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SATELLITE TRACKING AND EARTH DYNAMICS RESEARCH PROGRAMS

Grant NGR 09-015-002

Final Report

For the period 1 July 1959 through 31 December 1983

Principal Investigator
Dr. Michael R. Pearlman

April 1984

Prepared for
National Aeronautics and Space Administration
Washington, DC 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Office for this grant is Mr. David L. Townley, Code TN-1, Network Operations, Office of Space Tracking and Data Systems, NASA Headquarters, Washington, D.C. 20546.

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1. INTRODUCTION

This report describes the activites carried out by the Smithsonian Astrophysical Observatory (SAO) for the National Aeronautics and Space Administration (NASA) under Grant NGR 09-015-002 during the period 1 July 1983 through 31 January 1984. For technical progress for the period 1 July 1959 through 30 June 1983, see Semi-annual Progress Reports No. 1 through No. 48.

2. OPERATIONS

All field operations and support were terminated by the end of January. The Arequipa Station and its field personnel were transferred to the Mission Contractor as of 1 November 1983. An SAO Field Engineer remained on site at the Matera site through 31 January 1984, providing assistance in operations, maintenance, and training.

The cooperating sites began forwarding their quick-look data through NASA/GSFC as of early October. At the time that SAO ceased processing quick-look data in mid-November, the cooperating network was quite active, particularly in Lageos tracking.

3. ENGINEERING

At the time of transfer to the Mission Contractor, the Arequipa station was functioning well. The station had been plagued by problems stemming from extraneous leakage through the pulse chopper Pockels cell, giving abnormally large r.m.s. values in the pre- and post-target calibrations. In November, this was traced to problems in the pulse chopper electronics and poor electrical contracts to the Pockels cell crystal. A new Pockels was sent to the station along with some indum pellets to refasten the electrical contacts. This appears to have cured the problem. By the end of the year, the station had been provided with a full set of equipment spares.

A similar leakage problem also surfaced at Matera in October, and was addressed in the same manner. The Matera site has also been furnished with a full set of spare plus other components and equipment that may prove useful to the operation. A report on the "Performance of the SAO Laser System in Matera" was issued in December 1983. (See Appendix 1.) This report summarizes the measurement results of the key components of system accuracy and discusses the engineering problems experienced to date. A copy of this report has been submitted to the SLR Configuration Control Board.

All spare optics, including laser rods and dielectric polarizers, have been sent to the Mission Contractor. Two additional Pockels cells now being repaired by a vendor and several minicomputer boards being purchased are due for delivery in February and will also be forwarded.

The latest set of all engineering manuals has been sent to the Mission Contractor. Some updates, based on the last few months of operational experience with the upgraded lasers at Arequipa and Matera, have also been provided.

The Mission Contractor has been appraised of the recent engineering development programs at SAO and has been made aware of our thoughts on system upgrading and improvement.

4. TIMING

Responsibility for the Arequipa Stating timing was transferred with the station on November 1, 1983.

At Matera, station timing is being maintained by the Contractor responsible for operations. The station is equipped with a Cesium standard, a Loran-C receiver, and a TV synchronization receiver. A quick assessment of the timing data indicates that, with ground-wave Loran reception, they are tracking time relative to B.I.H. to within 1 microsecond.

5. DATA SERVICES

All final data from Arequipa through August 1983 was processed and submitted to the NASA Crustal Dynamics Project. Final data processing ceased with the completion of this work, except for spot checks of the September Matera data. The minicomputer processer for the final data was shipped to the Mission Contractor in late October. A technician from Bendix spent several days at SAO studying the hardware. He also participated in the packing for shipment.

Quick-look data processing and engineering review was conducted through November at SAO to provide sufficient overlap for quality assurance verification. Several individuals from Bendix spent time at SAO in September and October to familiarize themselves with the operation. A week of SAO programmer and systems engineering time was also spent diagnosing transfer and start-up problems. In our assessment, the transfer went very well. The Quick-Look Data Catalog through September 1983 was completed as were several interim (earlier) volumes. The entire SAO Quick-Look Data Catalog, for all laser data (SAO, NASA, Cooperating and Participating Stations) for the period April 1975 - September 1983, has been assembled. Copies have been sent to NASA Headquarters and the Project at GSFC.

Corrections have been made to the Orroral Valley laser data for the error in target survey. The corrected data have been forwarded to GSFC.

6. PROGRAMMING

All SAO software has been forwarded to the Mission Contractor, along with manuals and documentation. In October and November, the SAO staff worked closely with the Mission Contractor to expedite the transfer process.

7. PERSONNEL

As of February 1, 1984, all SAO Network personnel were either reassigned, resigned, transferred to the Mission Contractor, or placed on severance, except for Mr. Dana Seaman who is enroute to the U.S. to join the Mission Contractor on March 1.

The Peruvian personnel have also been transferred to the

Mission Contractor. They have been paid for all accumulated vacation and severance as required.

8. PROPERTY (EQUIPMENT)

All items at the Arequipa and Matera sites were transferred to NASA.

All hardware items at SAO Headquarters that were:

1. purchased under the Grant at a cost in excess of $1,000.
2. purchased under the Grant at a cost of less than $1,000 and considered important to the operation of the Network.

or

3. procured by SAO outside the Grant yet considered important to the operation of the Network

were offered for transfer to NASA. Representatives from GSFC, Bendix, and SAO reviewed the inventory lists and prepared the list of items for transfer. After final approval by NASA, these items were forwarded to the Mission Contractor in two shipments (October and December).

Those items remaining at SAO have been processed through the normal Smithsonian property procedures.

Since there is no requirement for the Mt. Hopkins prototype laser, SAO has initiated action to transfer this item to the Smithsonian Air and Space Museum. Several options for display have been considered, including a museum area with the laser and the Baker

Nunn Camera at Mt. Hopkins base headquarters, soon to be built in Amado, Arizona. All of the Mt. Hopkins laser electronics and most other components that would be interchangeable with the other SAO systems have been forwarded to the Mission Contractor.

9. COOPERATING AGREEMENTS

SAO has closed out its cooperating agreement with the Instituto Geofisico del Peru and the University of San Agustin for the operation of the tracking station in Arequipa. The University has requested that SAO give consideration to donating unneeded property at this time. Since SAO has turned all of the station property back to NASA, we have referred the issue of donation of property to NASA.

No other operating agreements are currently in force that would influence NASA laser tracking activities.

10. TRAVEL

Dr. Pearlman and Dr. David Smith visited Israel in mid-November to continue technical discussions with the Israeli Space Agency on the relocation of an SAO laser to Israel. Discussions included technical, administrative, and personnel requirements for operating such a station. Visits were made to several candidate sites around the country. Highest consideration is now being given to a location in the hills west of Jerusalem. This site already has a shelter, and electrical power and a road are in the immediate vicinity. Technical information including instrument specifications and building design have been furnished to the Israelis for their review. Based on current activity and interest, it seems reasonable to believe that a station could be operational by early 1985.

Dr. Pearlman attended the dedication of the Matera Station on 17 December, along with other U.S. dignitaries including Mr. Ray Arnold of NASA. The dedication was also attended by representatives of the Israeli Space Agency who were visiting Italy to learn about station operations and technical requirements. Dr. Pearlman conducted technical discussions with the station crew and also met with officials of the CNR to discuss programmatic issues and plans. Dr. Pearlman also visited with the Science Attache, Mr. Larry Finch, and the Ambassador, Hon. Maxwell Rabb, at the U.S. Embassy to brief them on the laser program.

As of 1 March, when Dana Seaman is transferred to Bendix, no SAO employees will be charging their time against the Grant except for occasional assistance required to (1) support the restoration of building and (2) provide final accounting. The bulk of the expenditures after this date will be for severance, which could run as late as January 1985, and room rental through the end of the current lease in September 1984.

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

UPGRADING AND PERFORMANCE OF THE SAO LASER RANGING SYSTEM IN MATERA

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

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 , n 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.

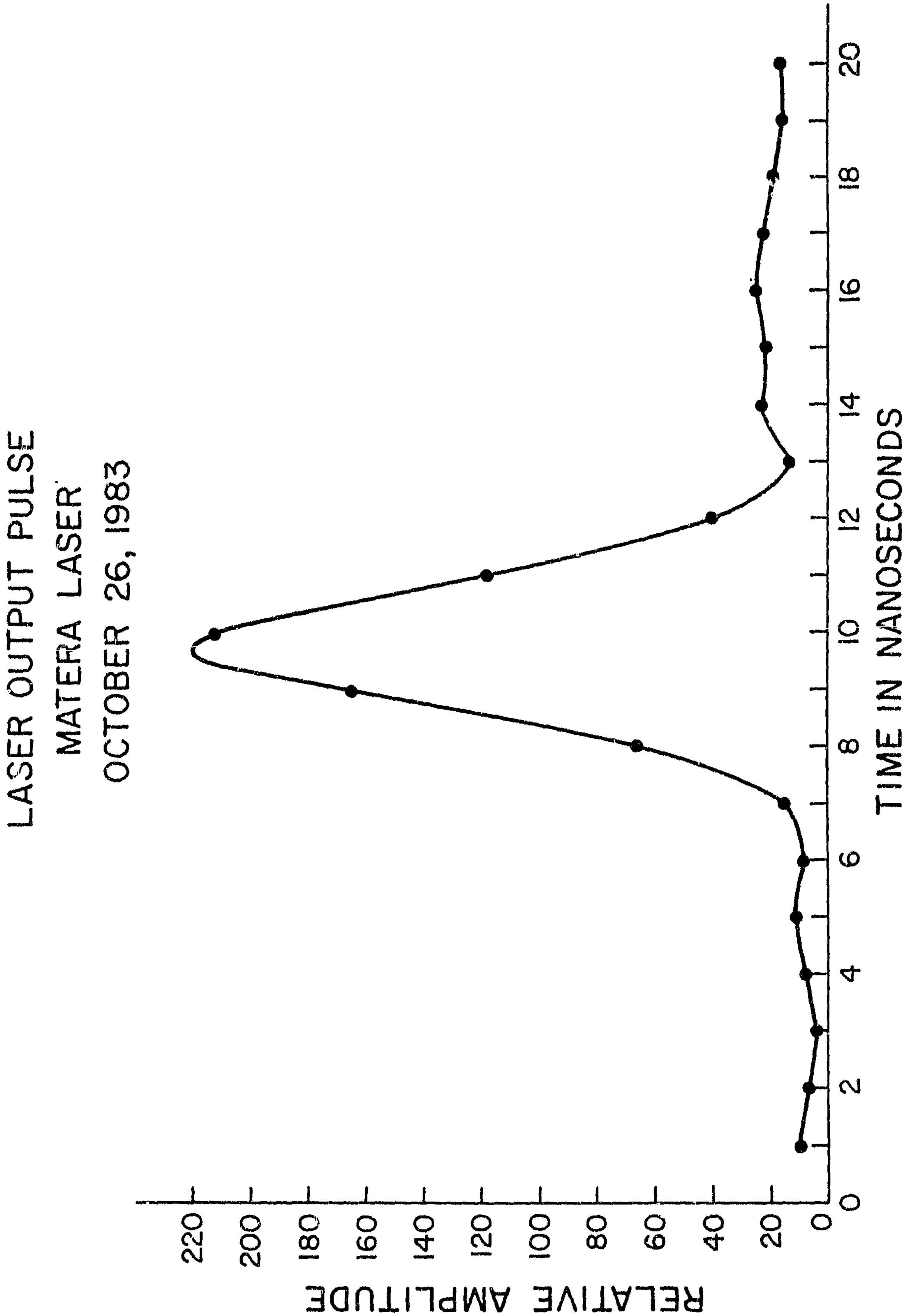
LASER OUTPUT PULSE
MATERA LASER
OCTOBER 26, 1983
TIME IN NANOSECONDS
RELATIVE AMPLITUDE
0 20 40 60 80 100 120 140 160 180 200 220
0 2 4 6 8 10 12 14 16 18 20

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 151 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.

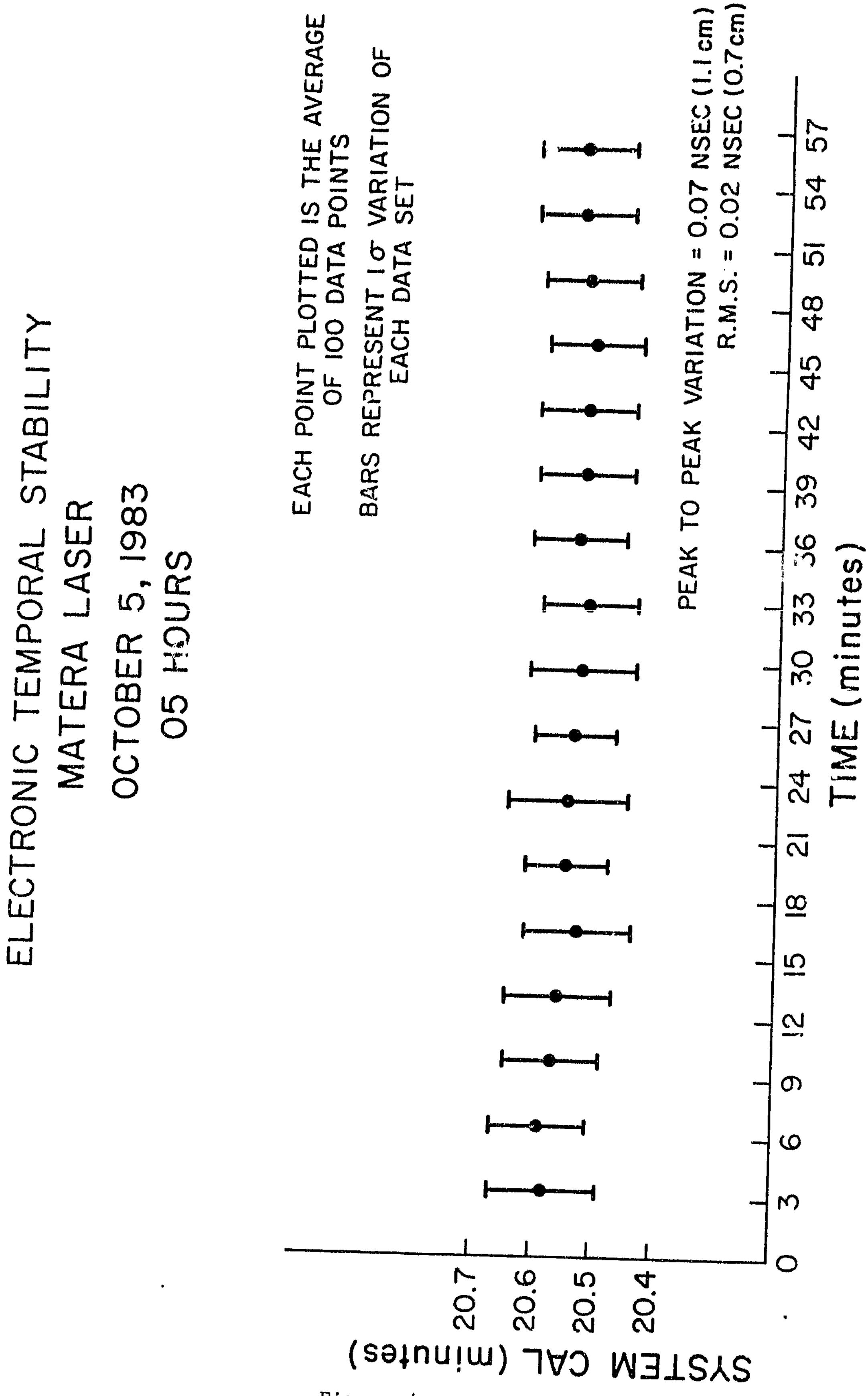
ELECTRONIC TEMPORAL STABILITY
MATERA LASER
OCTOBER 5, 1983
05 HOURS
EACH POINT PLOTTED IS THE AVERAGE OF 100 DATA POINTS
BARS REPRESENT 1σ VARIATION OF EACH DATA SET
PEAK TO PEAK VARIATION = 0.07 NSEC (1.1 cm)
R.M.S. = 0.02 NSEC (0.7 cm)
SYSTEM CAL (minutes)
20.7
20.6
20.5
20.4
0
3
6
9
12
15
18
21
24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

Figure 4

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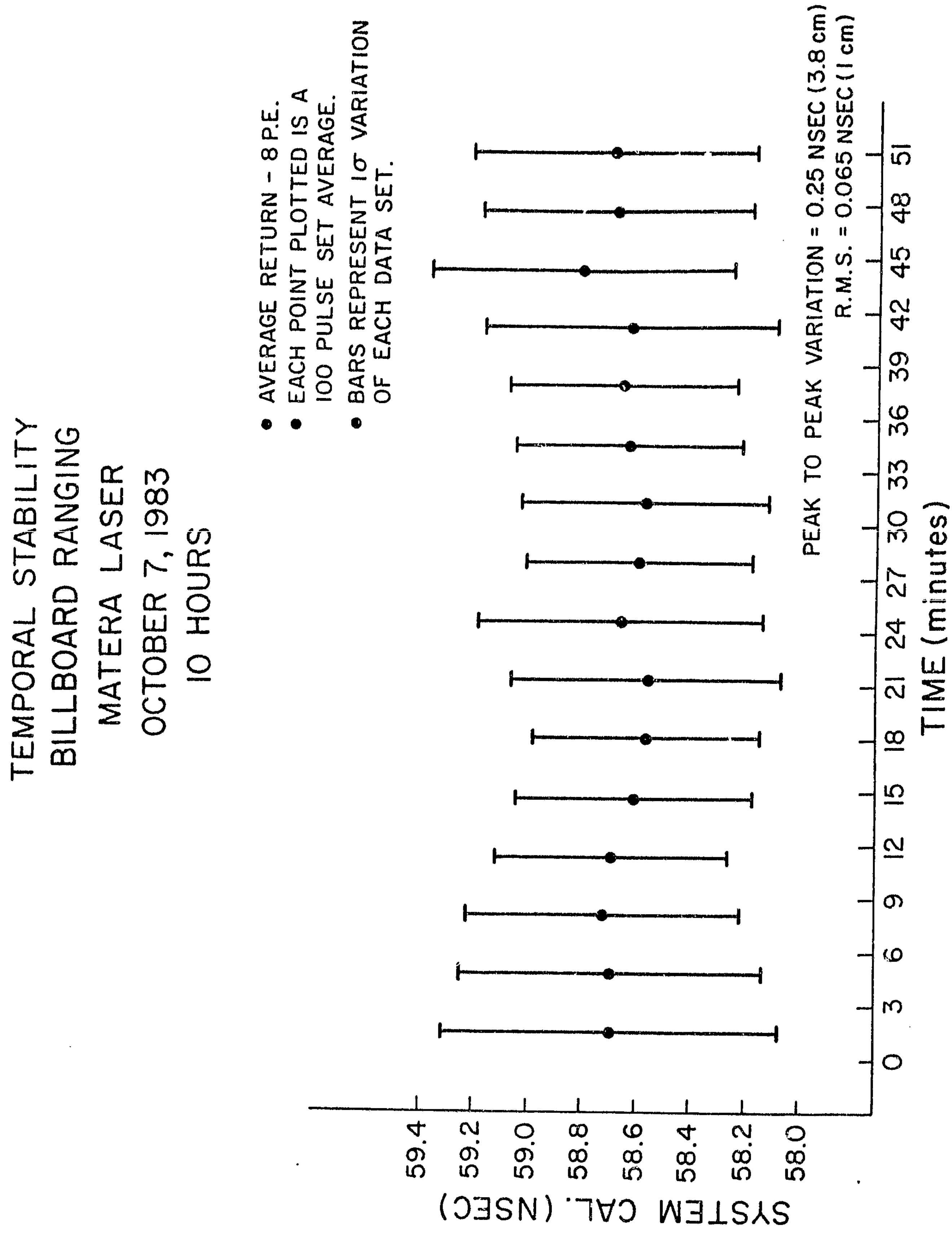

Figure 5

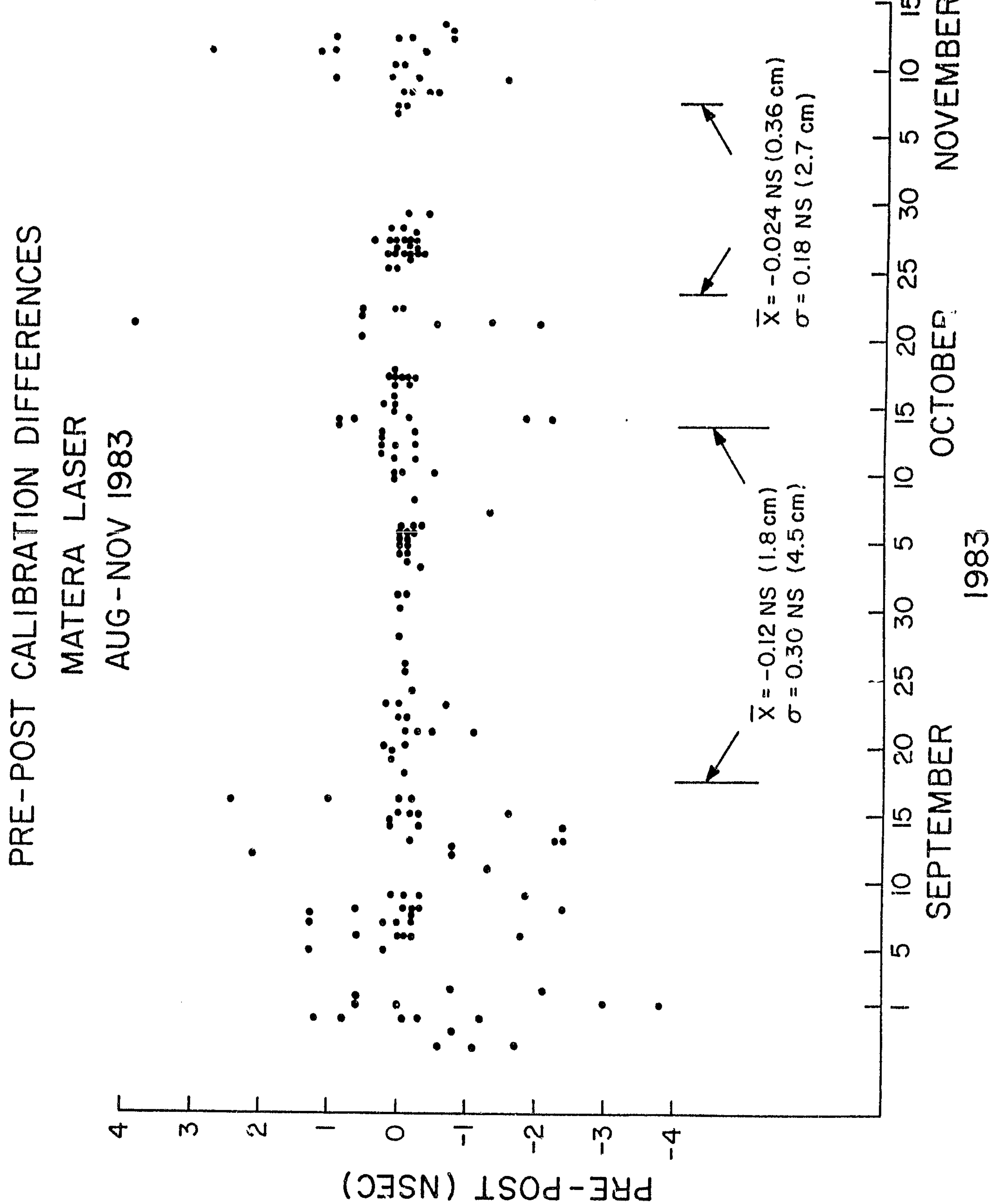
PRE-POST CALIBRATION DIFFERENCES
MATERA LASER
AUG-NOV 1983
PRE-POST (NSEC)
4
3
2
1
0
-1
-2
-3
-4
X̄ = -0.12 NS (1.8 cm)
σ = 0.30 NS (4.5 cm)
X̄ = -0.024 NS (0.36 cm)
σ = 0.18 NS (2.7 cm)
1
5
10
15
20
25
30
5
10
15
20
25
30
5
10
15
SEPTEMBER
OCTOBER
NOVEMBER
1983

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 ±.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.

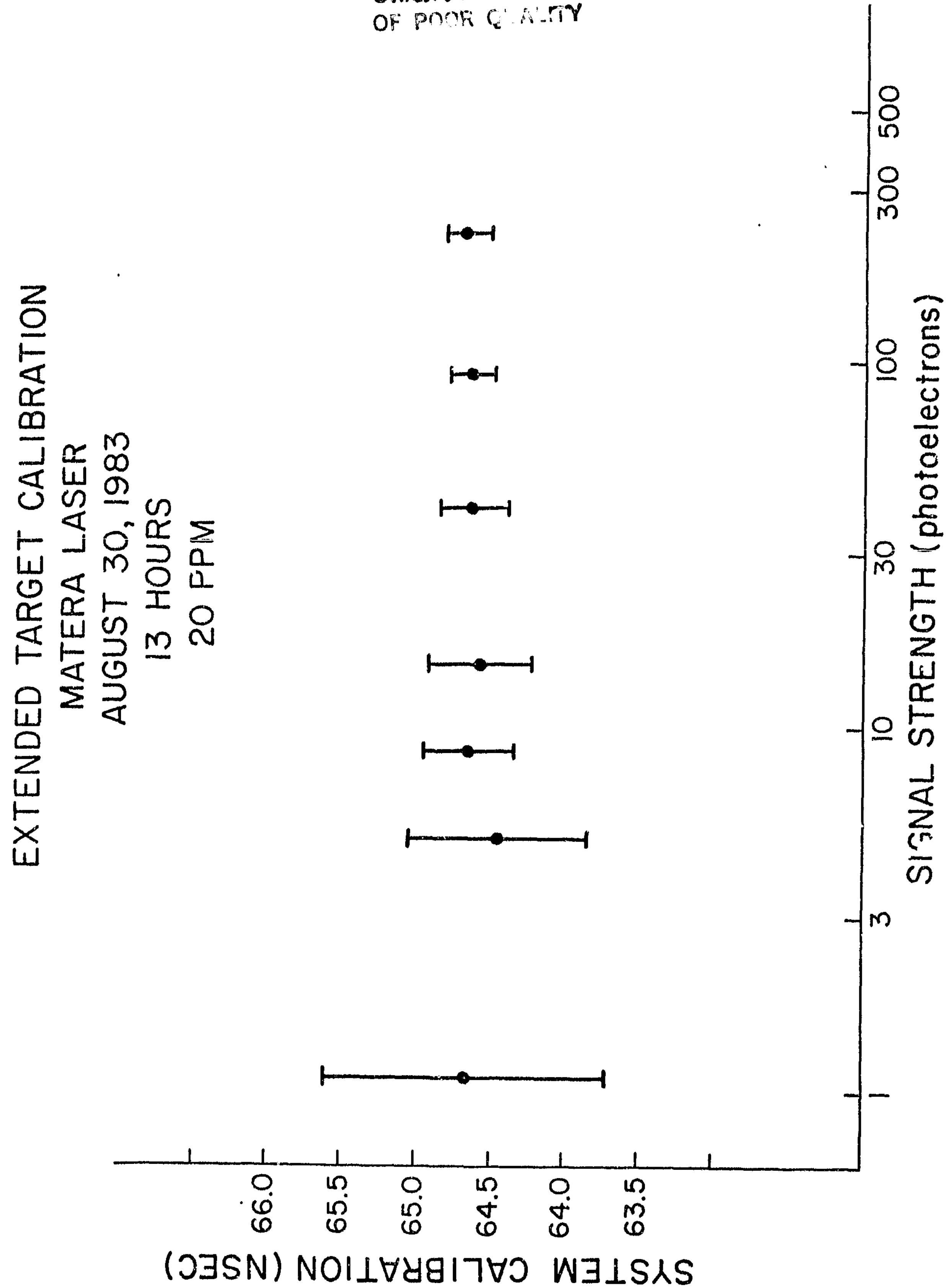
EXTENDED TARGET CALIBRATION
MATERA LASER
AUGUST 30, 1983
13 HOURS
20 PPM
SYSTEM CALIBRATION (NSEC)
66.0
65.5
65.0
64.5
64.0
63.5
1
3
10
30
100
300
500
SIGNAL STRENGTH (photoelectrons)

Figure 7

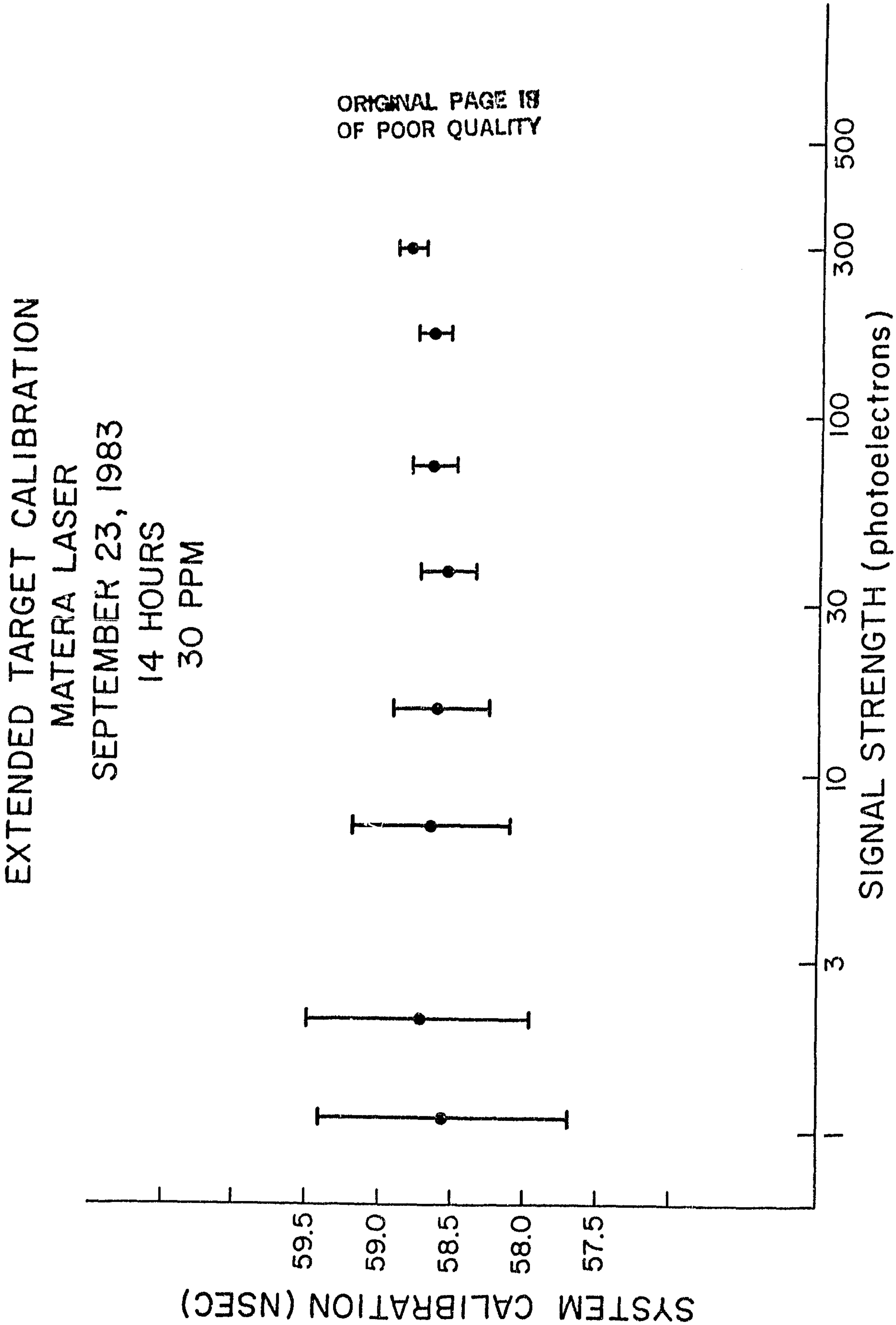
EXTENDED TARGET CALIBRATION
MATERA LASER
SEPTEMBER 23, 1983
14 HOURS
30 PPM
SIGNAL STRENGTH (photoelectrons)
1
3
10
30
100
300
500
SYSTEM CALIBRATION (NSEC)
59.5
59.0
58.5
58.0
57.5

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 me 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.

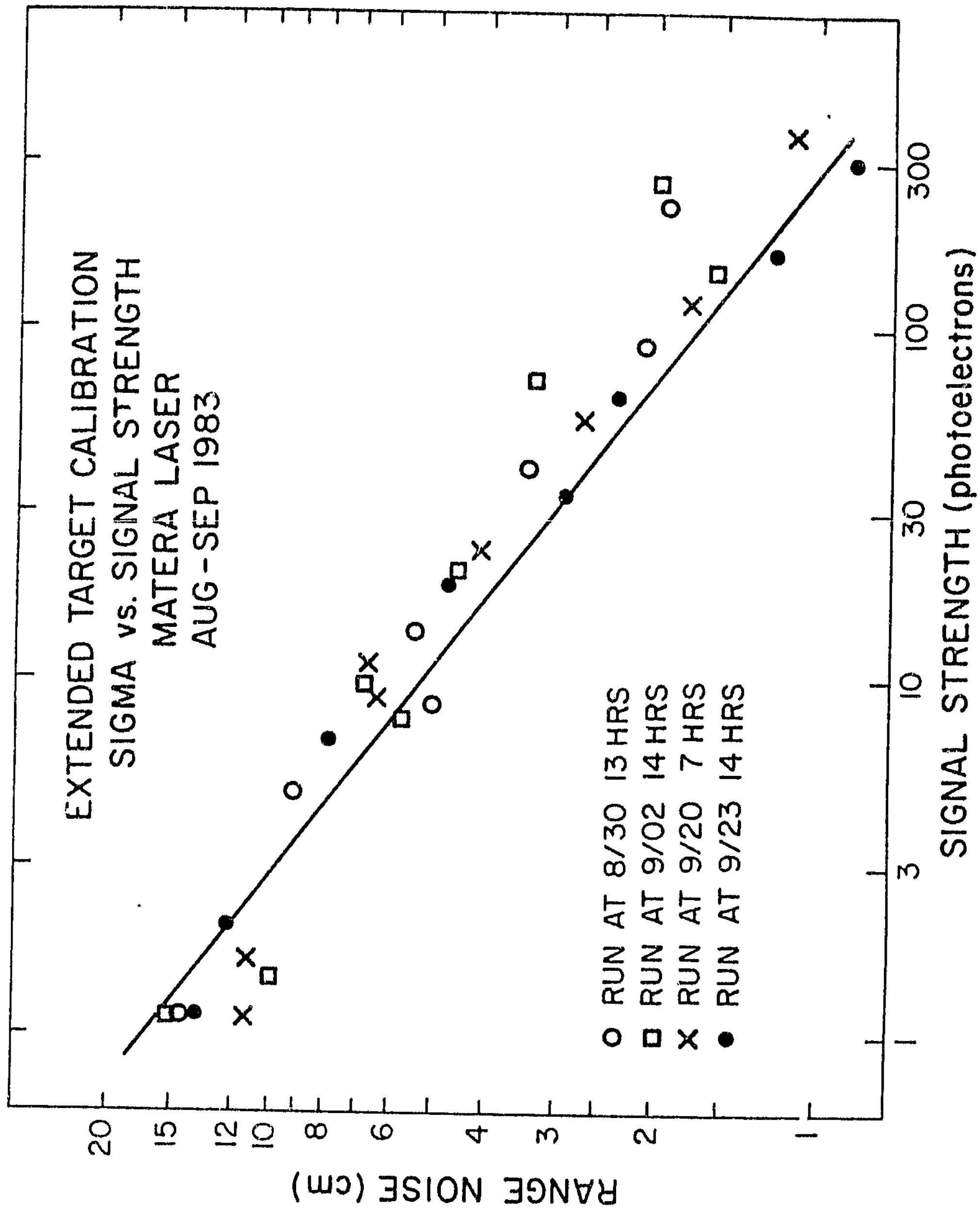
EXTENDED TARGET CALIBRATION
SIGMA vs. SIGNAL STRENGTH
MATERA LASER
AUG-SEP 1983
○ RUN AT 8/30 13 HRS
□ RUN AT 9/02 14 HRS
× RUN AT 9/20 7 HRS
● RUN AT 9/23 14 HRS
SIGNAL STRENGTH (photoelectrons)
1
3
10
30
100
300
RANGE NOISE (cm)
20
15
12
10
8
6
4
3
2
1

Figure 10

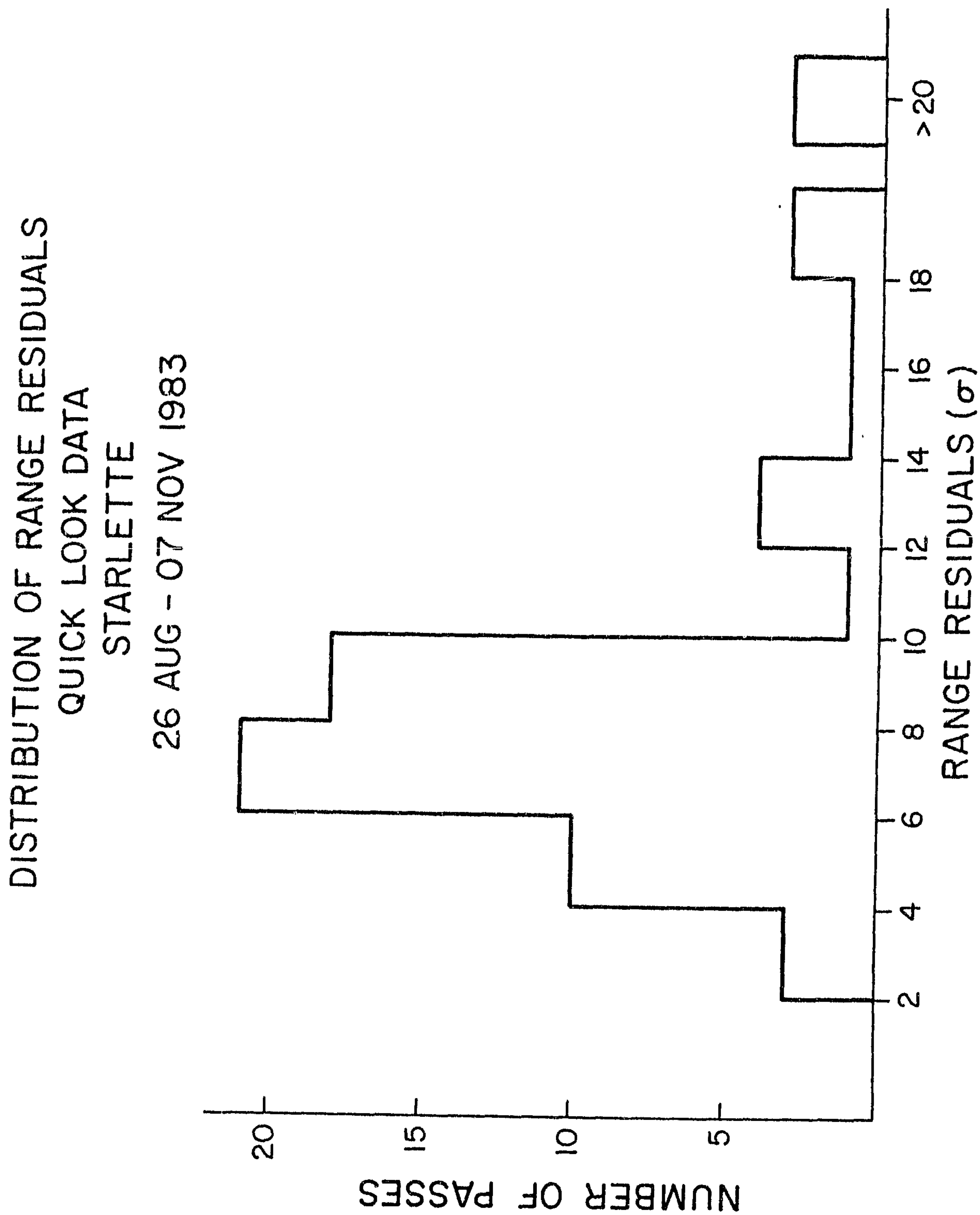
DISTRIBUTION OF RANGE RESIDUALS
QUICK LOOK DATA
STARLETTE
26 AUG - 07 NOV 1983
NUMBER OF PASSES
20
15
10
5
2
4
6
8
10
12
14
16
18
>20
RANGE RESIDUALS (σ)

Figure 11

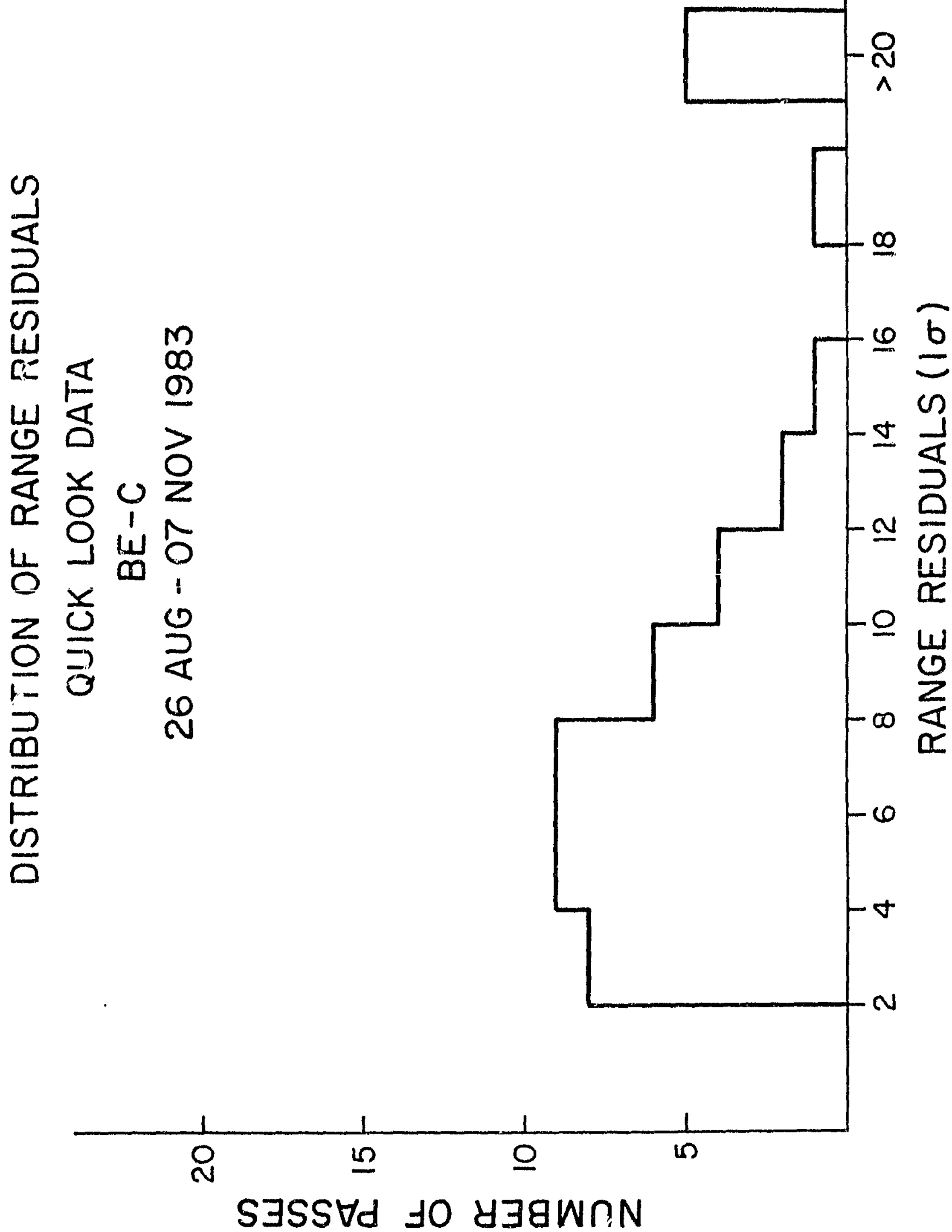
DISTRIBUTION OF RANGE RESIDUALS
QUICK LOOK DATA
BE-C
26 AUG - 07 NOV 1983
NUMBER OF PASSES
5
10
15
20
RANGE RESIDUALS (1σ)
2
4
6
8
10
12
14
16
18
>20

Figure 12

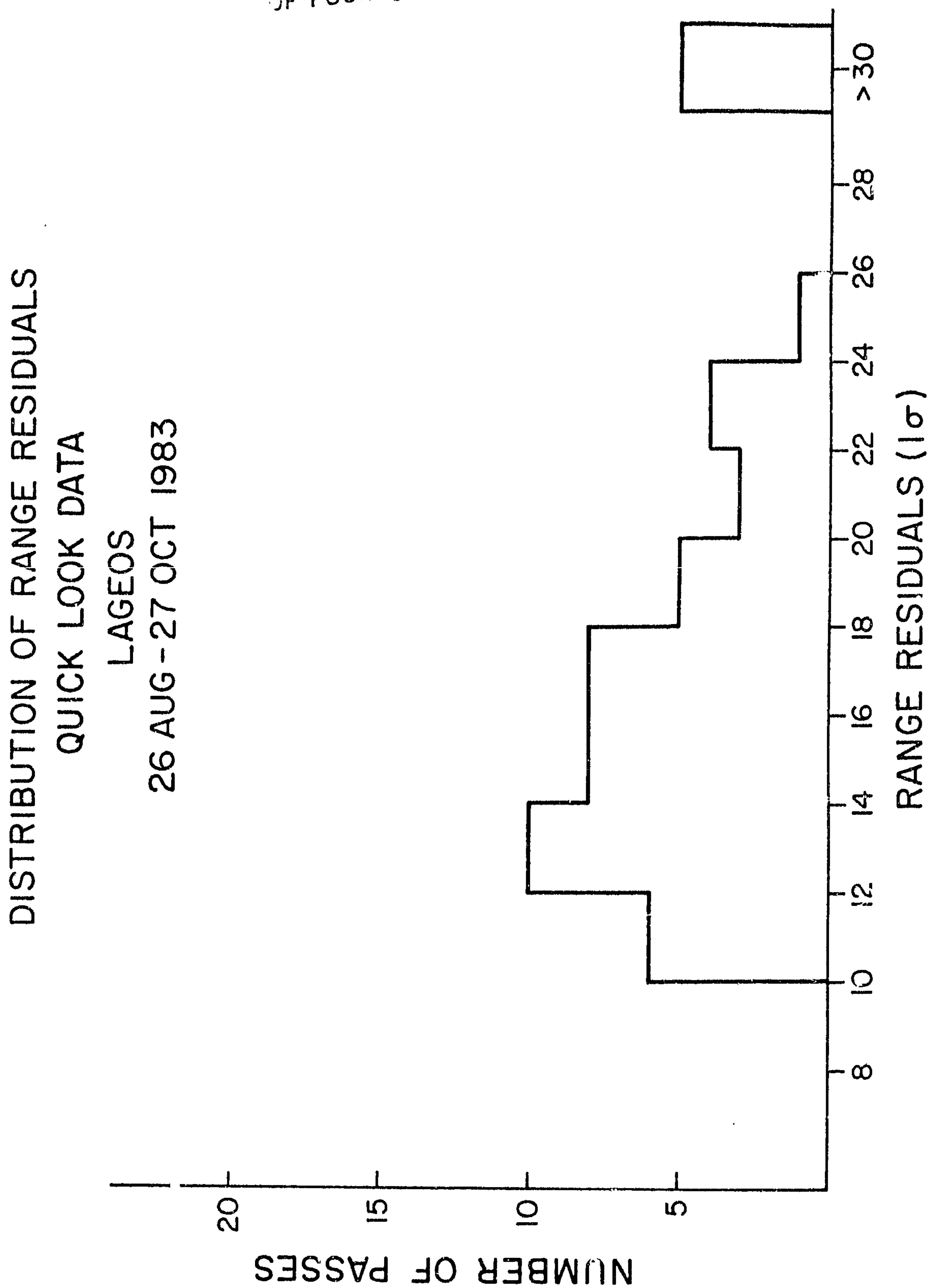
DISTRIBUTION OF RANGE RESIDUALS
QUICK LOOK DATA
LAGEOS
26 AUG - 27 OCT 1983
NUMBER OF PASSES
5
10
15
20
RANGE RESIDUALS (1σ)
8
10
12
14
16
18
20
22
24
26
28
>30

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.

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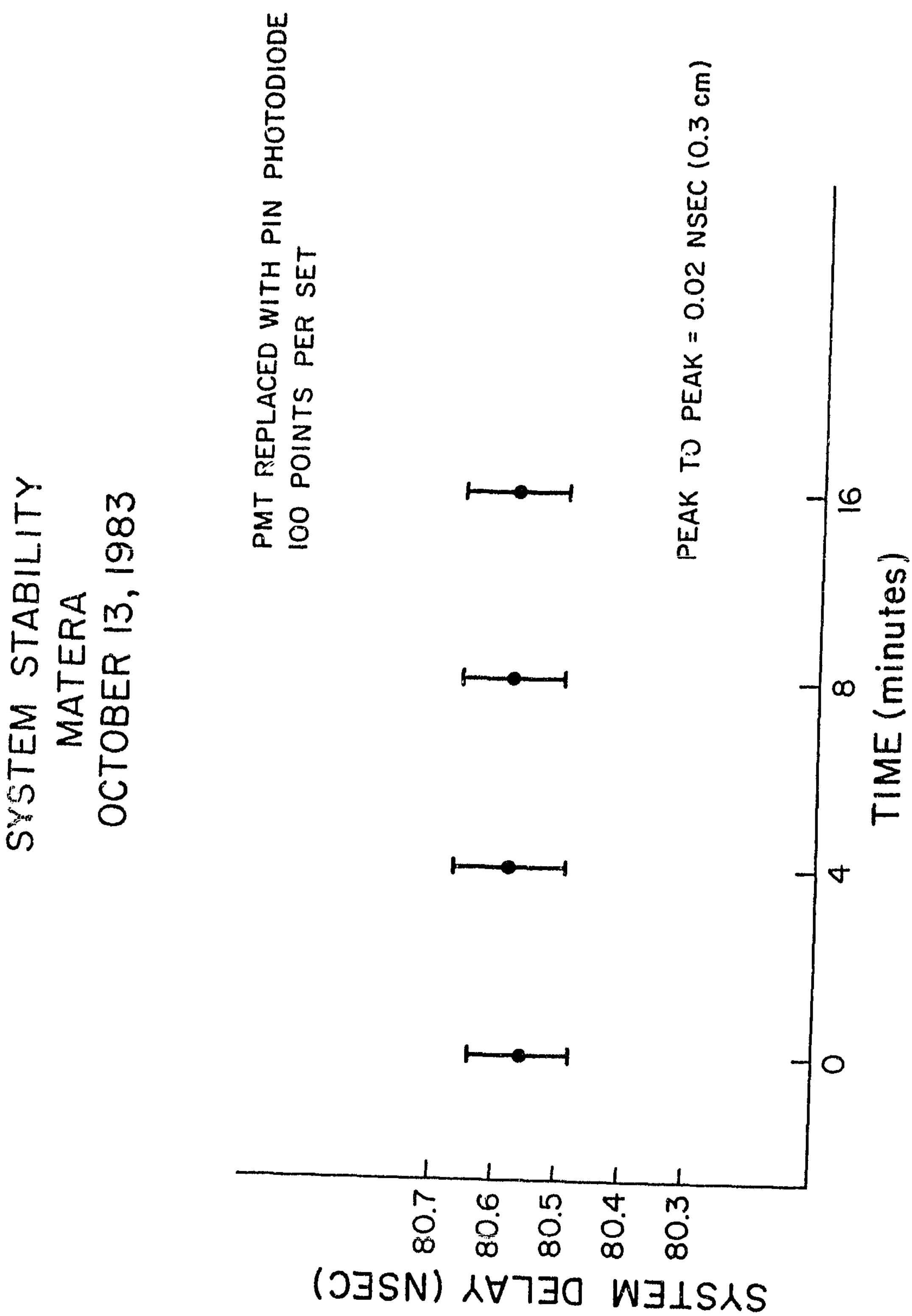

Figure 14

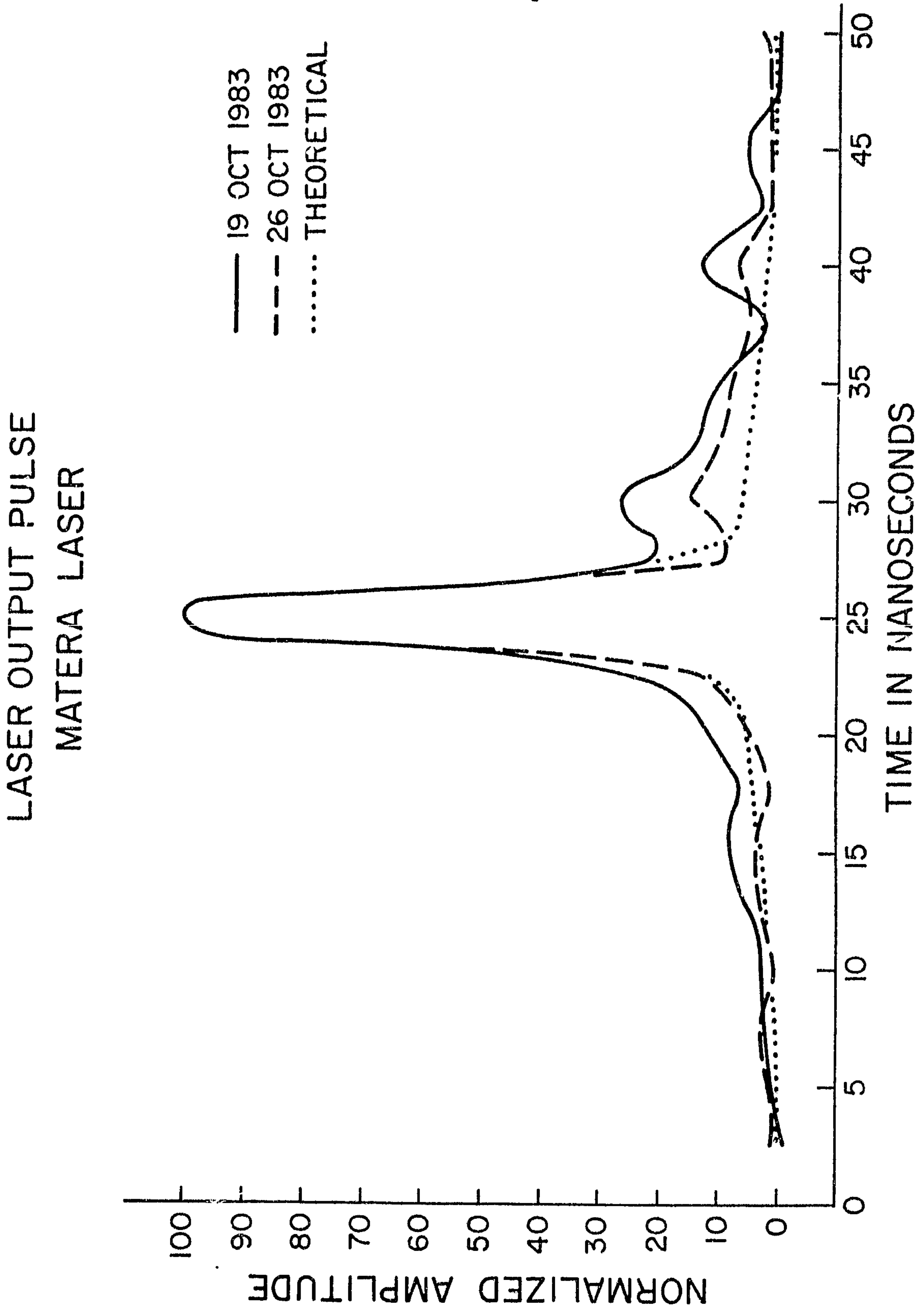
LASER OUTPUT PULSE
MATERA LASER
19 OCT 1983
26 OCT 1983
THEORETICAL
NORMALIZED AMPLITUDE
100
90
80
70
60
50
40
30
20
10
0
TIME IN NANOSECONDS
0
5
10
15
20
25
30
35
40
45
50

Figure 15