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UPGRADING AND PERFORMANCE OF THE SAO LASER RANGING SYSTEM IN MATERA

Technical Report

Under Grant NGR 09-015-002
Supplement No. 93

J. Maddox, M. Pearlman
J. Thorp and J. Wohn

December 1983

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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J. Maddox, M. Pearlman,
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Through the most recent upgrading program, the performance of the SAO lasers has been improved considerably in terms of accuracy, range noise, data yield, and reliability. With the narrower laser pulse (2.5-3.0 nsec) and a new analog pulse processing system, the systematic range errors have been reduced to 3-5 cm and range noise has been reduced to 5-15 cm on low satellites and 10-18 cm on Lageos. Pulse repetition rate has been increased to 30 ppm and considerable improvement has been made in signal-to-noise ratio by using a 3 Angstrom interference filter and by reducing the range gate window down to 200-400 nsec.

The first upgraded system was installed in Arequipa, Peru in the spring of 1982. The second upgraded system is now in operation in Matera Italy. The third system is expected to be installed in Israel during 1984.

1. HARDWARE STATUS

The SAO laser systems, prior to the last upgrading are described in detail in Pearlman et. al., 1978 and 1981A. The upgrading is described fully in Pearlman et. al., 1982. Briefly, the upgrading involves:

1. Restructuring the blumlein to decrease the laser pulse width from 6 to 3 nanoseconds.

2. Using a pin photodiode detector to sample the laser pulse.

3. Increasing the maximum laser repetition rate from 8 to 30 ppm.

4. Replacement of a digital cross correlation detector with an analog detector.

5. Replacement of the photomultiplier tube and base combination for better time response.

6. The addition of a shutter and a 0.3 nanometer interference filter in front of the PMT to improve the signal to noise ratio.

7. Narrowing of the minimum window in the range gate to allow the system to operate further into daylight conditions on Lageos.

The new laser pulse output is shown in Figure 1, and Figure 2 provides a summary of the system characteristics.

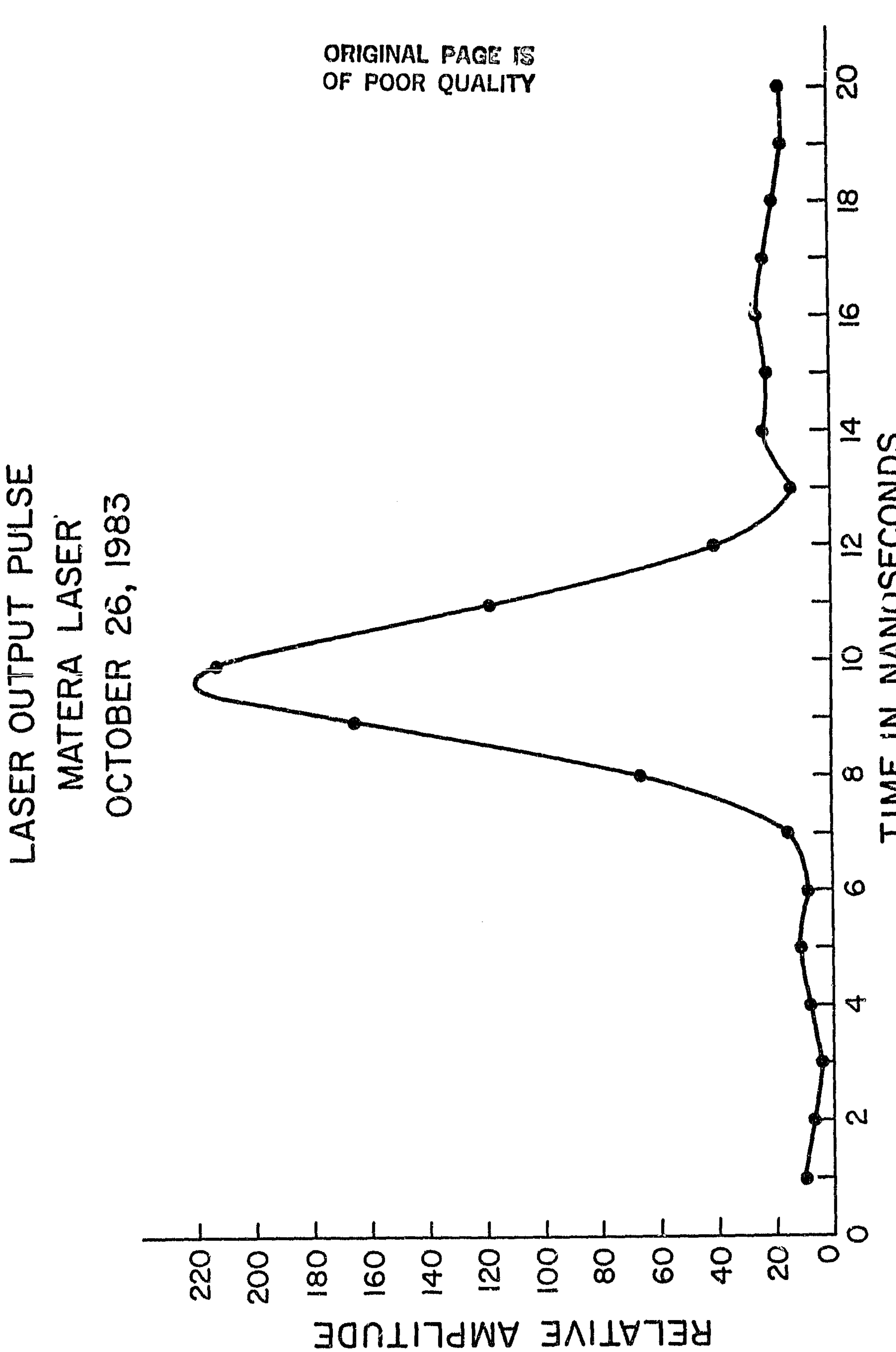
LASER OUTPUT PULSE
MATERA LASER
OCTOBER 26, 1983
TIME IN NANOSECONDS
0 2 4 6 8 10 12 14 16 18 20
RELATIVE AMPLITUDE
0 20 40 60 80 100 120 140 160 180 200 220

Figure 1

SAO LASER SYSTEM

Wavelength (Nanometers)	694.3
Energy/Pulse (J)	.3 - .5
Pulse Width (nsec)	2.5 - 3.0
Rep. Rate (per min)	30 (Max)
Divergency (MR)	0.6 (Min)
Quantum Efficiency (%)	4
System Efficiency (%)	25
Receiver Diameter (m)	.50
System Range Error (cm)	<5
Range Noise (cm)	
Lageos	10 - 18
Low Orbiting Satellites	5 - 15

Figure 2

2. ASSESSMENT OF PERFORMANCE

The ranging performance capability of the lasers has been assessed by examination of both systematic errors and range noise. These refer to performance of the ranging machine itself, leaving aside issues such as atmospheric correction, spacecraft center of mass correction, and epoch timing for discussion elsewhere.

DATA YIELD

In the first 74 days of operation the laser in Matera tracked 131 satellite passes, of which 50 were Lageos. Lageos passes averaged a few hundred points with some going as high as 400-600 points. During a "good" pass, the rate of return was typically 20%-50% depending upon sky conditions and satellite altitude. In some of the passes the satellite was acquired at altitudes as low as 10 degrees, and tracked through zenith back down to 10 degrees.

In the lower orbiting satellites, (Starlette and BE-C), data yield per pass varied from 50-100 points with occasional yields as high as 150 points. Here the rate of return was in the range of 20%-80% with intervals as high as 100%. The low altitude acquisition experience with these satellites was similar to that of Lageos.

RANGE ACCURACY

The systematic errors of the laser system have been divided into three categories: spatial, temporal, and signal-strength variations (see Pearlman 1981A). Spatial variations refer to differences in time of flight depending on the position of the target within the laser beam. Temporal variations relate to system drift between prepass calibration and postpass calibration. Variations in range due to changes in signal strength from pulse to pulse are a function of receiver characteristics.

Spatial Variations

Spatial variations, or the wavefront error, which arise from the multimode operation of the ruby lasers, have been measured at Matera using a distant target retroreflector to probe the beam. Figure 3 shows the results for two tests. The wavefront measurements show an r.m.s. variation across the wavefront of 1.0 cm and peak-to-peak variations of 2.9 and 3.2 cm. It appears however that a large component of this variation is the temporal stability or measurement reproducibility as evidenced by the averaging of measurements at the beam center, where the r.m.s. variations were 0.9 and 1.3 while the peak to peak differences were 2.3 and 2.6 cm. This indicates that the wavefront measurements are probably giving an overestimation of wavefront distortion.

WAVEFRONT MEASUREMENT
MATERA LASER

DATE	TIME	SPACING BETWEEN POINTS (ARC MIN)	PRF (PER MIN)	AVERAGE* NUMBER OF PHOTOELECTRONS RECEIVED PER PULSE	TEMPORAL STABILITY AT BEAM CENTER		WAVEFRONT DISTORTION	
					RMS (CM)	MAXIMUM EXCURSION (CM)	RMS (CM)	MAXIMUM EXCURSION (CM)
Sep 30	14 Hrs	0.42	30	30	0.9	2.3	1.0	2.9
Oct 12	15 Hrs	0.42	30	35	1.3	2.6	1.0	3.2

* Fifty pulses at each of twenty positions

Figure 3

Temporal Variations

The temporal variations or system drift are estimated through electronic and range calibrations.

Electronic calibrations using a 3 nsec pulse through a fixed delay line to start and stop the ranging system have been used at Matera to estimate the stability of the electronics. An example of the results are shown in Figure 4. The r.m.s. variation of the means is less than 1 cm with peak-to-peak values slightly more than 1 cm.

Temporal stability of the full system was measured with the billboard target, ranging over a period commensurate with a Lageos pass. The results are shown in Figure 5. The r.m.s. variation of the set means is 1.0 cm while the peak-to-peak variation is 3.8 cm, which is consistent with electronics tests.

Temporal stability is also estimated by the difference between pre-pass and post-pass calibrations to the billboard target. These measurements are taken at about 5 photoelectrons with 50-100 points in each calibration. The results of the first few months of ranging is shown in Figure 6. As this data shows the system has been plagued with a number of difficulties. These problems and their solutions are discussed in detail in section 3 of this report. The problems were corrected for the period October 25 through November 7th. During this time the pre-post differences had a r.m.s. variation of 0.18 nsec (2.7 cm). This value is consistent with the billboard target temporal tests and with the Arequipa system tests. We will adopt this value (2.7 cm) as the nominal temporal stability of the Matera system when the system is working properly.

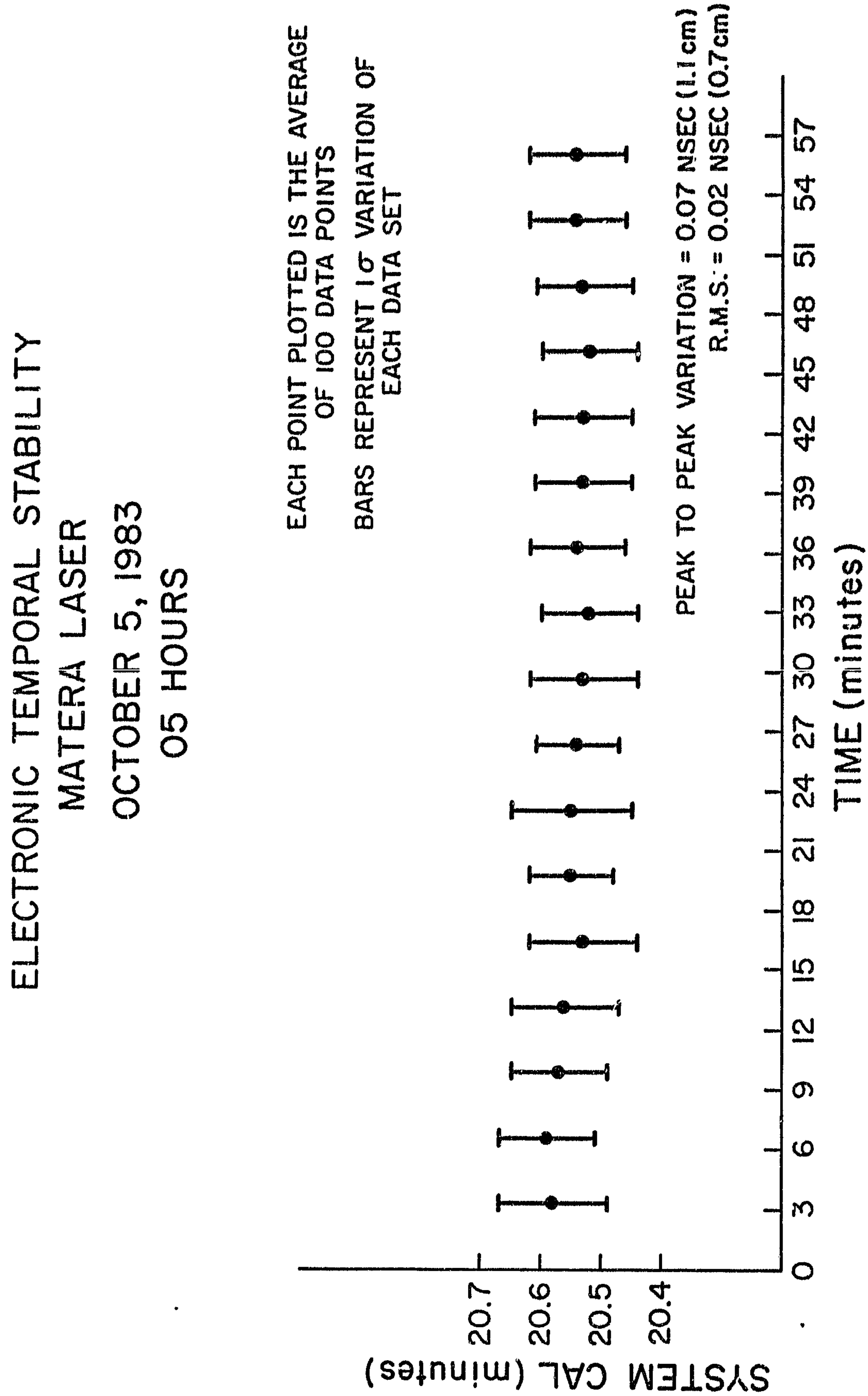
ELECTRONIC TEMPORAL STABILITY
MATERA LASER
OCTOBER 5, 1983
05 HOURS
EACH POINT PLOTTED IS THE AVERAGE OF 100 DATA POINTS
BARS REPRESENT 1σ VARIATION OF EACH DATA SET
PEAK TO PEAK VARIATION = 0.07 NSEC (1.1 cm)
R.M.S. = 0.02 NSEC (0.7 cm)
SYSTEM CAL (minutes)
20.7
20.6
20.5
20.4
TIME (minutes)
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
51
54
57

Figure 4

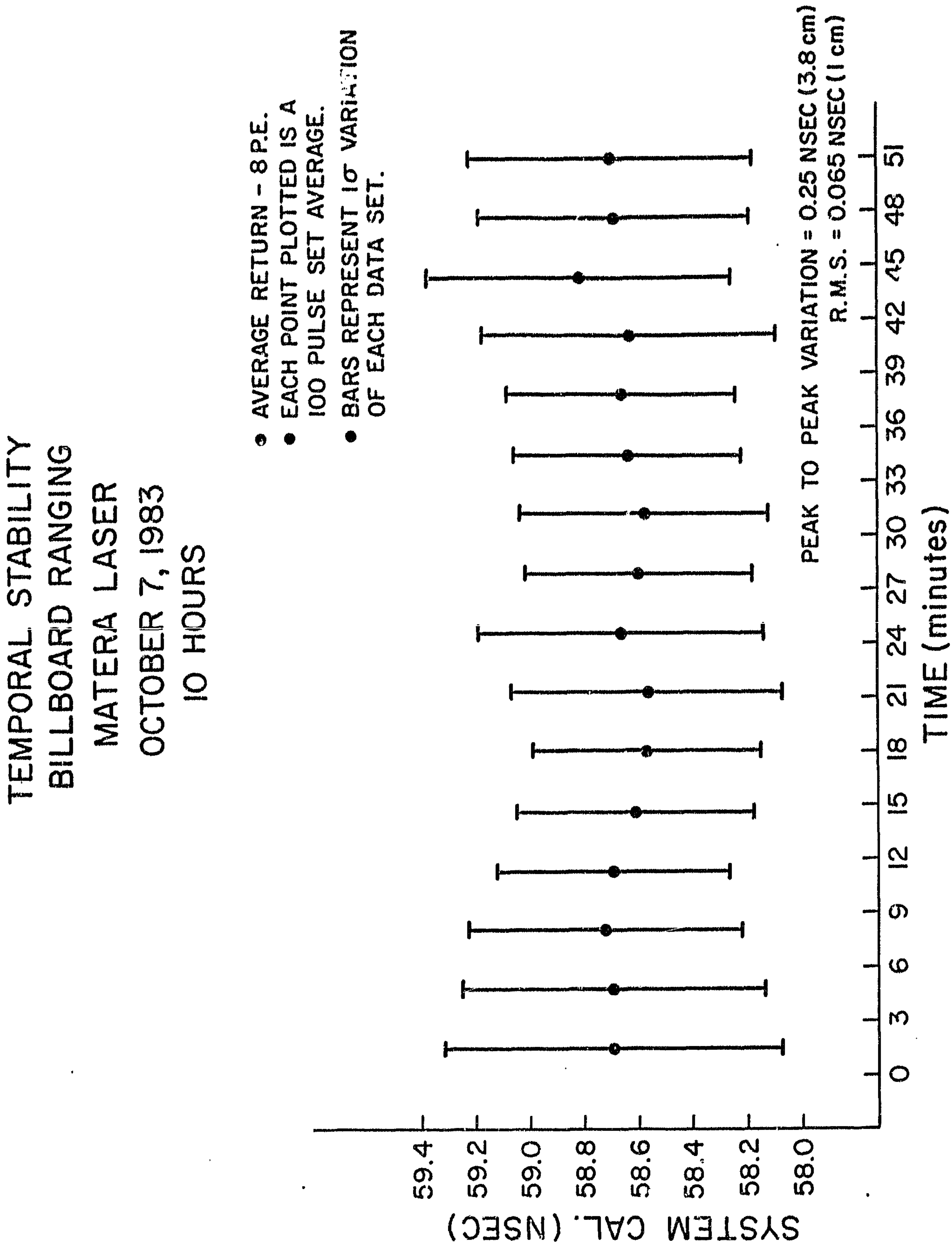
TEMPORAL STABILITY
BILLBOARD RANGING
MATERA LASER
OCTOBER 7, 1983
10 HOURS
AVERAGE RETURN - 8 P.E.
EACH POINT PLOTTED IS A 100 PULSE SET AVERAGE.
BARS REPRESENT 1σ VARIATION OF EACH DATA SET.
PEAK TO PEAK VARIATION = 0.25 NSEC (3.8 cm)
R.M.S. = 0.065 NSEC (1 cm)
SYSTEM CAL. (NSEC)
59.4
59.2
59.0
58.8
58.6
58.4
58.2
58.0
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
51
TIME (minutes)

Figure 5

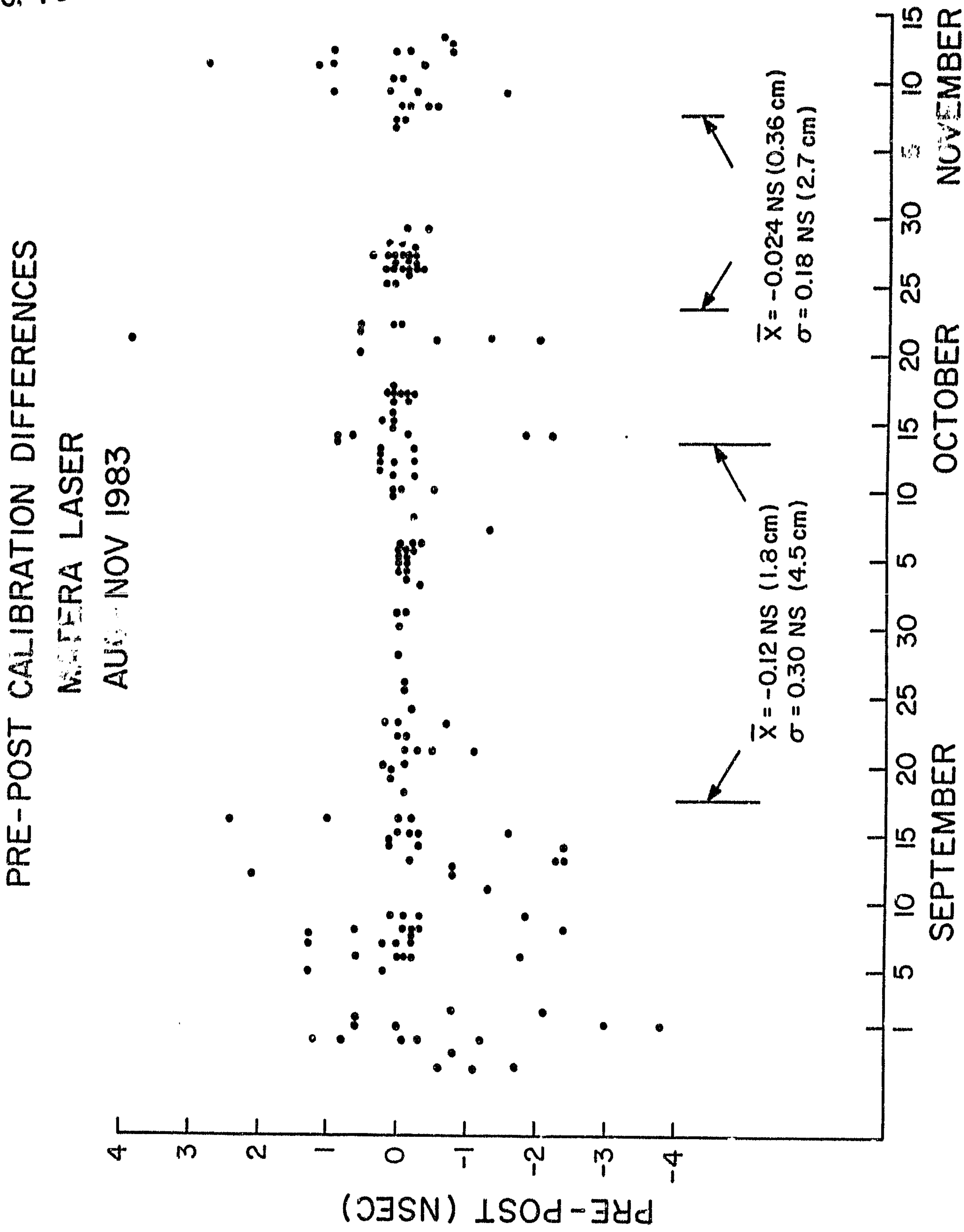
PRE-POST CALIBRATION DIFFERENCES
MATERA LASER
AUG - NOV 1983
PRE-POST (NSEC)
4
3
2
1
0
-1
-2
-3
-4
$\bar{X}$ = -0.12 NS (1.8 cm)
σ = 0.30 NS (4.5 cm)
$\bar{X}$ = -0.024 NS (0.36 cm)
σ = 0.18 NS (2.7 cm)
1
5
10
15
20
25
30
5
10
15
20
25
30
5
10
15
SEPTEMBER
OCTOBER
NOVEMBER
1983

Figure 6

Signal Strength

The SAO lasers operate at the single photoelectron level on Lageos and in the range of 1-50 photoelectrons on low orbiting satellites. Variations in apparent range with signal strength have been examined with extended target calibrations over the dynamic range of the laser instrument (See Figure 7 and 8). The mean calibration over the operating range of 1-50 photoelectrons is typically flat to $\pm$.15 nsec (2.2 cm) with maximum peak-to-peak excursion of 0.3 nsec (4.5 cm). We believe that the lowering trend at lower signal strengths is due to non-optimization of the matched filter. The matched filter was optimized for a nearly symmetrical laser output pulse, whereas the single photoelectron pulses tend to be somewhat asymmetric.

A summary of the range error components are tabulated in Figure 9. Assuming that these errors are independent, the root-sum square (rss) error due to the r.m.s. systematic sources is about 4 cm. We use this value to characterize the systematic errors that can be expected for data averaged over a pass during proper operation.

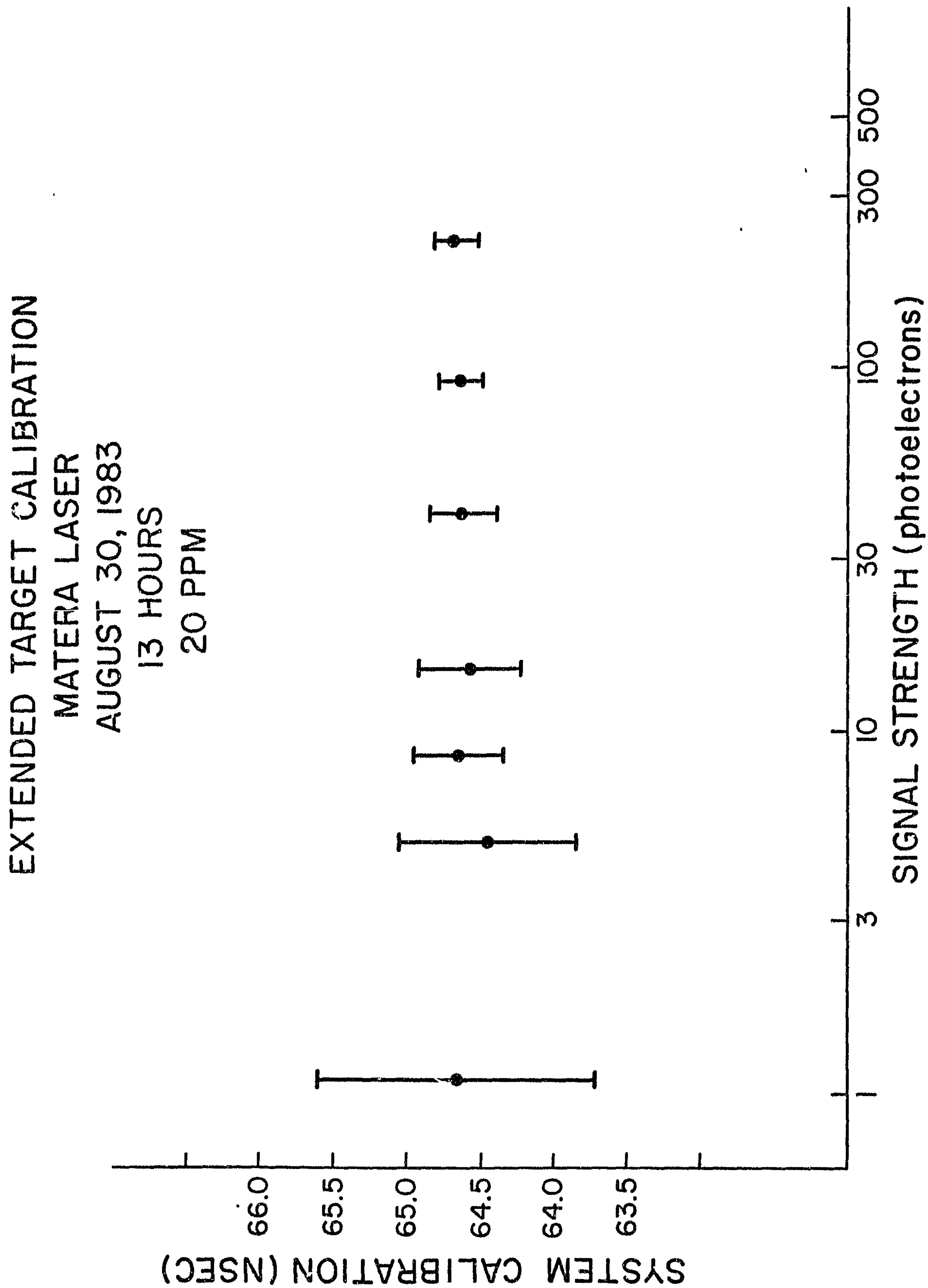
EXTENDED TARGET CALIBRATION
MATERA LASER
AUGUST 30, 1983
13 HOURS
20 PPM
SIGNAL STRENGTH (photoelectrons)
1
3
10
30
100
300
500
SYSTEM CALIBRATION (NSEC)
66.0
65.5
65.0
64.5
64.0
63.5

Figure 7

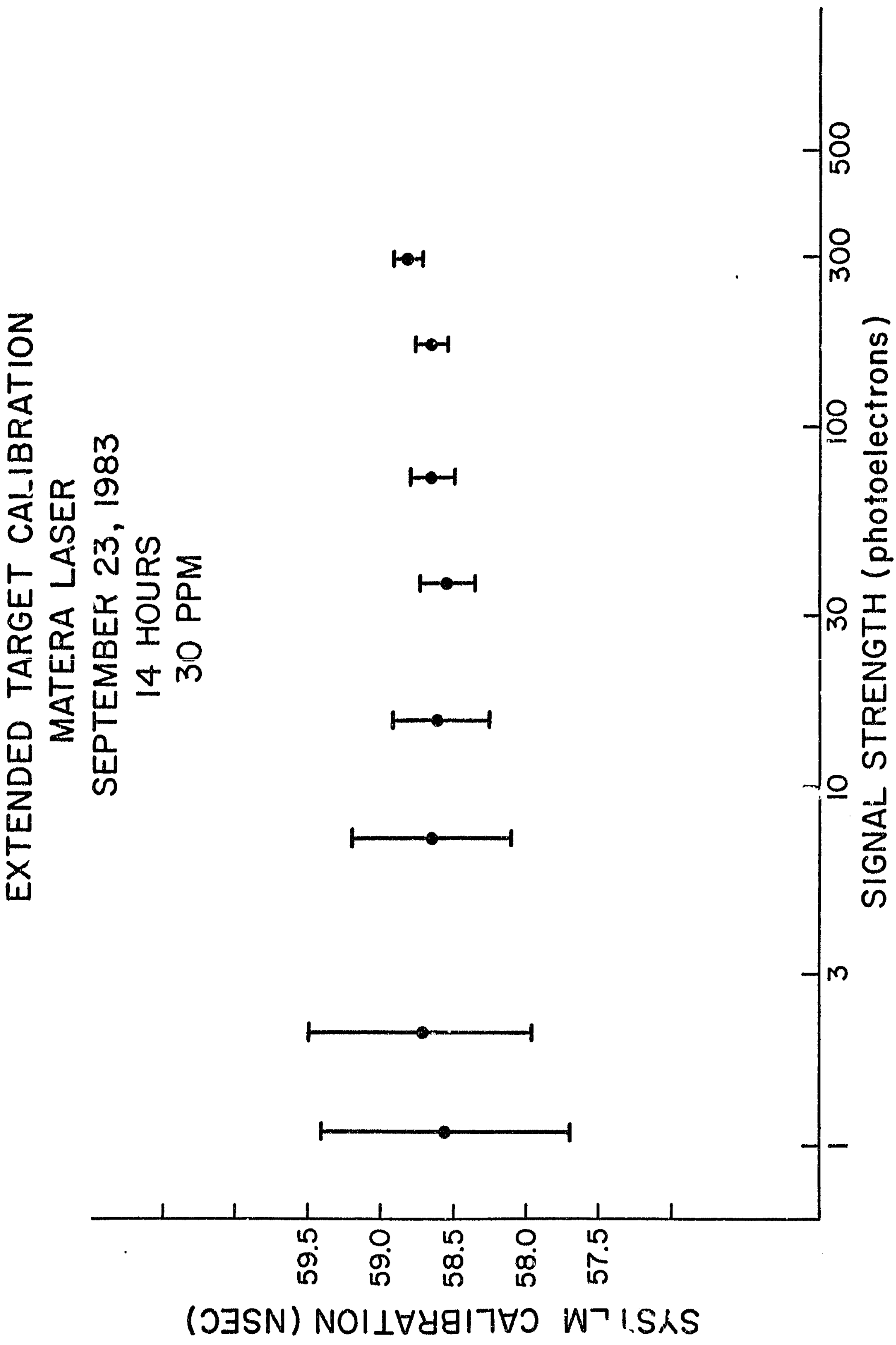
EXTENDED TARGET CALIBRATION
MATERA LASER
SEPTEMBER 23, 1983
14 HOURS
30 PPM
SIGNAL STRENGTH (photoelectrons)
1
3
10
30
100
300
500
SYSTEM CALIBRATION (NSEC)
59.5
59.0
58.5
58.0
57.5

Figure 8

SAO LASER NETWORK

SYSTEMATIC ERROR SUMMARY

Source	Est. Error (RMS)	Est. Error (PEAK)
Wavefront (Spatial)	1.0 cm	3.2 cm
System Drift (Temporal)	2.7 cm	6.8 cm
Calibration (Signal Strength)	2.2 cm	4.5 cm
R.S.S.	3.6 cm	8.8 cm

Figure 9

SYSTEM NOISE

The noise performance of the system has been measured by examining range noise (1 sigma) verses signal strength in calibration runs on the billboard target. This has the advantage of highlighting system jitter by averaging out effects of wavefront distortion. The results of several calibration sequences are shown in Figure 10, along with the theoretical results for a 3 nsec gaussian pulse for reference. At low and intermediate signal strengths, the range noise follows closely the anticipated $n^{-\frac{1}{2}}$ dependence and is consistent with a pulse of about 3 nsec width. At high signal strengths, the system noise levels off at about .2-.3 nsec (3-4.5 cm) which is probably dominated by the jitter in the PMT.

The distribution of range residuals (1 sigma) on a per pass basis for Lageos, Starlette, and BE-C during the first 74 days of operation in Matera are shown in Figures 11, 12 and 13. Range noise on Lageos varies typically from 10-18 cm as would be anticipated for 1-2 photoelectron events with a 3.0 nsec wide pulse. There is probably some corruption due to the jitter in the electronics and the PMT. Also some of the data has been degraded by malfunctions as detailed in Section 3 (Problems and Solutions).

On the lower satellites, returns signal strength are typically 2-20 photoelectrons. Short arc fits to quick-look data give r.m.s. values of 5-18 cm. At the higher signal strengths, the range jitter in the PMT and the electronics becomes significant and tends to degrade the $n^{-\frac{1}{2}}$ noise dependence.

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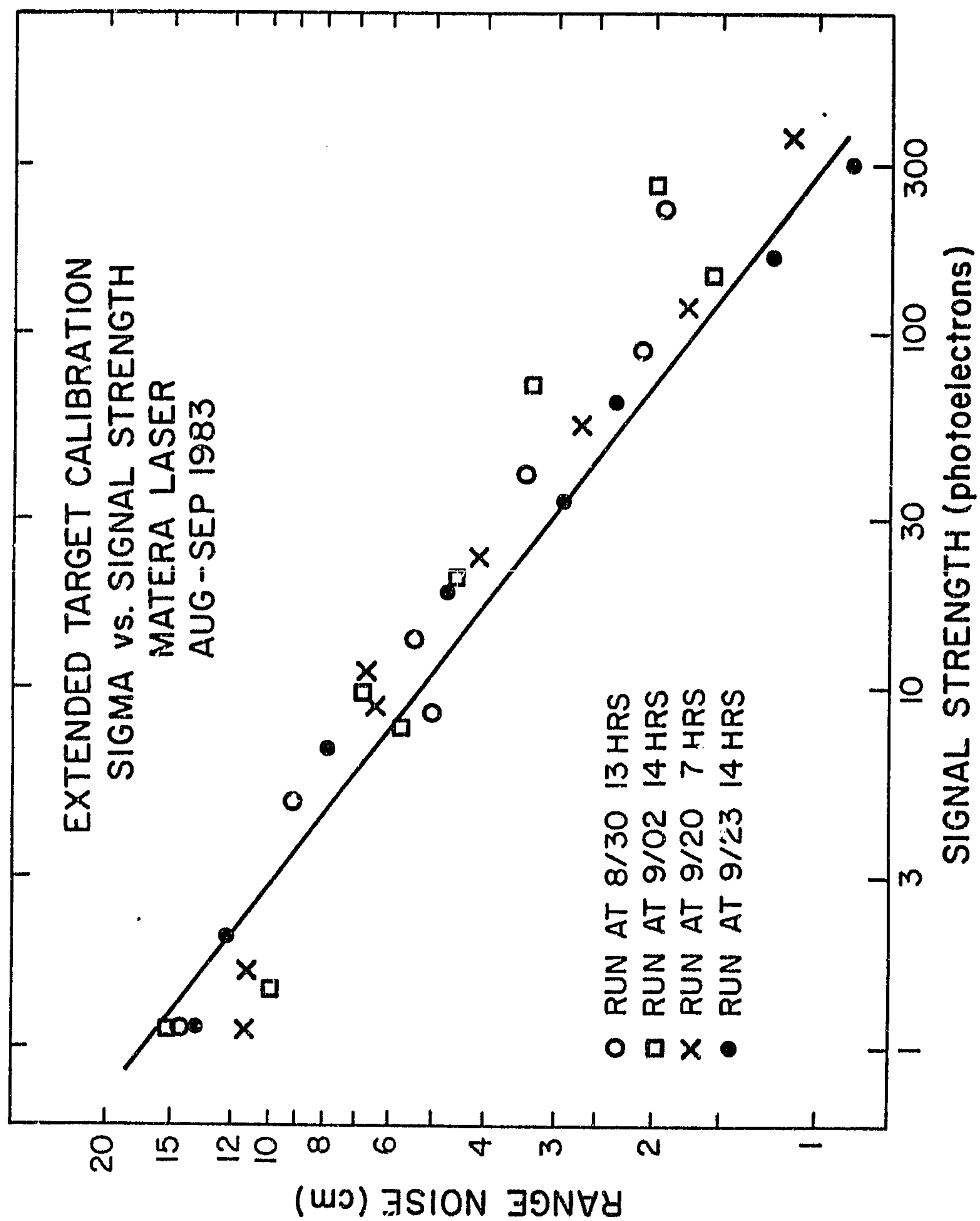

Figure 10

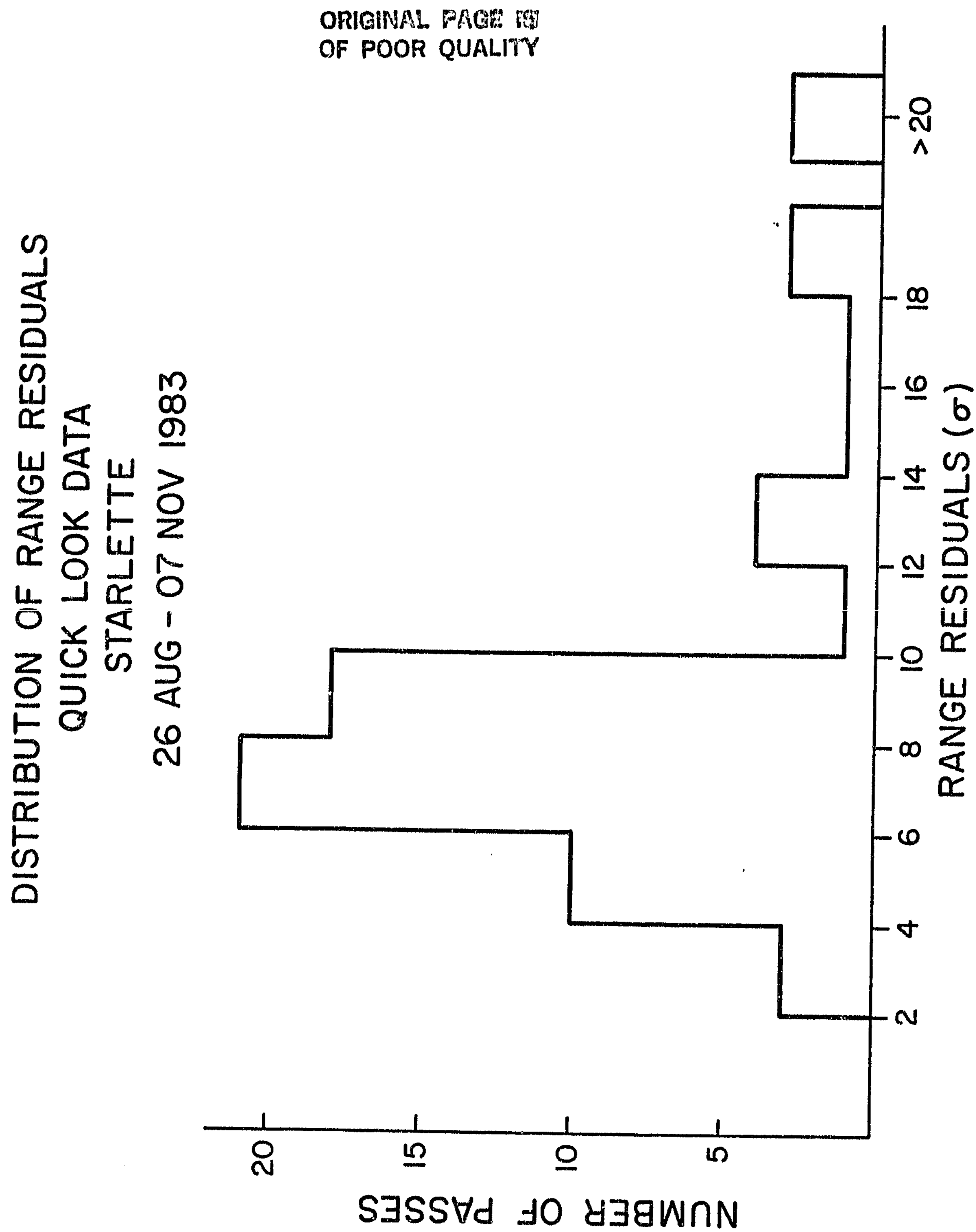
DISTRIBUTION OF RANGE RESIDUALS
QUICK LOOK DATA
STARLETTE
26 AUG - 07 NOV 1983
NUMBER OF PASSES
20
15
10
5
RANGE RESIDUALS (σ)
2
4
6
8
10
12
14
16
18
>20

Figure 11

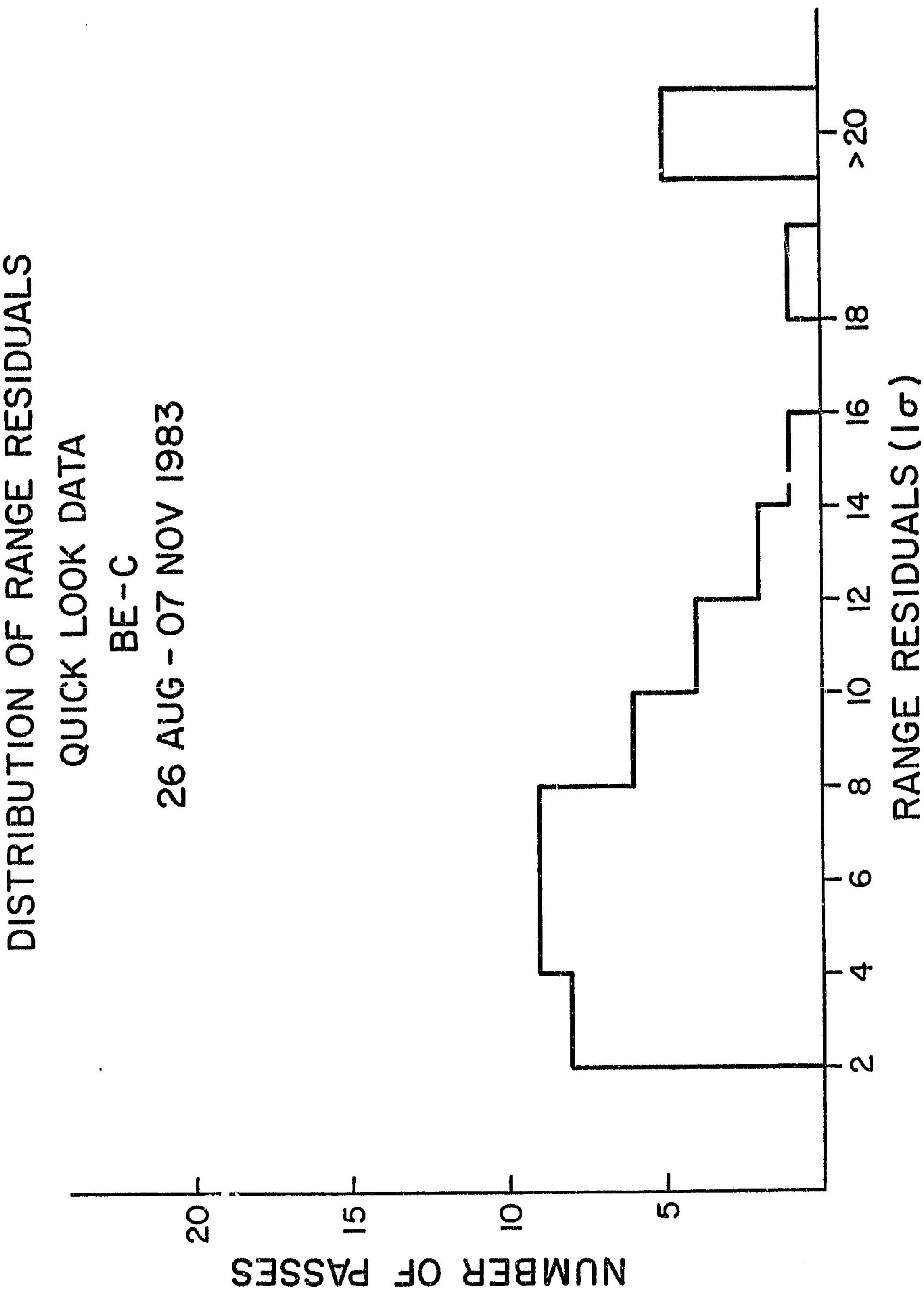
DISTRIBUTION OF RANGE RESIDUALS
QUICK LOOK DATA
BE-C
26 AUG - 07 NOV 1983
NUMBER OF PASSES
5
10
15
20
RANGE RESIDUALS (1σ)
2
4
6
8
10
12
14
16
18
>20

Figure 12

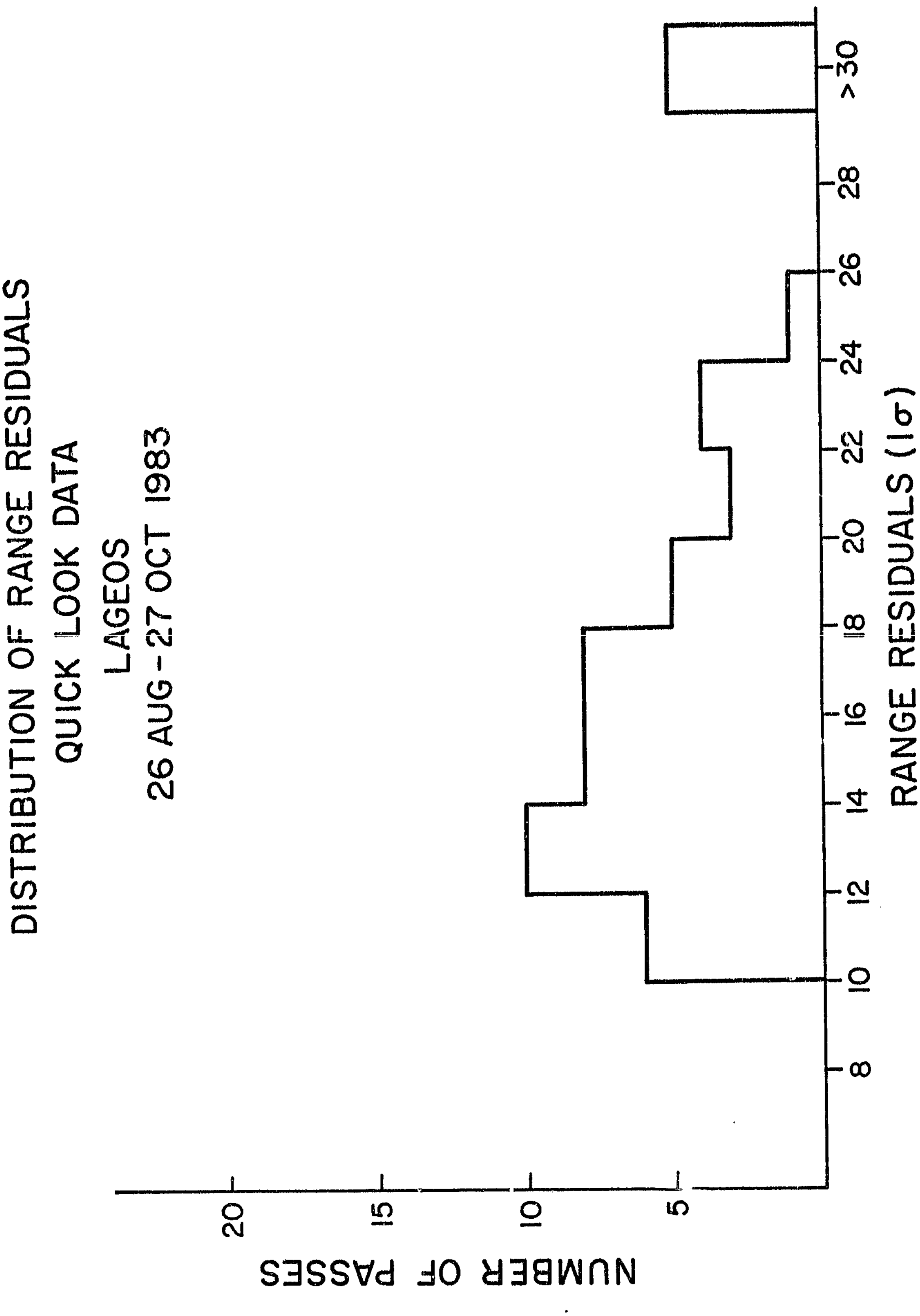
DISTRIBUTION OF RANGE RESIDUALS
QUICK LOOK DATA
LAGEOS
26 AUG - 27 OCT 1983
NUMBER OF PASSES
5
10
15
20
RANGE RESIDUALS (1σ)
8
10
12
14
16
18
20
22
24
26
28
>30

Figure 13

3. PROBLEMS AND SOLUTIONS

Since installation of the hardware in Matera, the station has been plagued by a series of hardware malfunctions. The most persistent problem has been leakage of a fraction of the laser oscillator pulse thru the pulse chopper. As a result of this leakage, the transmitted laser pulse is the desired 3 nsec waveform riding on a 20 nsec base.

The effect of this excessive energy outside the chop pulse is to introduce spurious stops outside the chopped pulse in the pre and post calibrations and occasionally in satellite data. When the 20 nsec base is of sufficient amplitude there is sufficient noise in the calibration to give false system delay and excessive pre-minus post calibration values.

The problem was found after initial set up. The same technique that was successfully used in Arequipa to minimize the leakage was tried in Matera. This technique involves reducing the width of the oscillator pulse from 20-25 nsec FWHA to 18 nsec FWHA. This then reduces the underlying pedestal. To narrow the oscillator pulse, we inserted a scratched plate into the oscillator cavity. This reduces the Q of the cavity which then suppresses some of the longitudinal laser modes and reduces the oscillator pulse width.

Unfortunately, this technique involved a great deal of trial and error. With this technique, leakage was reduced to an acceptable level most of the time, but full reliable performance was elusive and occasionally the leakage became a problem.

The laser was operated in this mode until October 23rd while the rest of the system was checked out. Knowing that the problem still remained to be solved, but not wanting to bias the data, the thresholds were raised to further minimize the leakage effect. During this time an ongoing series of tests were performed to localize the cause of the intermittent problem.

To verify that the problem was pulse shape related and not in the electronics, the PMT was replaced with the spare pin photodiode transmitter detector. This detector, which sampled a portion of the outgoing beam directly at the output of the transmitting telescope, was connected to the PMT cable and the rest of the detection system. The photodiode detector provided a smooth reproducible pulse (with a minimum of statistical effects) which could then be monitored and used as a reference. The results of these tests are shown in Figure 14. The system response was extremely flat with very low r.m.s. values for each signal strength range, indicating clearly that the system start and stop electronics were functioning properly.

The laser detector output pulse is shown in Figure 15 along with a theoretical pulse shape. The data from October 19 showed evidence of reflections in the system which were traced to a burned center pin in the coaxial adapter (which connects the 50 ohm load to the chop Pockels cell). In addition, the Kryton that drives the Blumlein was replaced to further reduce the small after pulse effect. Pulse shapes taken subsequently (October 26) show a marked improvement.

The system performed well to October 29, when a major failure caused by a water leak occurred. As a result, the pulse chopper and Pockels cell crystal was damaged and had to be replaced. Shortly thereafter, the replacement cell developed a problem with electrical contacts to the Pockels' cell crystal. This problem was repaired and the laser now appears to be operating well.

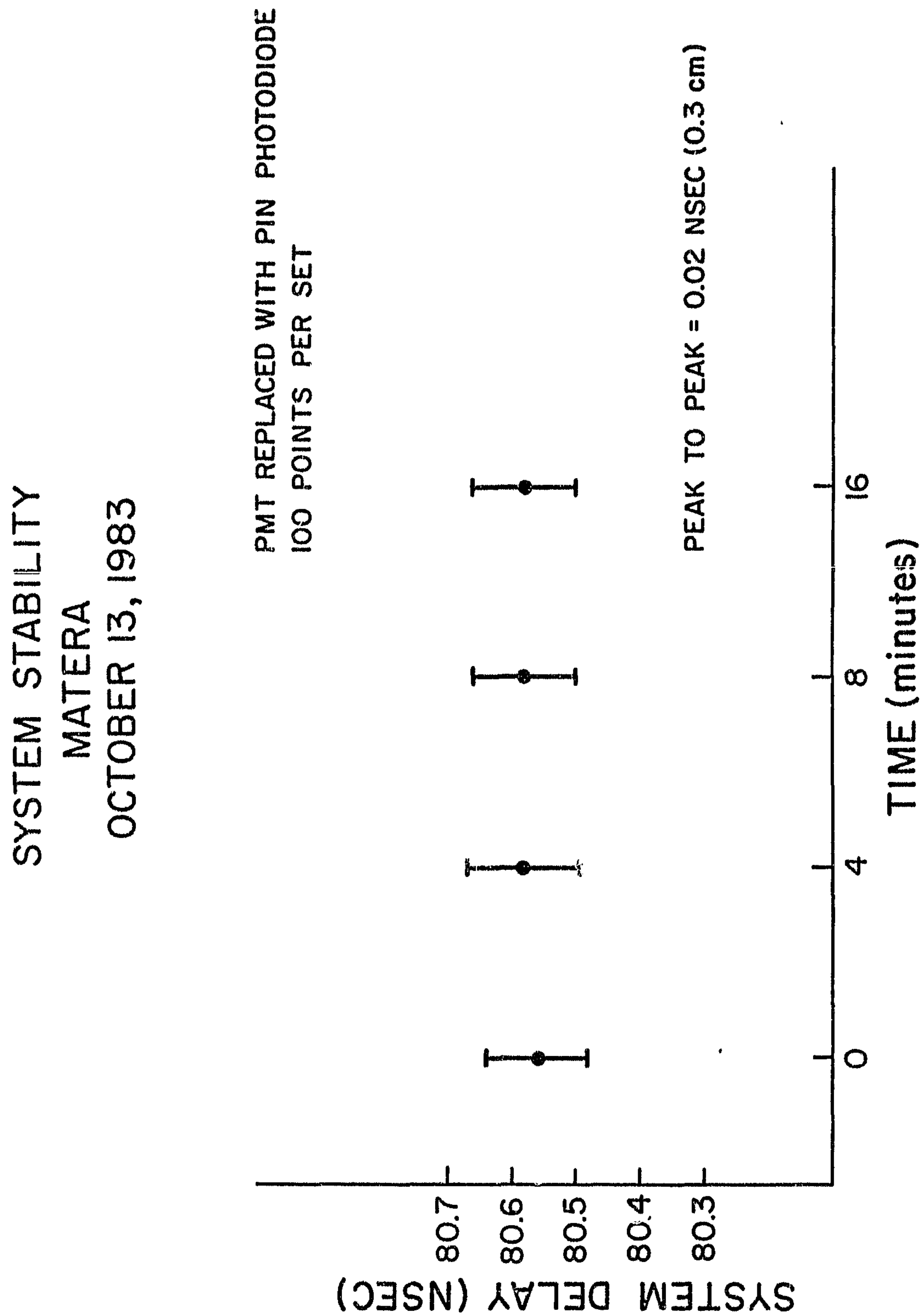
SYSTEM STABILITY
MATERA
OCTOBER 13, 1983
PMT REPLACED WITH PIN PHOTODIODE
100 POINTS PER SET
PEAK TO PEAK = 0.02 NSEC (0.3 cm)
SYSTEM DELAY (NSEC)
80.7
80.6
80.5
80.4
80.3
TIME (minutes)
0
4
8
16

Figure 14

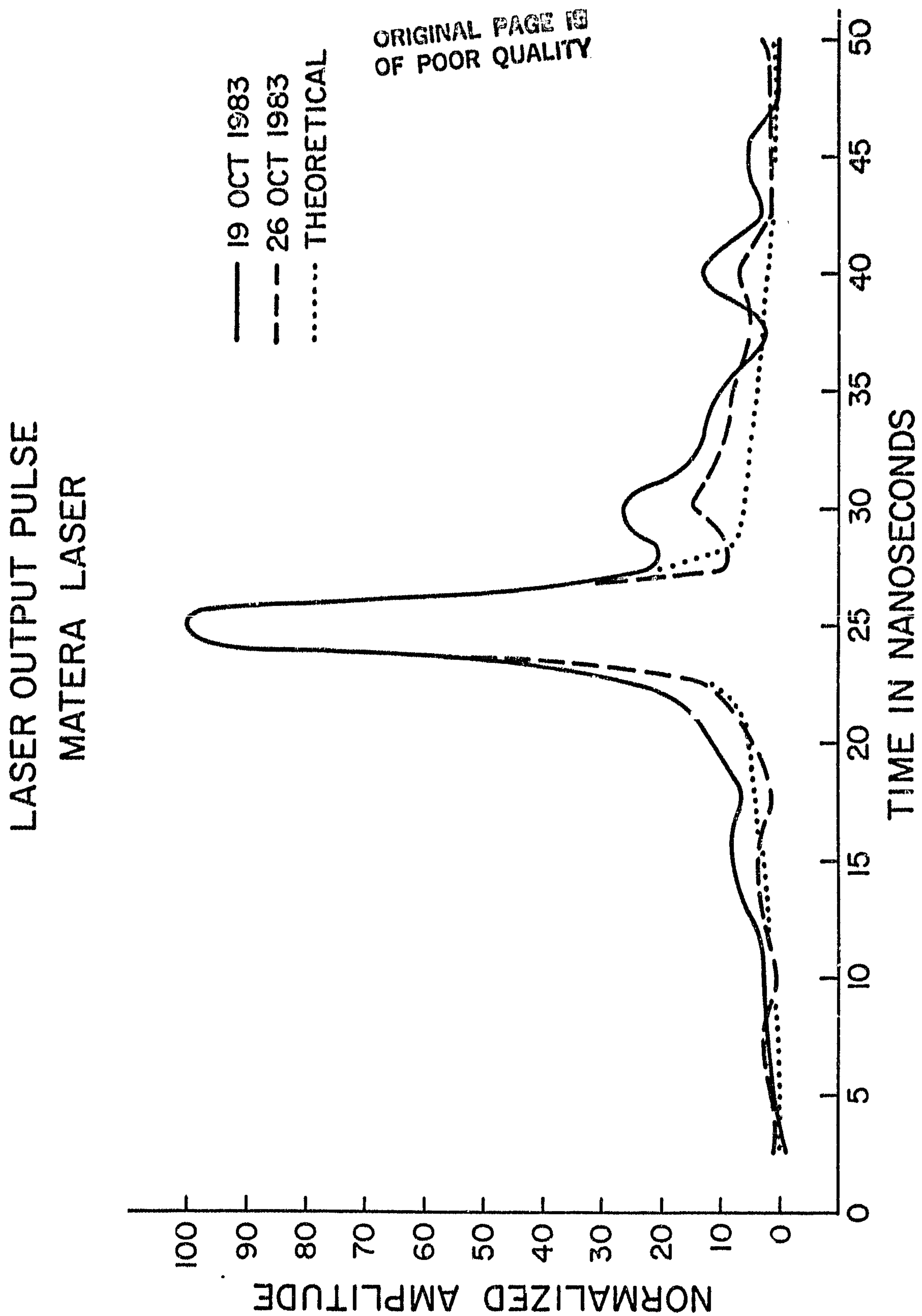
LASER OUTPUT PULSE
MATERA LASER
19 OCT 1983
26 OCT 1983
THEORETICAL
ORIGINAL PAGE IS OF POOR QUALITY
NORMALIZED AMPLITUDE
0
10
20
30
40
50
60
70
80
90
100
TIME IN NANOSECONDS
0
5
10
15
20
25
30
35
40
45
50

Figure 15

REFERENCES

Pearlman, M. R., N. W. Lanham, J. Wohn, J. M. Thorp, E. Imbier, F. D. Young, J. Latimer and I. G. Campbell, 1978. A report on the Smithsonian Astrophysical Observatory Laser Ranging System, presented at the Third International Workshop on Laser Ranging Instrumentation, Lagonissi, Greece, in May.

Pearlman, M. R., N. W. Lanham, J. Wohn, J. M. Thorp, 1981A. A report on Current Status and Upgrading of the SAO Laser Ranging Systems, presented at the Fourth International Workshop on Laser Ranging Instrumentation, Austin, Texas, in October.

Pearlman, M. R., 1981B. Some Current Issues in Laser Ranging to Satellite Laser Workshop, invited paper, presented at the Fourth International Workshop on Laser Ranging Instrumentation, Austin, Texas, in October.

Pearlman, M. R., N. W. Lanham, J. Maddox, J. M. Thorp, and J. Wohn, 1982. A report on the Upgrading and Performance of the SAO Laser Ranging System in Arequipa. Issued as a technical report under Grant NGR 09-015-002 Supplement No. 85, in July.