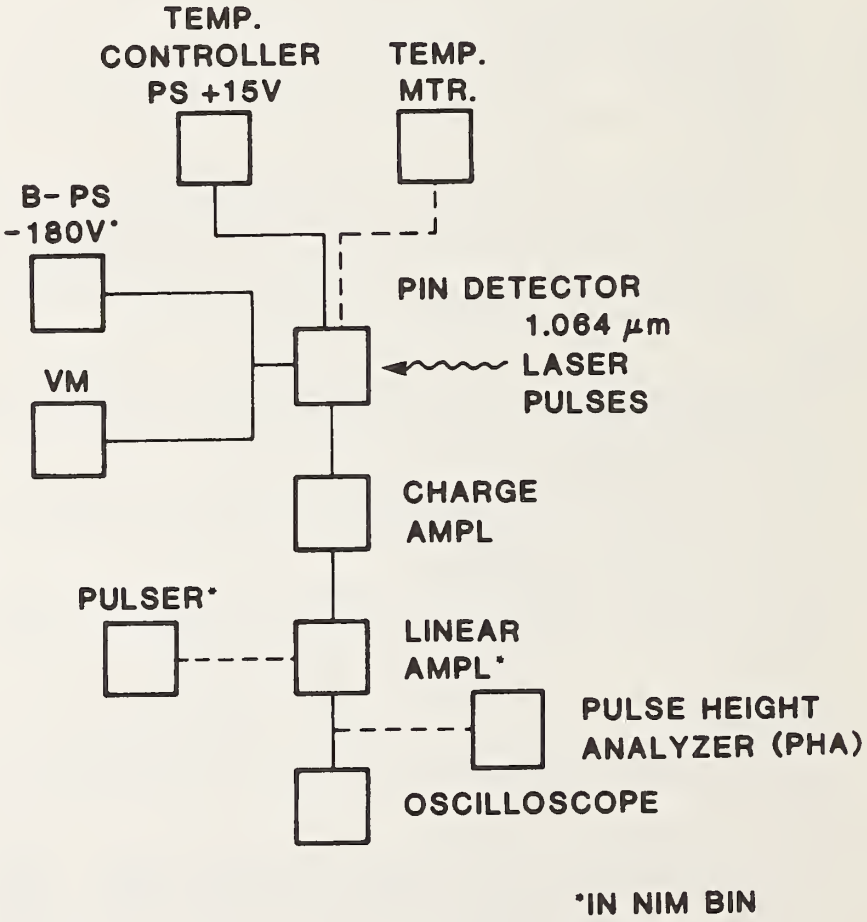

Figure 6.8-1. PIN transfer standard system.

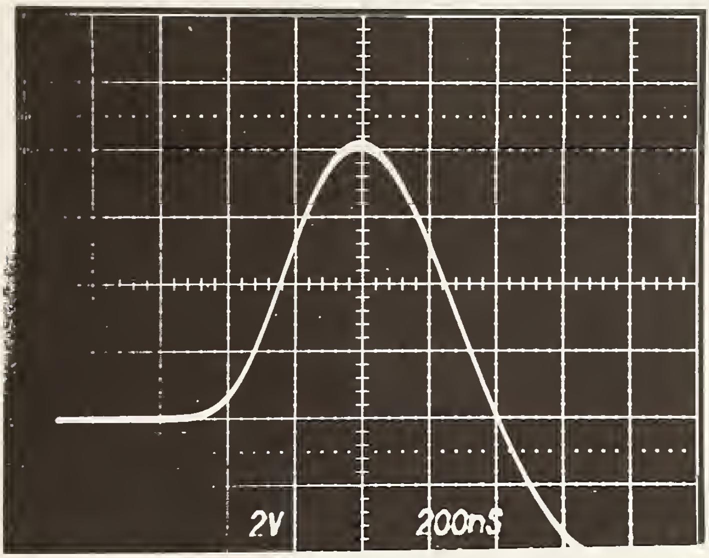

Figure 6.8-2. Typical output of PIN transfer standard system.

7. Analysis of the Systematic and Random Errors [1-8]

The NBS measuring system generates low-level beams of known peak power and energy for calibrations. Peak power or energy is determined from the known splitting ratios of a precision beamsplitter attenuator, Model 1 (BA-1), and transfer standard measurements in a higher level beam. Measurement uncertainties are calculated at the 95 percent CI. Error budgets of each transfer standard are given in reference 1.

Comparing low-level transfer standards in the modulated cw system, the pulse energy from APD and from PIN TS measurements were with 1 to 2 percent of each other (February 1984).

Table 5. PIN 4-1 system calibration.*

Linear amplifier TC 222**		Calibration J/(V cm^2) † ‡	Number of calibrations n	Uncertainty in the average of the measurements at 95% CI %	Total estimated uncertainty at 95% CI %	Energy range fJ/cm^2 †	Readout range V ‡
coarse gain	fine gain						
5	0.500	$1.07 \cdot 10^{-12}$	75	0.4	7.9	220 - 8900	0.20 - 8.3
10	1.000	$2.71 \cdot 10^{-13}$	38	0.6	8.0	210 - 1700	0.75 - 6.2
50	1.000	$5.3 \cdot 10^{-14}$	34	0.5	12.2	35 - 440	0.67 - 8.2
100	1.000	$2.72 \cdot 10^{-14}$	36	0.6	12.3	12 - 220	0.44 - 8.3

* Calibration period 40 months.

** BLR: ASYM 1, RATE OUT.
OUTPUT: Bipolar positive peak.
INSIDE: TC 2 μs, x 0.2, delay out set at NBS.
MAKE NO OTHER ADJUSTMENTS.

† Aperture area 0.819 cm^2.

‡ TX 7904 oscilloscope, Ch2, 7A26 1 MΩ plug-in, sweep 0.2 μs.

Table 6. PIN 4-3 system calibration.*

Linear amplifier TC 222**		Calibration J/(V cm^2) † ‡	Number of calibrations n	Uncertainty in the average of the measurements at 95% CI %	Total estimated uncertainty at 95% CI %	Energy range fJ/cm^2 †	Readout range V ‡
coarse gain	fine gain						
5	0.500	$9.3 \cdot 10^{-13}$	91	0.4	8.0	18 - 9200	0.02 - 9.7
10	1.000	$2.33 \cdot 10^{-13}$	54	0.3	8.0	160 - 1400	0.69 - 5.9
50	1.000	$4.64 \cdot 10^{-14}$	64	0.4	12.4	11 - 380	0.24 - 8.3
100	1.000	$2.35 \cdot 10^{-14}$	68	0.4	12.4	10 - 190	0.44 - 8.1

* Calibration period 59 months.

** BLR: ASYM 1, RATE OUT.
OUTPUT: Bipolar positive peak.
INSIDE: TC 2 μs, x 0.2, delay out set at NBS.
MAKE NO OTHER ADJUSTMENTS.

† Aperture area 1.00 cm^2.

‡ TX 7904 oscilloscope, CH 1, 7A12 and Ch2, 7A26 1 MΩ plug-ins, sweep 0.2 μs.

Table 7. Error budget PIN 4-1 system.

Source of error	Uncertainty %*
Redw 3 TS for linear amplifier gain of 5, 0.500 and 10, 1.000	1.9
PIN 4-3 TS for linear amplifier gain of 50, 1.000 and 100, 1.000 of PIN 4-1: Redw 3 TS 1.9% + Beamsplitter 2.5% + Precision 0.6% + Oscilloscope 3.0%	8.0
Beamsplitter attenuator	
(1) Linear amplifier gain of 5, 0.500 and 10, 1.000 and beam ratios of (m=0)/(m=2) and (m=0)/(m=3)	2.5
(2) Linear amplifier gain of 50, 1.000 and 100, 1.000 and beam ratio of (m=2)/(m=3)	0.7
Oscilloscope readout	3.0
Precision and uniformity for linear amplifier gain	
5, 0.500	0.5
10, 1.000	0.6
50, 1.000	0.5
100, 1.000	0.6
Total error budget for linear amplifier gain	
5, 0.500	7.9
10, 1.000	8.0
50, 1.000	12.2
100, 1.000	12.3

*At the 95 percent CI.

Table 8. Error budget PIN 4-3 system.

Source of error	Uncertainty %*
Redw 3 TS for linear amplifier gain of 5, 0.500 and 10, 1.000	1.9
PIN 4-1 TS for linear amplifier gain of 50, 1.000 and 100, 1.000 of PIN 4-3: Redw 3 TS 1.9% + Beamsplitter 2.5% + Precision 0.6% + Oscilloscope 3.0%	8.0
Beamsplitter attenuator	
(1) Linear amplifier gain of 5, 0.500 and 10, 1.000 and beam ratios of (m=0)/(m=2) and (m=0)/(m=3)	2.5
(2) Linear amplifier gain of 50, 1.000 and 100, 1.000 and beam ratio of (m=2)/(m=3)	0.7
Oscilloscope readout	3.0
Precision and uniformity for linear amplifier gain	
5, 0.500	0.6
10, 1.000	0.6
50, 1.000	0.6
100, 1.000	0.6
Total error budget for linear amplifier gain	
5, 0.500	8.0
10, 1.000	8.0
50, 1.000	12.3
100, 1.000	12.3

*At the 95 percent CI.

7.1 Analysis of Errors of the APD Transfer Standards

Source of Error	Analysis
1. Redw 3 transfer standard in the (m = 0) beam (commercial calorimeter and power meter)	1. Calibrated by the C and Q-series calorimeters [2,3,6]. Random and systematic errors of calibration are added.
2. Precision beamsplitter attenuator (unknown polarization)	2. [4]
3. Inequivalence of pulsed and cw power	3. Pulses should reach the level of cw power during the pulse duration. a. Checked by measuring the variation of the pulse peak for durations from ~200 to ~600 ns. b. Checked by comparing pulsed and cw power calibration measurements.
4. Oscilloscope	4. Calibrated oscilloscope deflection factor, time base, and impulse response [5].
5. Amplitude response of the wideband amplifiers	5. Calibrated by measuring the variation in the pulse peak for durations from 10 to 200 ns of pulse generator pulses passing through the wideband amplifier.
6. Precision and uniformity	6. a. Precision determined over each gain calibrated. b. Uniformity determined at a given input over the collector area by measuring the responsivity at the center and in the four cardinal directions near the edge of the photodiode.
7. Field of view	7. Calibrated by measuring the responsivity at several input angles into the APD in the four cardinal directions.
8. Impulse response	8. Correction factors for the peak voltage determined from the convolution of the impulse response and Gaussian pulses and skewed Gaussian pulses.
9. Time interval	9. Calibrated by a timer/counter.

7.2 Analysis of Errors of the PIN Transfer Standards

Source of Error	Analysis
1. Redw 3 transfer standard in the (m = 0) beam (commercial calorimeter and power meter)	1. Calibrated by the C- and Q-series calorimeters [2,3,6]. Random and systematic errors of calibration are added.
2. Precision beamsplitter attenuator (unknown polarization)	2. [4]
3. Oscilloscope	3. Calibrated oscilloscope deflection factor, time base, and impulse response.
4. Precision and uniformity	4. a. Precision determined over each gain calibrated. b. Uniformity determined at a given input over the diode area by measuring the responsivity at the center and in the four cardinal directions near the edge of the photodiode. c. Uniformity also determined by scanning the area of the photodiode with an ultrastable cw laser beam and photographing the oscilloscope readout.
5. Pulse rate	5. Calibrated by a timer/counter or frequency counter.
6. Time interval (shutter)	6. Calibrated by a readout of a light sensor and amplifier attached to a timer/counter.
7. Pulse height analyzer readout	7. Linear if the pulse duration is <200 ns and the internal settings of the linear amplifier are TC 2 μs, mult X0.2.*

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*Linear amplifier settings greater than these pass excessive noise and less than these make calibrations nonlinear.

7.3 Calibration of Redw 3 (TC15) Transfer Standard (Time Dependent)

Redw 3 (TC15)   Date: Apr 85

National reference standard used	Scales	Calibration (meter units/ joule)	n	95% CI	Date of latest calibration
C-series	10 J, 100 s	1.092	21	0.13	24 Apr 85
	1 J, 100 s	1.094	28	0.18	23 Apr 85
	0.1 J, 100 s	1.088	20	0.40	24 Apr 85
Q-series	10 J, 100 s	1.090	20	0.22	24 Mar 82
	1 J, 100 s	1.086	21	0.27	25 Mar 82

Currently, the C-series national reference standard only is used to calibrate the Redw 3 (TC15) TS. Calibrations are independent of the reference standards. The C-series reference standard is easier to use.

7.4 Summaries of the Uncertainties at the 95 Percent Confidence Interval of Calibrations of the APD and the PIN Transfer Standards

APD 5-1 Date: Aug 85
Summary of the uncertainties at the 95 percent CI of the calibration of APD 5-1 transfer standard (time dependent)

Source of uncertainty	Source of information	Date	Uncertainty %*	Comments
Redw 3 TS	Calibration	4/85	1.9	
Precision beam-splitter attenuator (unpolarized beam)	[4]		2.5	
Inequivalence of pulsed & cw power	Calibration	4/81	2.5	
Oscilloscope	Calibration	2/85	3 (vertical deflection)	
Amplitude response of the wideband amplifier	Calibration	12/81	2.5	
Time interval cw input	Calibration	8/85	0.0	
Impulse response	Calibration	7/81	0.0	Correction factors of the pulse height between 10 ns and 100 ns
Precision	Calibration	5/85	0.4,0.6, 0.6	For gains of 0, 20, and 40 dB, resp.
Uniformity	Calibration	11/80	0.9	
Field of view	Calibration	12/80	1.0	For divergence of 25 mrad
				For APD 5-1 the precision, uniformity, and field of view uncertainty are combined into the largest uncertainty, 1.0%
	Total		10.9, 13.4, 13.4	For gains of 0, 20, and 40 dB, resp.

*At the 95 percent CI.

APD 5-5 Date: Aug 85
Summary of the uncertainties at the 95 percent CI of the calibration of APD 5-5 transfer standard (time dependent)

Source of uncertainty	Source of information	Date	Uncertainty %*	Comments
Redw 3 TS	Calibration	4/85	1.9	
Precision beam-splitter attenuator (unpolarized beam)	[4]		1.9	Without HP 462A amp.
			2.5	With HP 462A amp.
Inequivalence of pulsed & cw power	Calibration	4/81	2.5	
Oscilloscope	Calibration	2/85	3	Vertical deflection
Amplitude response of the wideband amplifier	Calibration	12/81	2.5	
Time interval cw input	Calibration	8/85	0.0	
Impulse response	Calibration	7/81	0.0	Correction factors of the pulse height between 10 ns and 100 ns
Precision	Calibration	6/85	0.5,0.5, 0.7	For gains of 0, 20, and 40 dB, resp.
Uniformity** with alignment (1) and (2)	Calibration	5/85	0.9 and 1.7, resp.	
Field of view	Calibration	12/81	1.1	For divergence of 15 mrad
Correction factor for alignment (2)†	Calibration	5/85	0.6	Correction factor† = 1.05
				For APD 5-5 the precision, uniformity, and field of view uncertainty are combined into the largest uncertainty, alignment (1)** 1.1% and alignment (2)** 1.7%
Alignment (1)**	Total 10.4, 13.5, 13.5			For gains of 0, 20, and 40 dB, resp.
Alignment (2)**	Total 11.6, 14.7, 14.7			

* At the 95 percent CI.

**(1) Incoming beam reflected on itself from mirror attached to the detector entrance.

(2) Maximum output with the beam entering the center of the detector and moving the detector parallel to this position for other measurements.

† Correction factor for alignment (2)

$$= \frac{\text{average alignment (2) uniformity measurements}}{\text{average alignment (1) uniformity measurements}}.$$

PIN 4-1 Date: Aug 85

Summary of the uncertainties at the 95 percent CI of the calibration of PIN 4-1 transfer standard (time dependent)

Source of uncertainty	Source of information	Date	Uncertainty %*	Comments
Redw 3 TS	Calibration	4/85	1.9	For linear amplifier gain of 5, 0.5; 10, 1; 50, 1; and 100, 1.
PIN 4-3 TS	Calibration	5/85	8.0	For linear amplifier gain of 50, 1 and 100, 1.
Precision beam-splitter attenuator	[4]		2.5 and 0.7	For linear amplifier gain of 5, 0.5 and 10, 1; and 50, 1 and 100, 1; resp.
Oscilloscope	Calibration	2/85	3.0	For vertical deflection
Pulse rate	Calibration	4/82	0.0	
Time interval (shutter)	Calibration	8/85	0.0	
Precision	Calibration	5/85	0.4 0.6 0.5 0.6	For linear amplifier gain of 5, 0.5; 10, 1; 50, 1; and 100, 1; resp.
Uniformity	Calibration	2/82	0.5	The uniformity is referred to only if it exceeds the precision.
	Totals 7.9, 8.0, 12.2, 12.3			For linear amplifier gain of 5, 0.5; 10, 1; 50, 1; and 100, 1; resp.

*At the 95 percent CI.

PIN 4-3 Date: Aug 85

Summary of the uncertainties at the 95 percent CI of the calibration of PIN 4-3 transfer standard (time dependent)

Source of uncertainty	Source of information	Date	Uncertainty %*	Comments
Redw 3 TS	Calibration	4/85	1.9	For linear amplifier gain of 5, 0.5; 10, 1; 50, 1; and 100, 1.
PIN 4-1 TS	Calibration	5/85	8.0	For linear amplifier gain of 50, 1 and 100, 1.
Precision beam-splitter attenuator	[4]		2.5 and 0.7	For linear amplifier gain of 5, 0.5 and 10, 1; and 50, 1 and 100, 1; resp.
Oscilloscope	Calibration	2/85	3.0	For vertical deflection.
Pulse rate	Calibration	8/85	0.0	
Time interval (shutter)	Calibration	8/85	0.0	
Precision	Calibration	5/85	0.4 0.3 0.4 0.4	For linear amplifier gain of 5, 0.5; 10, 1; 50, 1; and 100, 1; resp.
Uniformity	Calibration	6/80	0.6	The uniformity is referred to only if it exceeds the precision.
	Totals 8.0, 8.0, 12.3, 12.3			For linear amplifier gain of 5, 0.5; 10, 1; 50, 1; and 100, 1; resp.

*At the 95 percent CI.

8. Procedures for Quality Control of the Modulated cw Measurement System and of the APD and PIN Transfer Standards

8.1 Alignment Verification

1. Before measurements proceed each day, the modulated cw measurement system is aligned or realigned as described elsewhere.
2. APD and PIN transfer standards are aligned as described elsewhere.
3. APD and PIN transfer standards previously aligned do not need realignment each day, if the modulated cw measurement system required little alignment at the beginning of the day.

8.2 Optical Surface Maintenance

1. The mirrors and first lens are always covered.
2. The modulator, the second lens and the precision beamsplitter attenuator are covered between uses.
3. When uncovered, dust is blown off their surfaces with a hand-squeeze type air blower.
4. If the surfaces appear dirty and calibration values appear out of control, the precision beamsplitter attenuator is cleaned by passing lens tissue containing methanol across its surfaces and letting the alcohol evaporate.

8.3 Laser Mode and Stability Requirements

1. The laser should have single mode output.
2. If the laser shows a multimode pattern at the first mirror, the laser should be realigned as described elsewhere.
3. If the oscilloscope readout of the APD or PIN transfer standard are too unstable to read, the laser current is increased; or if instability persists, the flash lamp of the laser is replaced.

8.4 Shutter for Timed Laser Input Calibration

1. The shutter time is calibrated for a 100 s input periodically as described elsewhere.
2. If the time error is greater than 0.05 percent, the time base of the time generator in the shutter system is corrected.

8.5 Redw 3 Transfer Standard Calibration

1. The Redw 3 transfer standard to which all calibrations are referred is calibration checked once a year.
2. Calibrations are performed on the C-series system only since C-series and Q-series calibrations of the Redw 3 transfer standard are within the experimental error of each other.
3. Calibrations are performed on the 0.1 J, 1 J, and 10 J and 100 s scales for at least three settings of each J scale.

8.6 Oscilloscope Calibration

1. The vertical deflection of the oscilloscope readouts is calibrated every 12 to 18 months using the NBS or commercial amplitude calibrator.

2. The time base of the oscilloscope readout is calibrated every 12 to 18 months using a time mark generator.
3. The impulse response of the oscilloscope readout for the APD transfer standard is calibrated using a step generator (rise time <25 ps).
4. Vertical deflection and time base scales are adjusted to be within the manufacturer's specification when necessary.

8.7 Time and Frequency Measurement Equipment Calibration

1. The timer/counter is calibrated every 12 to 18 months.
2. The electronic counter is calibrated every 12 to 18 months.

8.8 APD and PIN Transfer Standard Calibration

1. The APD and PIN transfer standards are calibrated at least six levels for each gain setting.
2. The APD TS gain settings calibrated are 0 dB (without the wideband amplifier) and 20 dB and 40 dB (with the wideband amplifier).
3. The PIN TS coarse and fine gain settings calibrated are 5, 0.500; 10, 1.000; 50, 1.000; 100, 1.000; and, when needed, 200, 1.000.
4. APD and PIN transfer standards are recalibrated at one or more levels of each gain setting every 6 to 12 months and before and after their use.

8.9 APD and PIN Transfer Standard Uniformity and Field of View Calibrations

1. APD and PIN transfer standards should be calibrated at least near the center and the edge of approximately a 1 cm^2 area in the four cardinal directions at one input level to determine the uniformity of the calibration over the surface.
2. APD transfer standards should be calibrated at various angles to the incoming beam in the four cardinal directions to determine the field of view or the calibration correction factor versus the beam divergence.
3. Each PIN TS should be scanned with a stabilized cw Nd:YAG laser, and the surface responsivity from an oscilloscope readout should be photographed. The most uniform responding PIN silicon photodiodes should be selected as PIN transfer standards.

8.10 Pulse Height Corrections of APD Transfer Standards from Impulse Response Measurements

1. These corrections and measurements are repeated if the preamplifier and/or wideband amplifier attached to the APD are changed.
2. These measurements are made in a linear region of the APD TS.

9. Computer Programs for Computation and Treatment of APD and PIN Transfer Standard Calibration Data

1. DMAKE is for creating a new disk data file.
2. RENAMEFILE is for changing the name of a disk data file to another name.
3. APD is for computing APD transfer standard calibration data.

4. APDSCAN sorts out specified APD calibration data for evaluating their status and for the APDDATE and the APDPLOT program sequence.
5. APDDATE (start with APDSCAN) processes run number data for a chronological plot of APD calibration data to detect trends in the calibration.
6. APDPLOT (start with APDSCAN) plots the percent variation of each APD calibration value from the average value versus time in months and years on the screen. It makes available on hard copy the average APD calibration value, the percent variation of each calibration value from the average value, the standard deviation, and the 95 percent CI. These data help show the stability, scatter, and trends of the calibration.
7. EDITAPD edits APD files. It also sorts them by date and run.
8. AREA creates data files at the areas specified for peak power density and energy density calibration data of the APD and PIN transfer standards, respectively.
9. PINSCAN sorts out specified PIN calibration data for evaluating their status and for the PINDATE and PINPLOT program sequence.
10. PINDATE (start with PINSCAN) processes run number data for a chronological plot of PIN calibration data to detect trends in the calibration.
11. PINPLOT (start with PINSCAN) plots the percent variation of each PIN calibration value from the average value versus time in months and years on the screen. It makes available on hard copy the average PIN calibration value, the percent variation of each calibration value from the average value, the standard deviation, and the 95 percent CI. These data help show the stability, scatter, and trends of the calibration.
12. EDITPIN edits PIN files. It also sorts them by date and run.
13. PIN J12 is for computing PIN transfer standard data referring to a Redw 3 transfer standard.
14. PIN J34 is for computing PIN transfer standard data referring to a PIN transfer standard.
15. DUPDISC creates a backup disc.
16. DELETEAPD generates new files from old ones and has multiline deleting procedure.
17. AREAAPD generates data files at areas specified.
18. APDPLOT1 plots chronologically the percent variation of each APD calibration value from the average. Otherwise it is similar to APDPLOT.
19. PINPLOT1 plots chronologically the percent variation of each PIN calibration value from the average. Otherwise it is similar to PINPLOT.
20. AREAPIN generates data files at areas specified.
21. LEASTSQR sorts data to be used for a least square fit, dumps the data into SQR and calls up program LINEAR to perform the least square fit.

10. Location of Programs and Data Files

10.1 Main Disc APD Rasmussen

Backup 1 APD for Rasmussen APD Disc
Backup 2 APD for Rasmussen APD Disc
Magnetic tape cartridge 34 with one of the above

10.2 Main Disc PIN Rasmussen

Backup 1 PIN for Rasmussen PIN Disc
Backup 2 PIN for Rasmussen PIN Disc

10.3 Redw 3 (TC 15)

Main Prog C Series
Main Data

10.4 Impulse Response

TAPE PAS9 Convolution of two waveforms

11. Data File Identification (e.g., I430505, A5500, or P411010)

A. Single Letter I (unity area), A (APD area specified), or P (PIN area specified)
B. Double digit identifying transfer standard like 41, 43, 51, 52, etc.
C. Double digit like 00, 20, or 40 for APD amplifier gain or
D. Four or five digits like 0505, 1010, 5010, or 10010 for PIN amplifier gain
E. Additional letters or digits for chronology like NEW, 85, etc.; for area like 20, 45, 81, etc.; for the purpose of the measurements like 2 (uniformity), 3 (field of view), et al.
F. In programs APD, J12 and J34 for computing data, codes are explained

12. Computer Calibration Data of Redw 3 and APD and PIN Transfer Standards

A. Redw 3 TS Calibration Data (files 10 J, 100 s; 1 J, 100 s, 0.1 J, 100s)
B. APD 5-1 TS Calibration Data (files I5100, I5120, I5140, A5100, A5120, A5140)
C. APD 5-5 TS Calibration Data (files I5500, I5520, I5540, A5500, A5520, A5540)
D. PIN 4-1 TS Calibration Data (files I410505, I411010, I415010, I4110010, P410505, P411010, P415010, P4110010)
E. PIN 4-3 TS Calibration Data (files I430505, I431010, I435010, I4310010)

13. References

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5. AUTHOR(S)

A. L. Rasmussen and A. A. Sanders

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

National Bureau of Standards APD (avalanche) and PIN silicon photodiode transfer standards are documented for a calibration service to measure 1.064 μm laser pulses from $\sim 10^{-8}$ to $\sim 10^{-4}$ W peak power and $\sim 10^{-16}$ to $\sim 10^{-11}$ J energy. A modulated cw measurement system generating known low-level pulses is described. Calibration support equipment, systematic and random errors, and computer programs and calibration data are also described.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

APD transfer standards; beamsplitter attenuator; calibration procedures; calibration service; low-level laser measurements; modulated cw measurement system; 1.064 μm laser pulse measurements; PIN transfer standards; pulse energy; pulse peak power.

13. AVAILABILITY

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