VLB ARRAY MEMO No. 312

A STUDY OF THE WATER VAPOR FLUCTUATIONS AT SELECTED SITES IN PUERTO RICO

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Introduction

From the standpoint of the coverage in the u-v plane, Puerto Rico is a critical site for a VLBA antenna. However, because the island has a tropical climate with no possibility of getting a site at the high altitudes available in Hawaii, there is concern that the atmosphere may not be sufficiently stable to enable VLB observations, particularly at the high frequencies now planned for the VLBA. It was therefore decided to make a study of selected sites in Puerto Rico to evaluate the possible atmospheric problems.

After considering several options, it appeared that the best technique would be to use a water vapor radiometer. Four sites on the island were chosen: Arecibo Observatory, where good technical support was available; Ramey, on the northwest coast of the island; La Parguera, on the southwest coast of the island near the region of minimum annual rainfall; and Cape San Juan, at the northeast, and windward side of the island with respect to the trade winds. Arecibo with an altitude of 500 m is the only site not at sea level.

The water vapor radiometer was loaned to us by the Jet Propulsion Laboratory. Bruce Gary of JPL traveled to Arecibo to set it up, and to train K. Turner (NAIC), G. Grove and D. Hogg in its use. The subsequent observations were conducted by Turner at Arecibo and Ramey, and by local people under Turner's supervision at the other two sites. The periods of observation were as follows: Arecibo, August 22-September 1; Ramey, September 2-19; La Parguera, September 19-30; and Cape San Juan, September 30-October 13, 1983.

Observations

The JPL water vapor radiometer consists of two independent radiometers operating at frequencies of 22.235 and 31.4 GHz using scaled feeds having beamwidths of 7 degrees. The radiometers are Dicke-switched between a reference load at 310 K and the sky which shows temperatures at 22 GHz in the range 60-120 K. The horns can be directed to various zenith angles by rotating a mirror which lies in front of them. The horns and receivers remain fixed.

The gain of the system is calibrated by making a tipping curve, requiring an observing time of 97 seconds to get two 4-second samples at each of 4 zenith angles. A least squares solution of the voltage variation with respect to zenith distance, compared to the voltage of the reference load of known temperature enables the solution of gain and sky temperature. The conversion of the observed temperatures to path delay and hence to equivalent phase at a given frequency is made using an algorithm provided by Bruce Gary, who made an extensive calibration of the device with respect to radiosondes during a period when it was used at Buffalo, NY. The amount of precipitable water, in gm cm^{-2} as indicated by the antenna temperatures T_1 and T_2 measured at 22.235 GHz and 31.4 GHz, respectively, is

$$V = -0.125 + 0.0661 * T_1' - 0.0346 * T_2'$$

where

$$T_1' = T_1 + \left[\frac{T_1 - 3}{21.3}\right]^2 , \quad T_2' = T_2 + \left[\frac{T_2 - 3}{21.3}\right]^2$$

The path delay arising from this amount of water vapor is then

$$L_V = 6.0 \text{ V cm}$$

$$= 28 \text{ V radians at } 22.235 \text{ GHz}$$

The accuracy with which the path delay can be retrieved in absolute terms is difficult to estimate, since we have not made the comparison of radiometer and radiosonde in the hot and humid climate of Puerto Rico, but computer simulations made by Gary suggest that uncertainties of at least 6 mm are to be expected. The relative error between two measurements separated by only a few minutes will have a much smaller uncertainty and indeed will be limited by receiver noise and receiver instability.

The system temperatures are 700 K at 22 GHz and 1000 K at 31 GHz. With a bandwidth of 100 MHz the expected rms in antenna temperature in 4 seconds is 0.07 K at 22 GHz and 0.1 K at 31 GHz. The observed rms is somewhat higher. Figure 1 shows the distribution of antenna temperatures observed at 22 GHz over a period of 18 minutes during a calm clear period at La Parguera. There is some drift in the temperature which has not been removed and which increases the scatter. Also shown is a gaussian of rms 0.21 K. If the rms of each of the channels is taken to be 0.2 K, the rms in the value deduced for L, measured in radians at a wavelength of 22 GHz, is 0.2.

The observations at each site were made using one of two observing modes. In one mode the radiometers were calibrated by means of a tipping curve and then the horns were pointed at the zenith while a string of 256 4-second integrations was taken. These data were used to study fluctuations on time scales between 4 seconds and 256 seconds. The second mode simply made tipping curves continuously, returning for a 4-second sample at the zenith every 97 seconds. This mode provides data on the receiver stability, on fluctuations in the time range 97 seconds and greater, and on the variation of atmospheric fluctuation with zenith angle.

Results

Perhaps the most straightforward way to characterize the quality of the site is to ask for the fraction of time that the rms in phase falls below a given value. The data from each of the days when the zenith mode was used were assembled in the basic 18 minute blocks, the antenna temperatures and equivalent phase delay calculated, a linear phase drift removed, and the rms residual phase for integration times between 4 and 256 seconds was computed. Figures 2-9 show for each site the incidence of phase fluctuations for integration times of 64 and 256 seconds. Figures 10 and 11 compare the sites.

From these plots La Parguera appears to be the best site by a small margin, and Ramey the worst. It is important that all sites are predicted to have the rms in phase for a 64 second average below 1 radian 70 percent of the time. It should be noted that this is the fluctuation in path over one telescope, and that the phase associated with an interferometer could be greater by $\sqrt{2}$.

Apart from the possible errors in the retrieval algorithm, the principal uncertainty is the amount of smearing introduced by the 7 degree beamwidth of the feeds. It is difficult to estimate this effect quantitatively without a detailed model of the atmosphere since it depends upon the number of clouds in the wide beam. The scale of the clouds (~200 m at 2 km distance) is unfortunately such that the effect could indeed be important. The phase fluctuations will be worse with a smaller beam.

The analysis of the phase described above involved just one-half of the data since the phase rms can not be computed directly from the tipping curve data. An alternative is to compute the Allan standard deviation (cf. Rogers and Moran IEEE Vol. IM-30, 283, 1981). This calculation can be made for both data bases for time intervals of approximately 96 and 292 seconds. Figures 12-15 give the Allan standard deviations found for each site. A summary (Figure 16) made for the time interval of 96 seconds shows that the ranking of the sites is the same as that found previously, although the difference among the sites is very small, and that the Allan standard deviation is less than 6.5×10^{-14} about one-half of the time.

It is of interest to measure the spectrum of the fluctuations. I have as yet looked at only a small part of the data from this standpoint. Figure 17 shows data from two periods at La Parguera when the atmosphere was relatively stable. The data for short intervals are from zenith runs, the data from longer intervals from tipping curves. Also shown are data from a VLB experiment at 89 GHz (Rogers, private communication).

The relationship between the Allan standard deviation and the time interval τ is approximately

$$\langle\sigma^2\rangle^{1/2} \propto \tau^{-2/3}$$

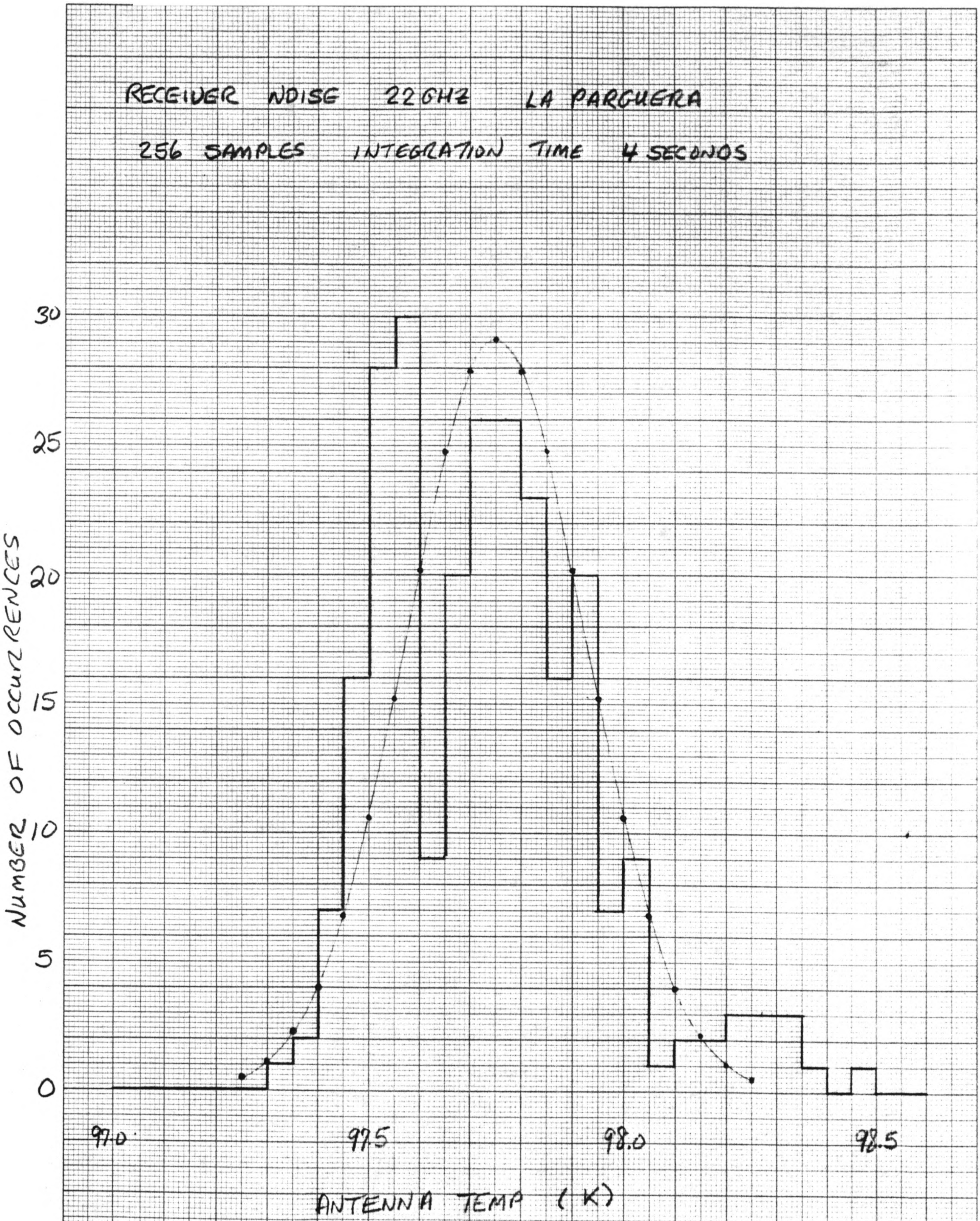
which is midway between the power law index for white phase noise (-1) and white frequency noise (-1/2).

Conclusion

The atmosphere over Puerto Rico, though containing large amounts of water vapor, is relatively stable, and observations with the VLB at 22 GHz should be possible up to two-thirds of the time, with the nights being better than the days.

Figures

Figure 1	The distribution of antenna temperatures, averaged over 4 seconds, observed at 22.235 GHz during a period of 18 minutes. The gaussian has an rms of 0.21 K.
Figures 2-9	The fraction of the time the rms in phase for a given integration time is less than a given value.
Figures 10, 11	A comparison of the rms in phase among the four sites.
Figures 12-15	The fraction of the time the Allan standard deviation is less than a given value, for two values of time interval at each site.
Figure 16	A comparison of the Allan standard deviations at the four sites.
Figure 17	The run of Allan standard deviation with time interval. The dots are data from zenith runs, the circles from tipping runs, and the crosses are VLB data at 89 GHz.



RECEIVER NOISE 22 GHZ LA PARGUERA
256 SAMPLES INTEGRATION TIME 4 SECONDS
NUMBER OF OCCURRENCES
30
25
20
15
10
5
0
97.0
97.5
98.0
98.5
ANTENNA TEMP (K)

FIGURE 1

ARECIBO AVERAGES OVER 64 SECONDS

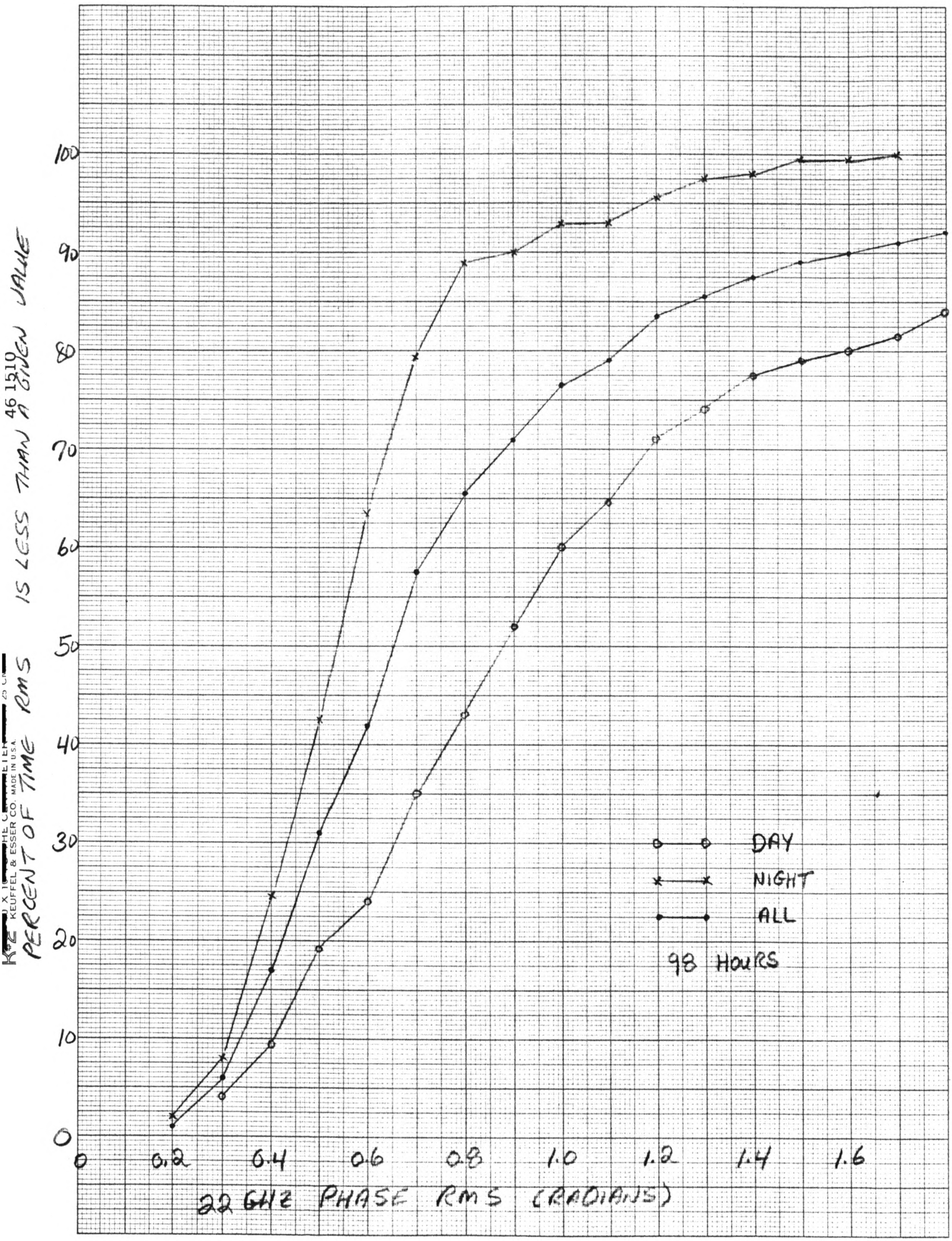


FIGURE 2

ARECIBO AVERAGES OVER 256 SECONDS

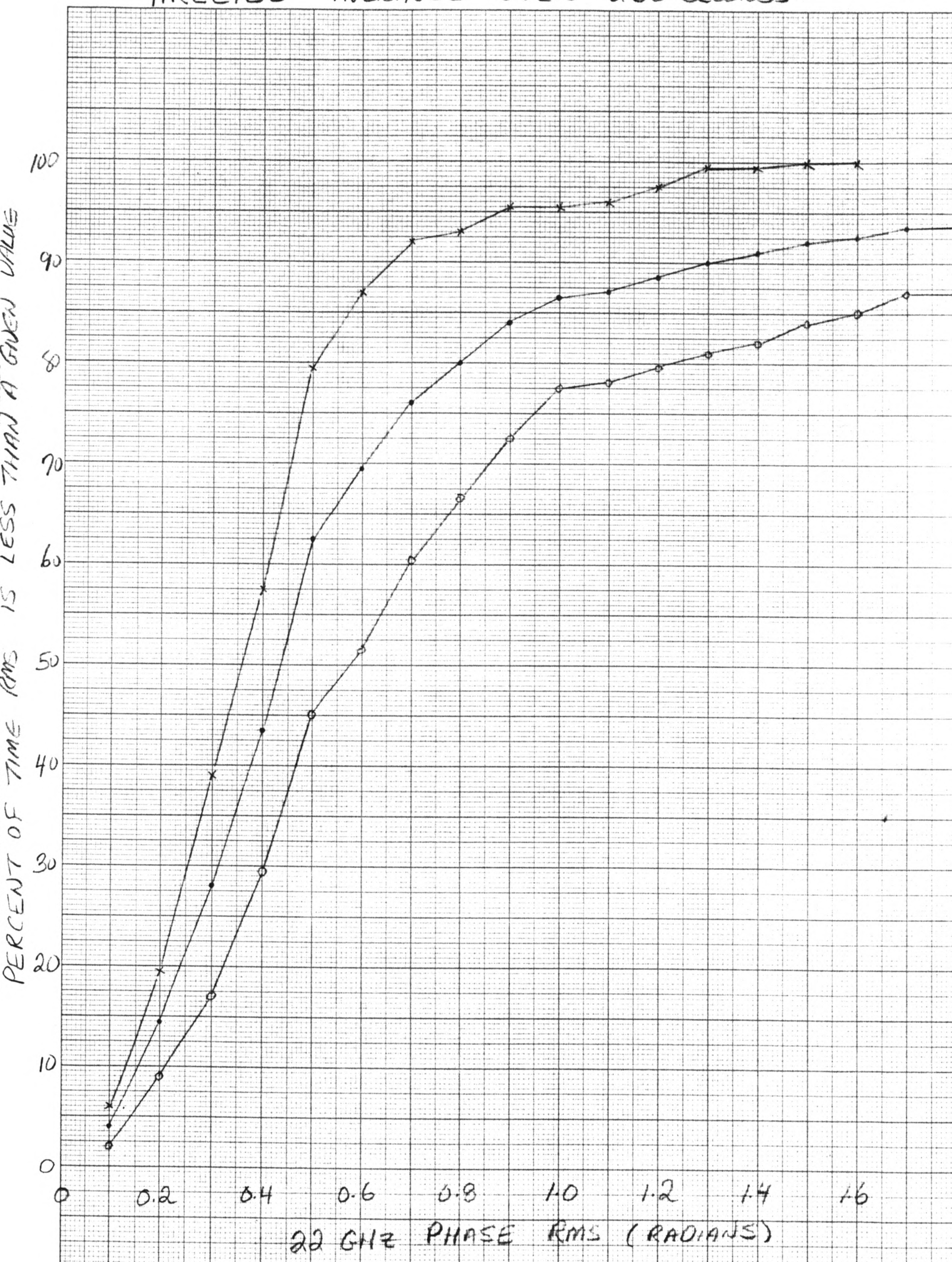


FIGURE 3

RAMEY AVERAGES OVER 64 SECONDS

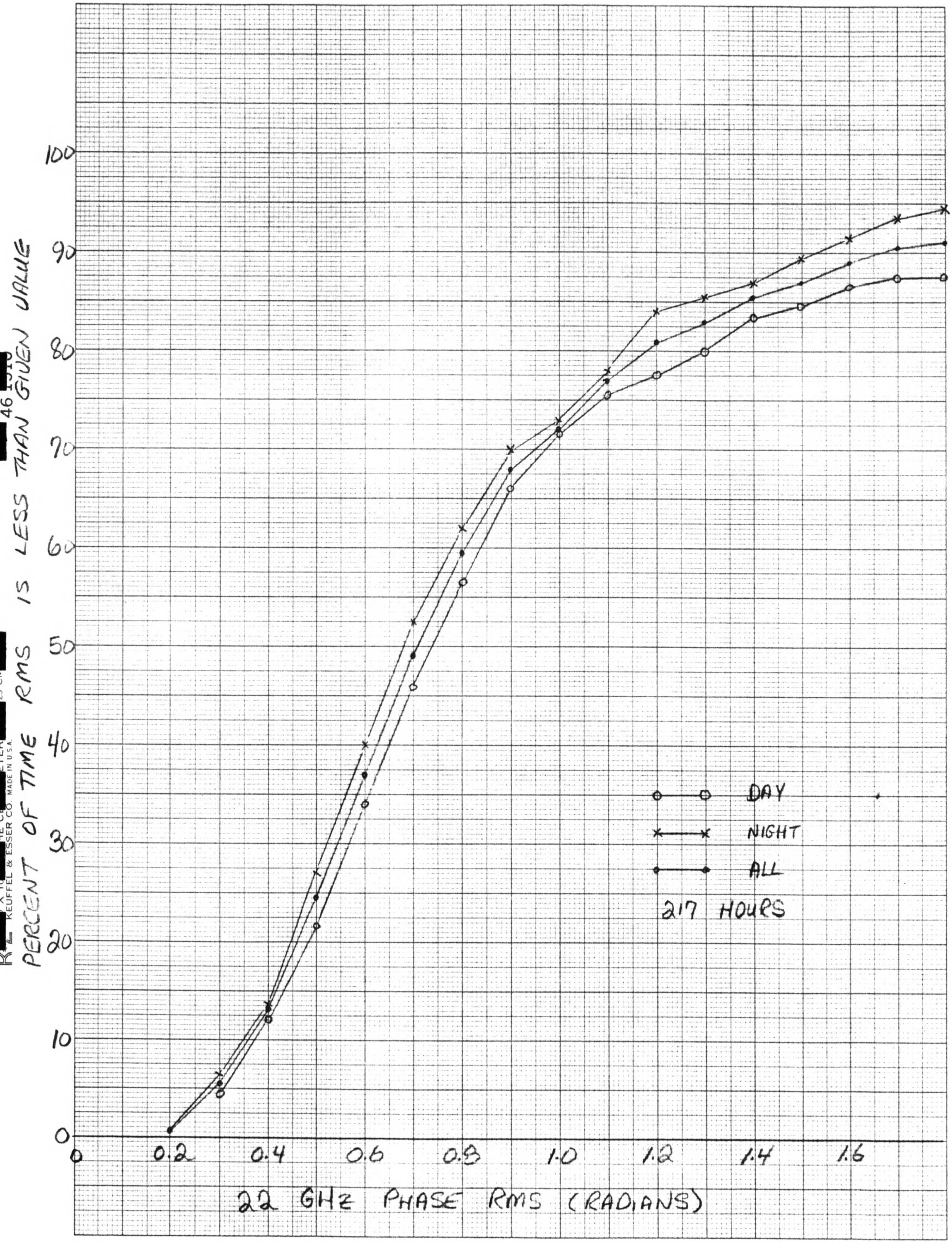


FIGURE 4

RAMEY AVERAGES OVER 256 SECONDS

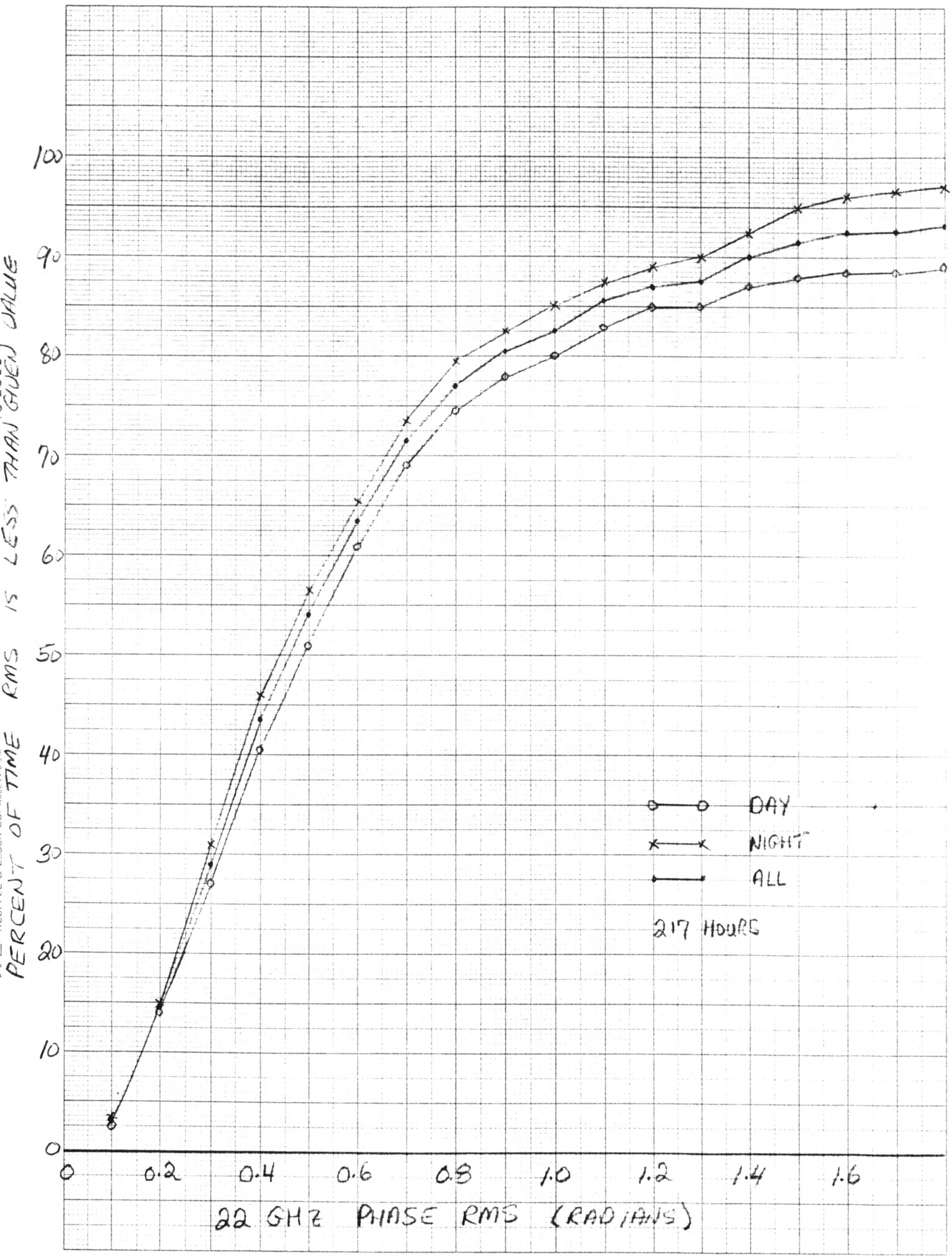


FIGURE 5

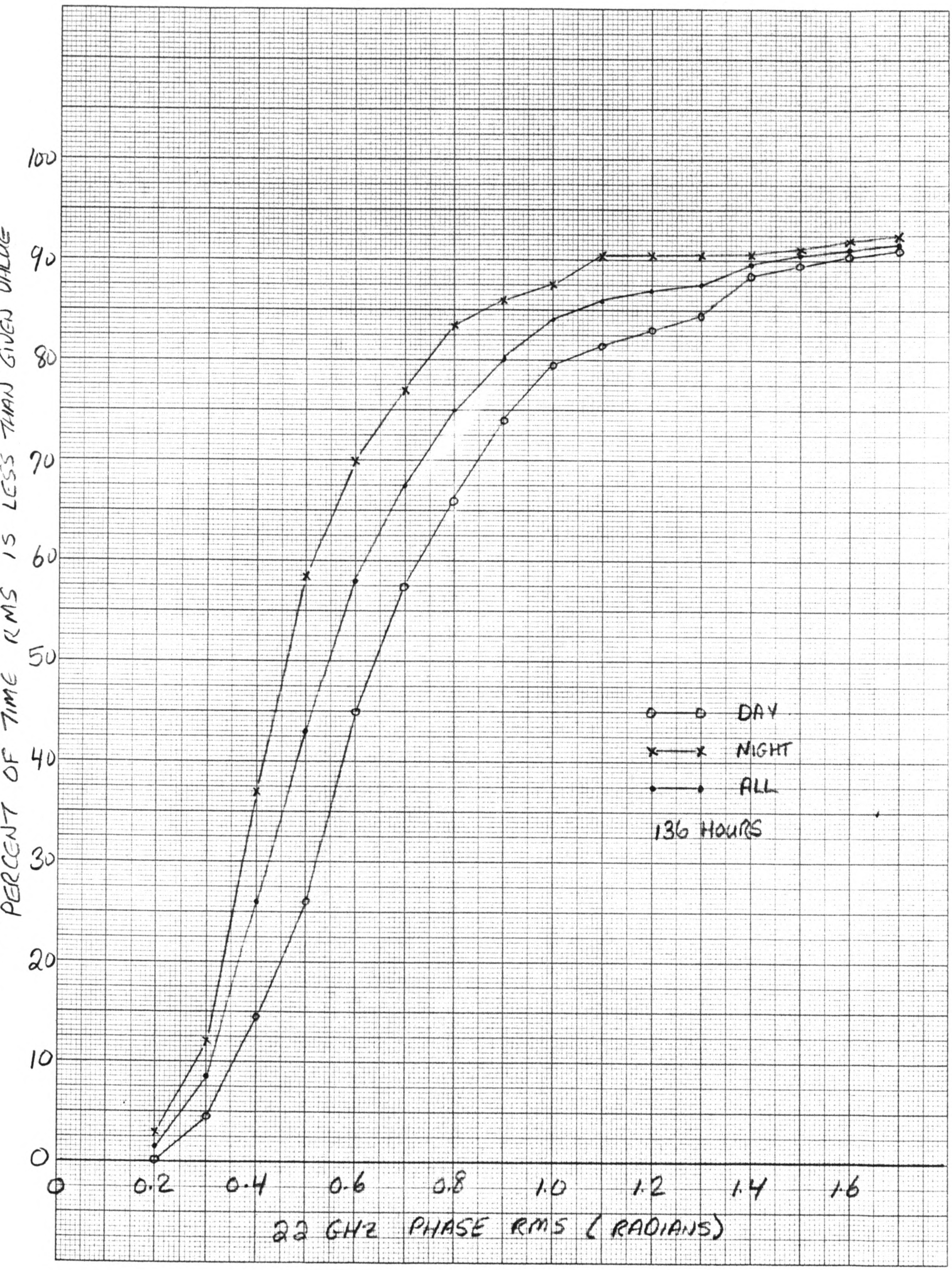
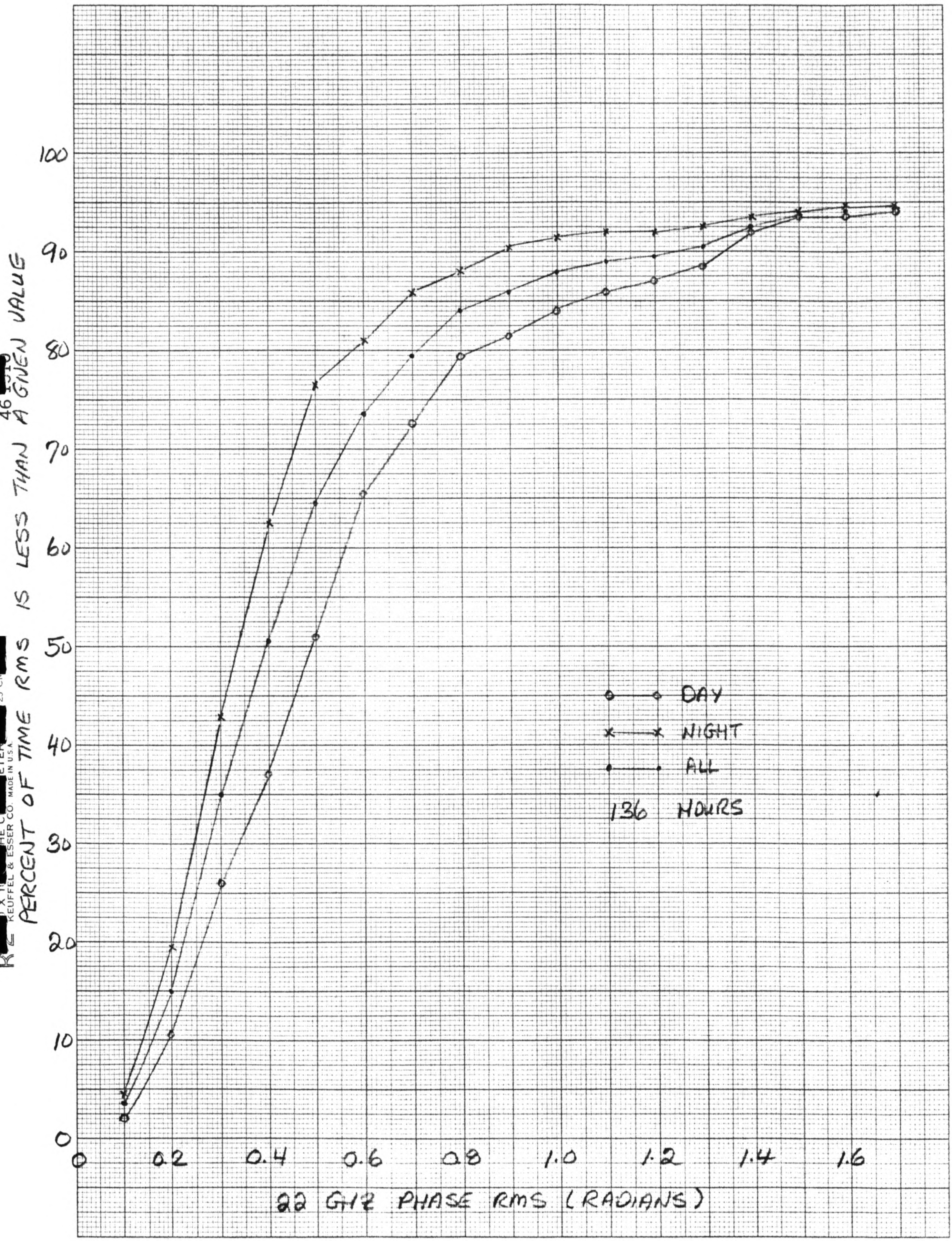

PERCENT OF TIME RMS IS LESS THAN GIVEN VALUE
100
90
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
22 GHz PHASE RMS (RADIANS)
DAY
NIGHT
ALL
136 HOURS

FIGURE 6



PERCENT OF TIME RMS IS LESS THAN A GIVEN VALUE
0
10
20
30
40
50
60
70
80
90
100
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
22 GHZ PHASE RMS (RADIANS)
DAY
NIGHT
ALL
136 HOURS

FIGURE 7

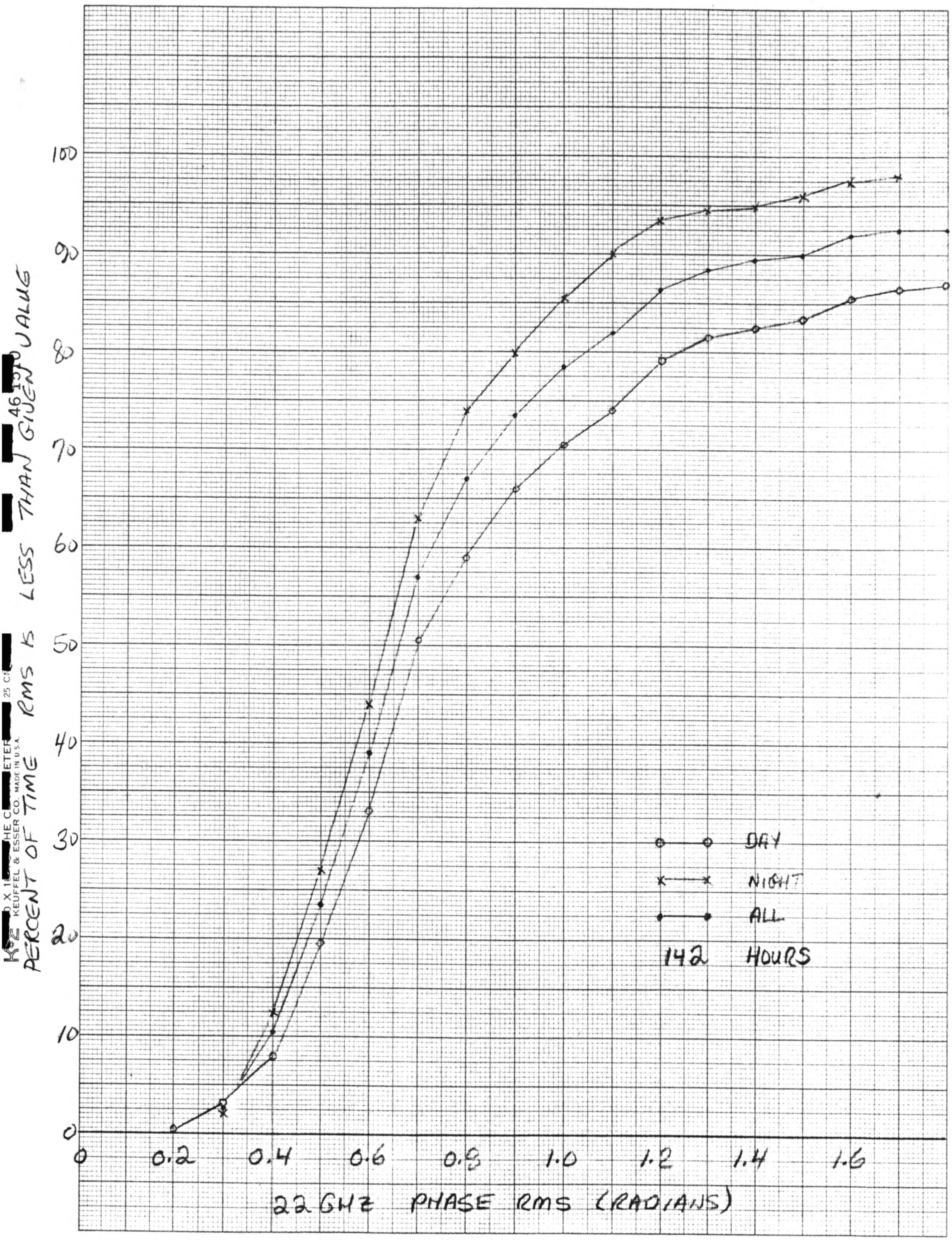

PERCENT OF TIME RMS IS LESS THAN GIVEN VALUE
0
10
20
30
40
50
60
70
80
90
100
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
22 GHZ PHASE RMS (RADIANS)
DAY
NIGHT
ALL
142 HOURS

FIGURE 8

CAPE SAN JUAN AVERA[illegible] OVER 256 [illegible]

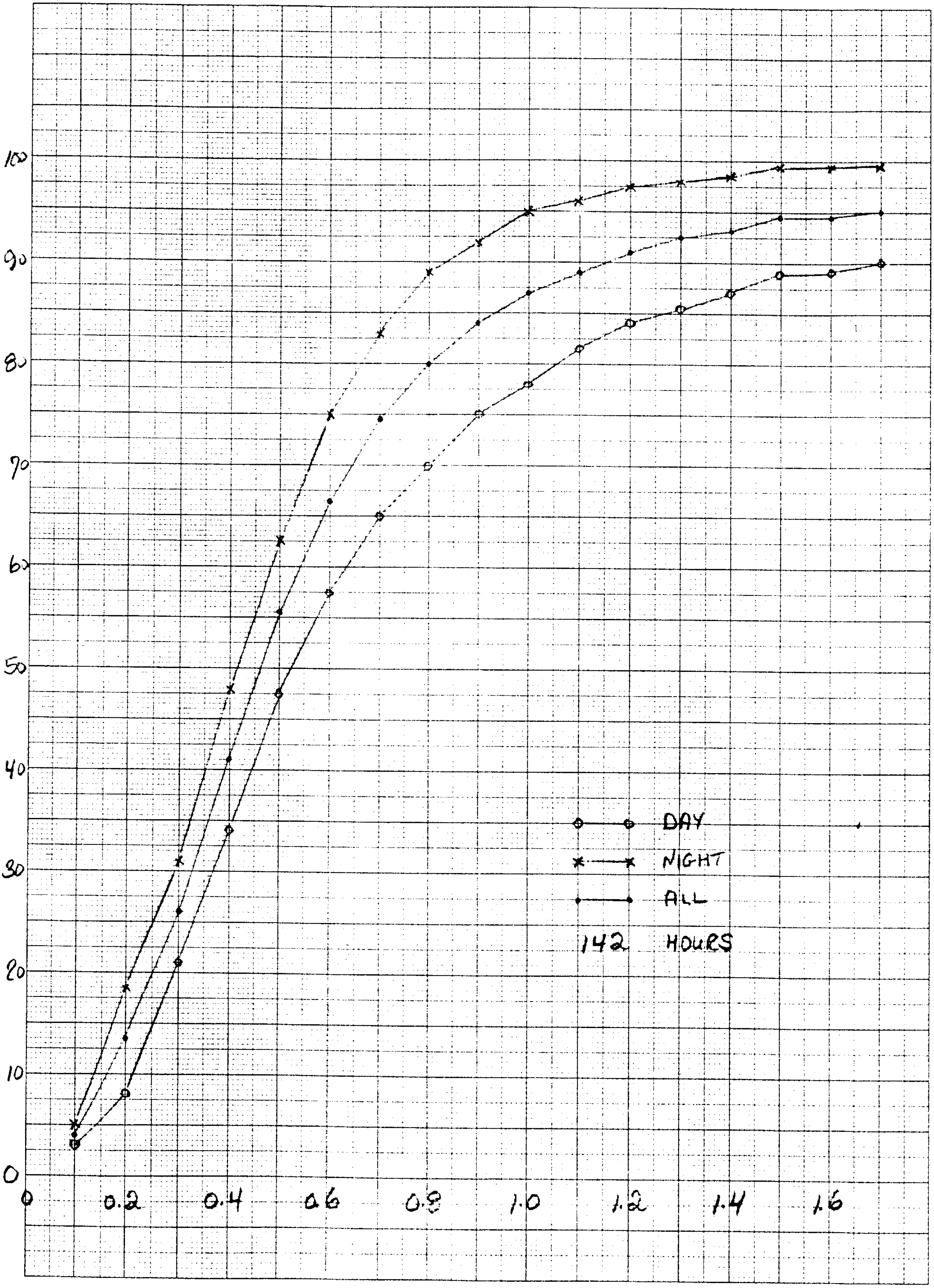


FIGURE 9

ALL SITES: AVERAGES OVER 64 SECONDS

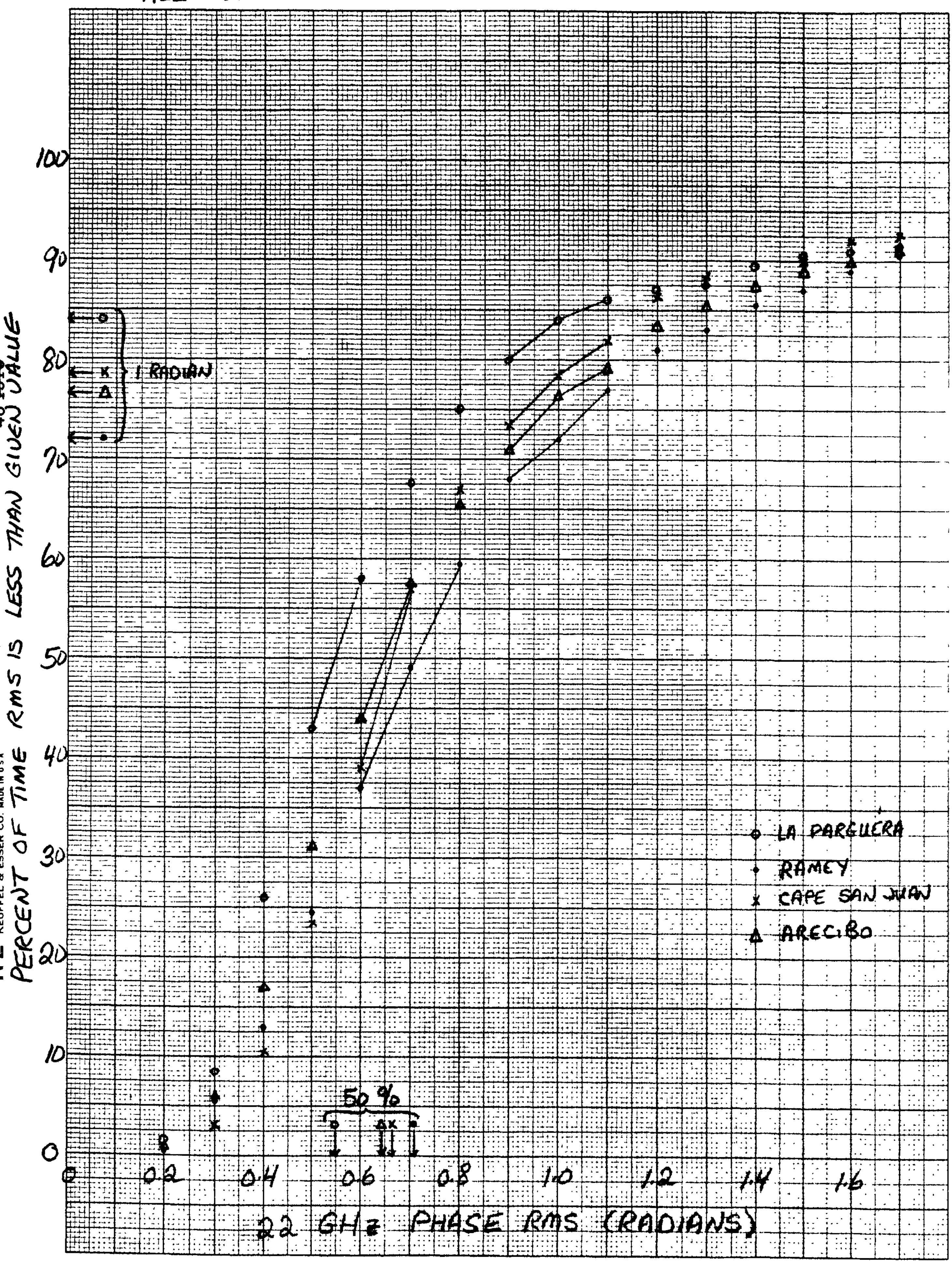


FIGURE 10

ALL SITES: AVERAGES OVER 256 SECONDS

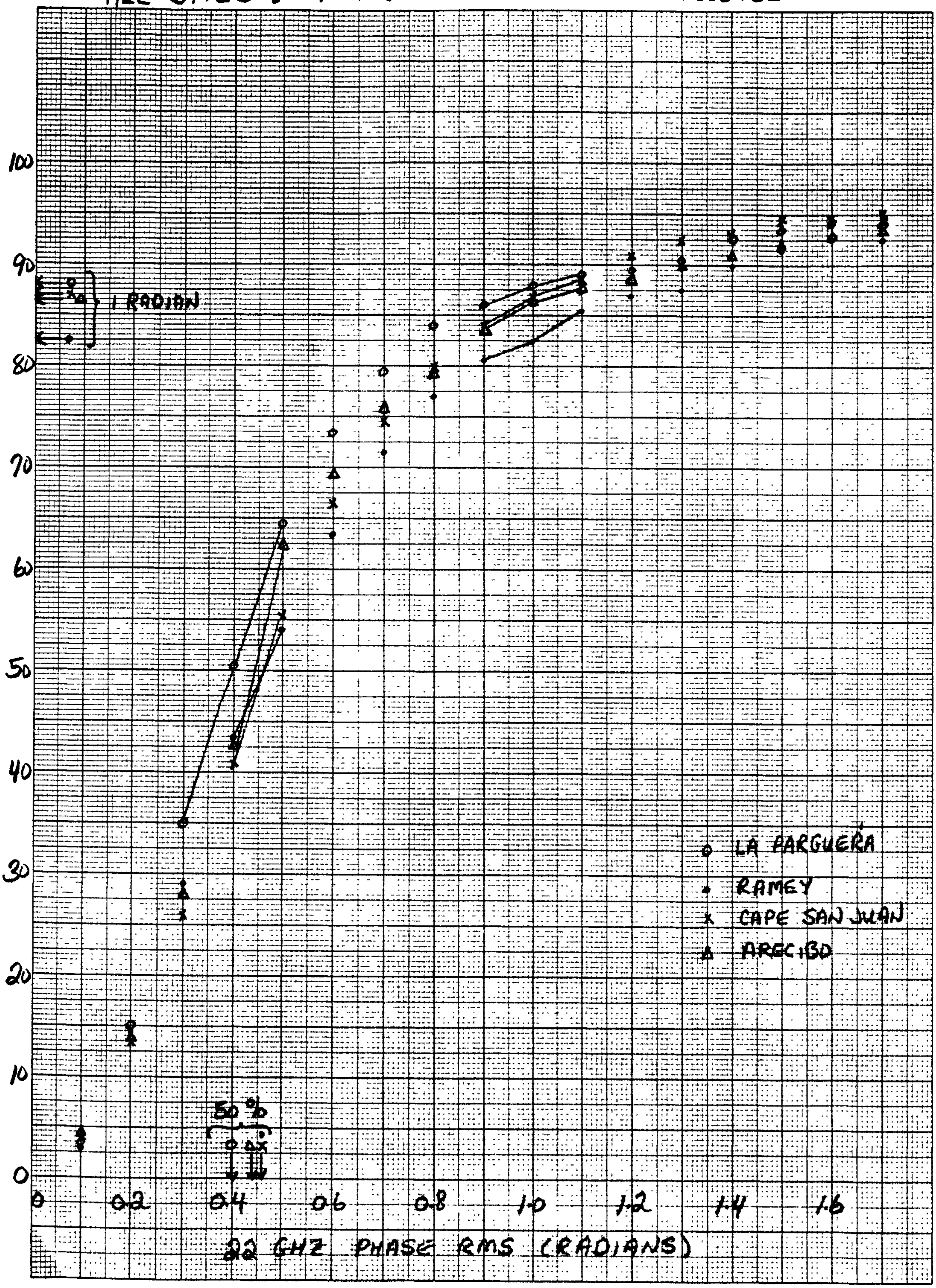


FIGURE 11

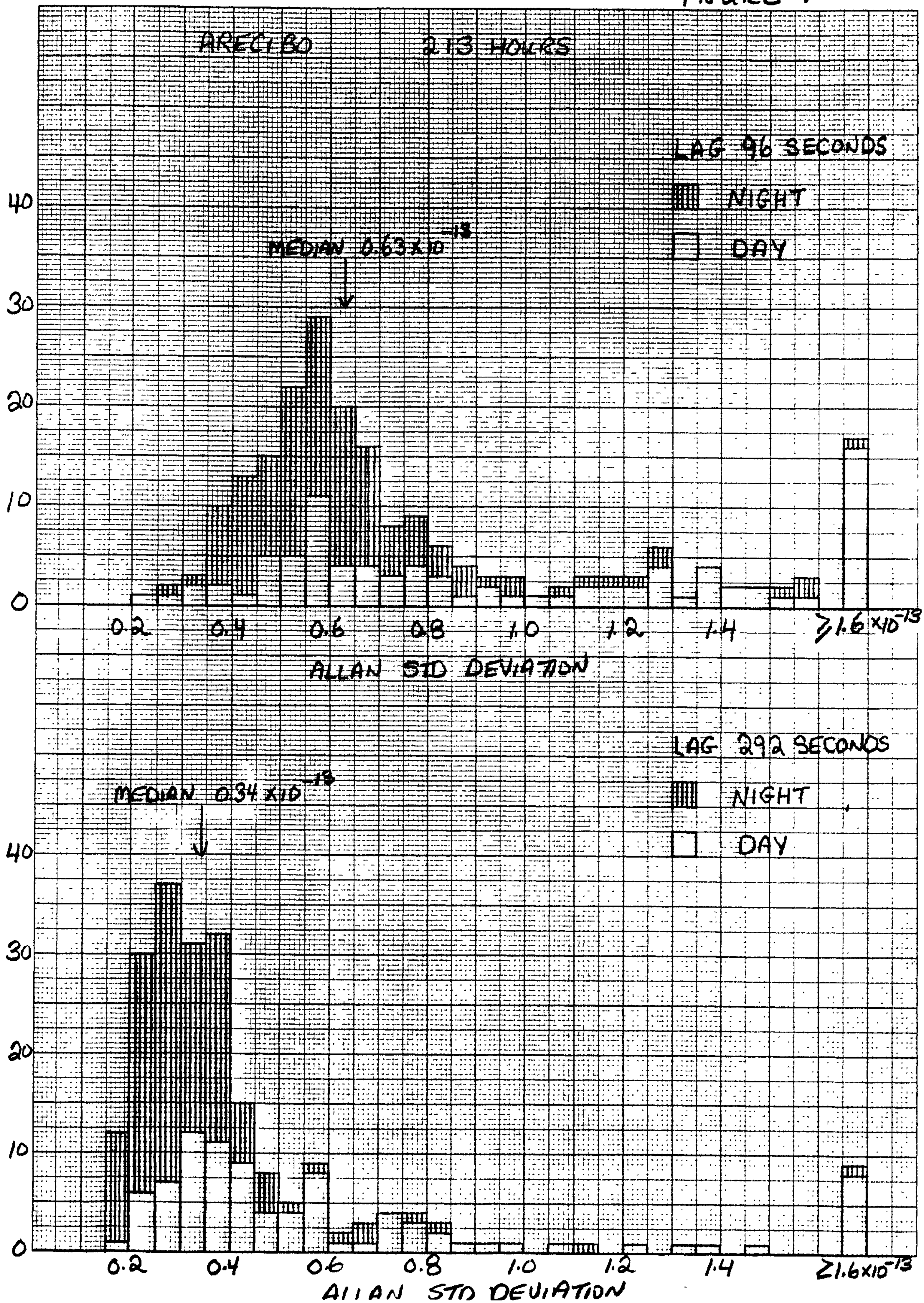
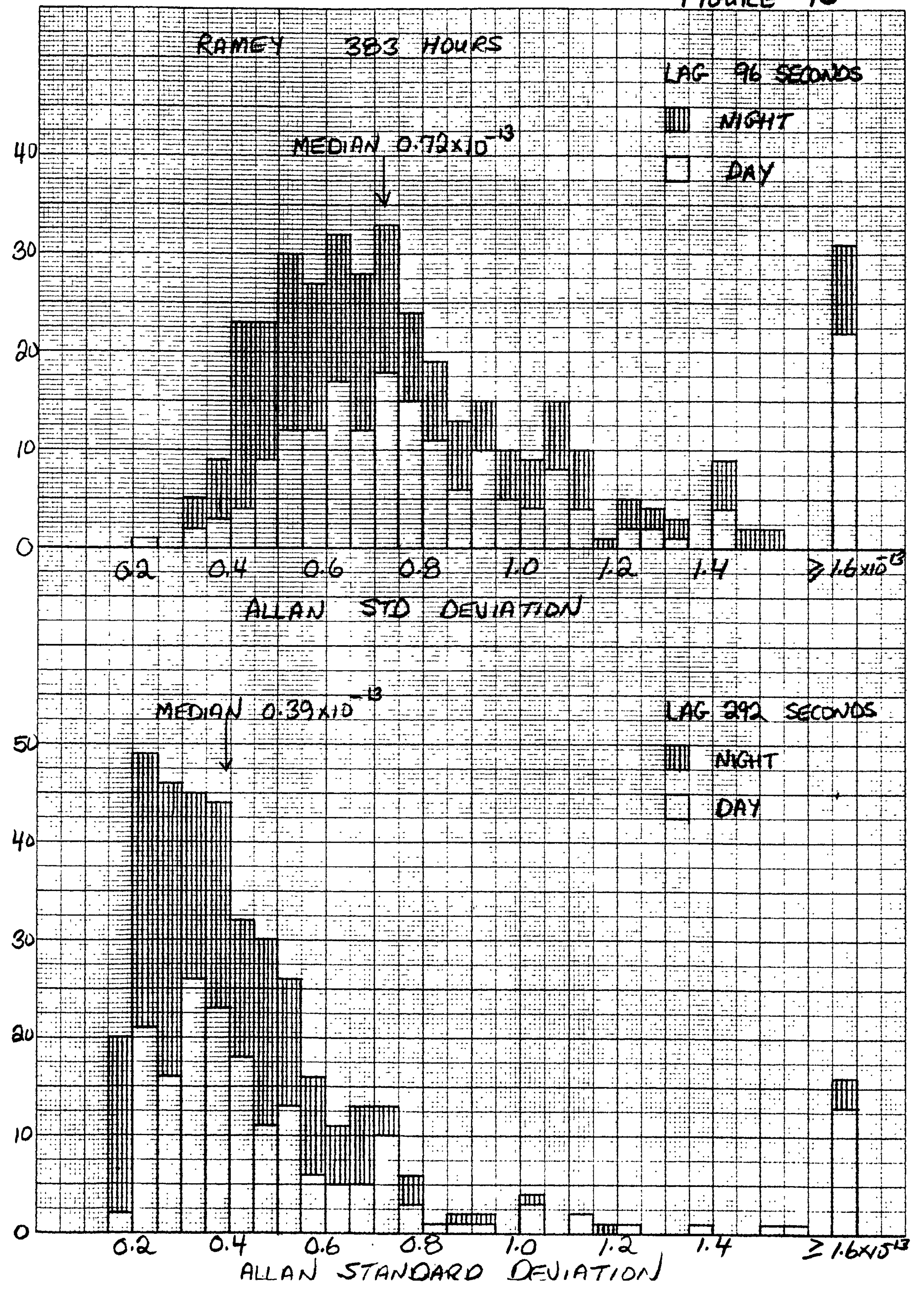

ARECIBO 213 HOURS
LAG 96 SECONDS
NIGHT
DAY
MEDIAN 0.63 X10-13
0
10
20
30
40
0.2
0.4
0.6
0.8
1.0
1.2
1.4
≥1.6 X10-13
ALLAN STD DEVIATION
LAG 292 SECONDS
NIGHT
DAY
MEDIAN 0.34 X10-13
0
10
20
30
40
0.2
0.4
0.6
0.8
1.0
1.2
1.4
≥1.6X10-13
ALLAN STD DEVIATION

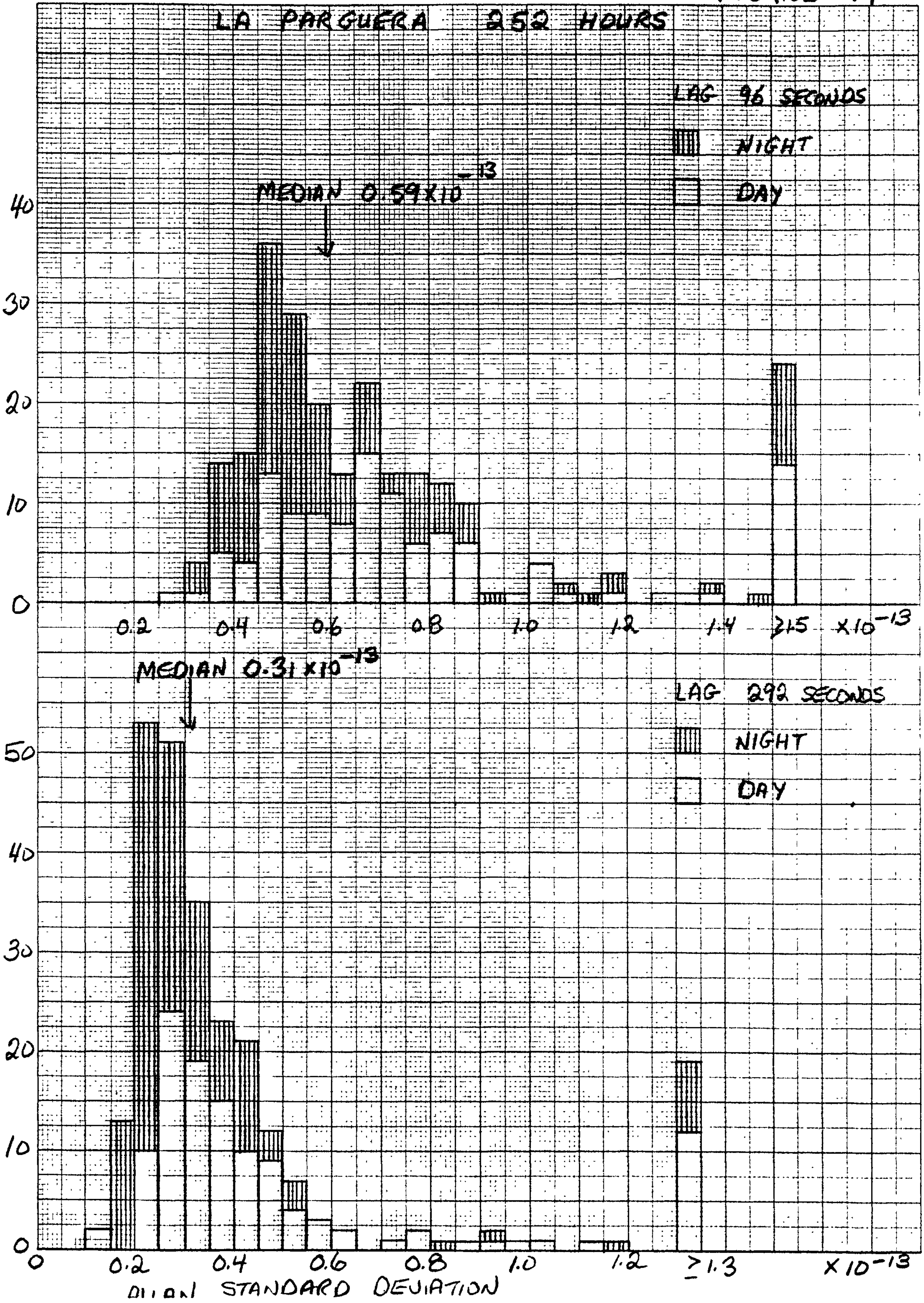
FIGURE 12

FIGURE 13



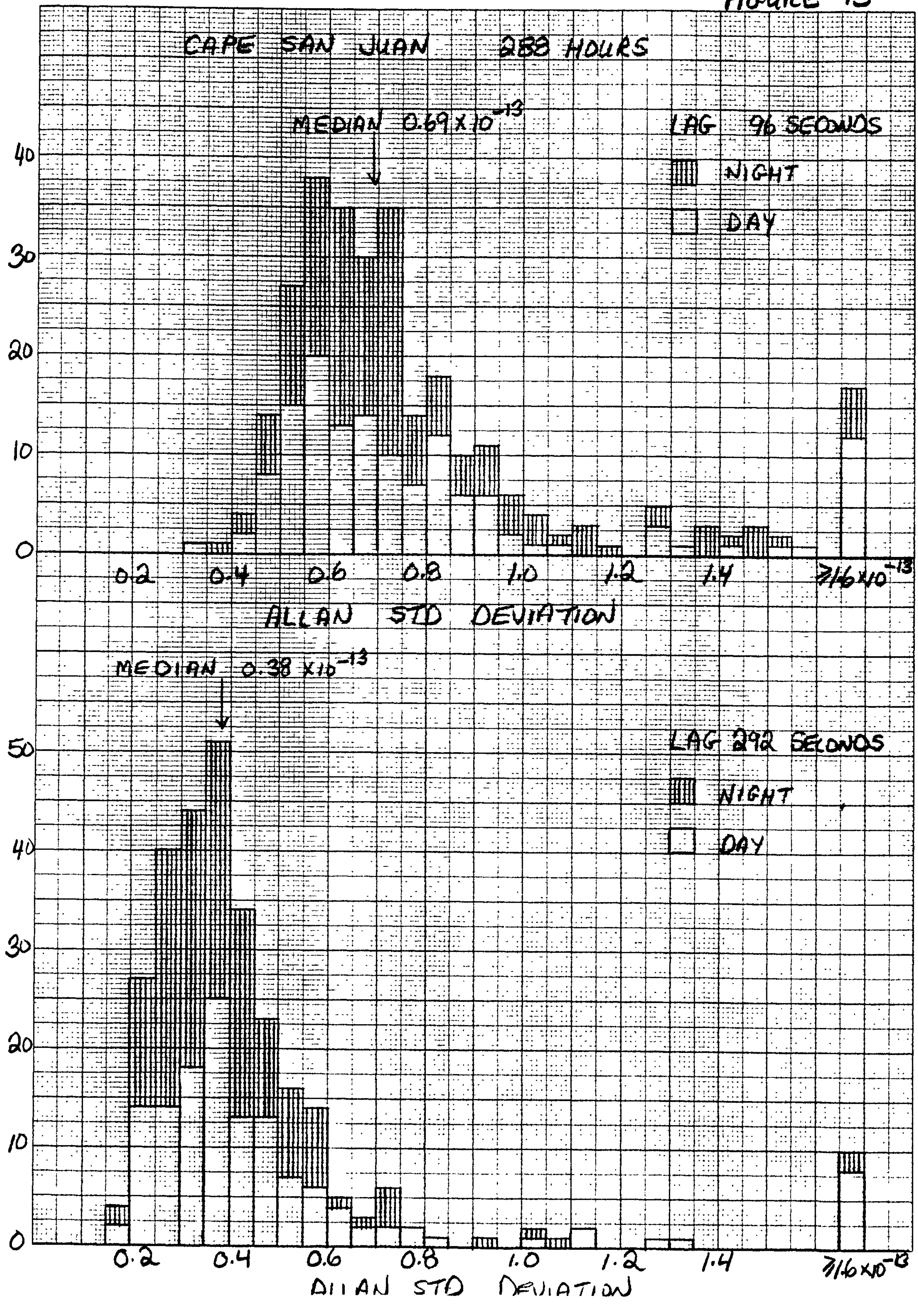
RAMEY 383 HOURS
LAG 96 SECONDS
NIGHT
DAY
MEDIAN 0.72x10^{-13}
0
10
20
30
40
0.2
0.4
0.6
0.8
1.0
1.2
1.4
≥ 1.6x10^{-13}
ALLAN STD DEVIATION
MEDIAN 0.39x10^{-13}
LAG 292 SECONDS
NIGHT
DAY
0
10
20
30
40
50
0.2
0.4
0.6
0.8
1.0
1.2
1.4
≥ 1.6x10^{-13}
ALLAN STANDARD DEVIATION

FIGURE 14



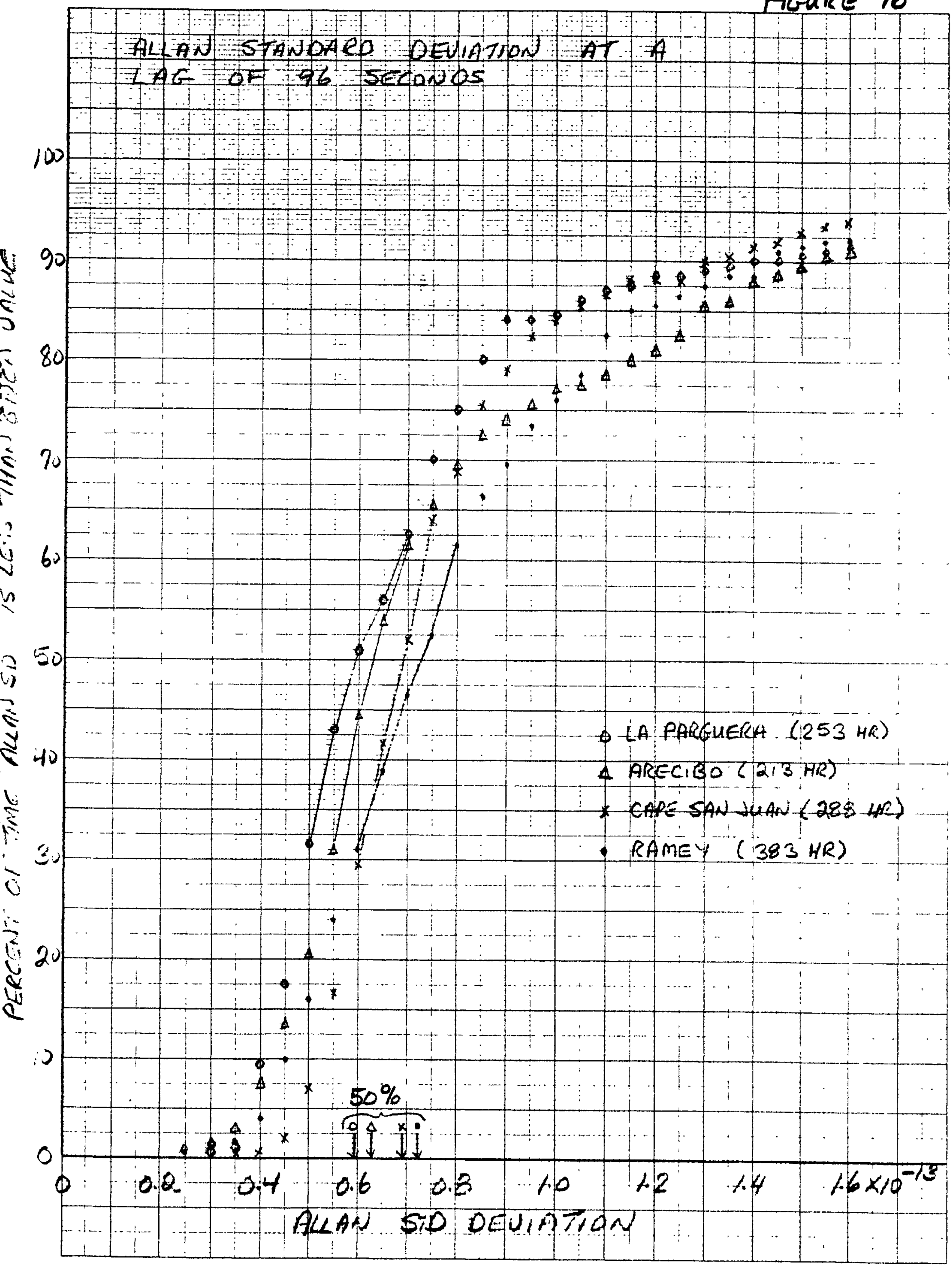
LA PARGUERA 252 HOURS
LAG 96 SECONDS
NIGHT
DAY
MEDIAN 0.59 X 10^{-13}
NUMBER OF HOURS
0
10
20
30
40
0.2
0.4
0.6
0.8
1.0
1.2
1.4
≥1.5
X 10^{-13}
MEDIAN 0.31 X 10^{-13}
LAG 292 SECONDS
NIGHT
DAY
0
10
20
30
40
50
0
0.2
0.4
0.6
0.8
1.0
1.2
≥1.3
X 10^{-13}
ALLAN STANDARD DEVIATION

FIGURE 15



CAPE SAN JUAN 288 HOURS
MEDIAN 0.69 X 10^-13
LAG 96 SECONDS
NIGHT
DAY
0
10
20
30
40
0.2
0.4
0.6
0.8
1.0
1.2
1.4
≥1.6 X 10^-13
ALLAN STD DEVIATION
MEDIAN 0.38 X 10^-13
LAG 292 SECONDS
NIGHT
DAY
0
10
20
30
40
50
0.2
0.4
0.6
0.8
1.0
1.2
1.4
≥1.6 X 10^-13
ALLAN STD DEVIATION

FIGURE 16



ALLAN STANDARD DEVIATION AT A LAG OF 96 SECONDS
100
90
80
70
60
50
40
30
20
0
50%
LA PARGUERA (253 HR)
ARECIBO (213 HR)
CAPE SAN JUAN (288 HR)
RAMEY (383 HR)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6 X10^-13
ALLAN STD DEVIATION

[redacted] OGAR [redacted] C • 2 [redacted] CLES
KEUFFEL & ESSER CO. MADE IN U.S.A.

[redacted] 46 7320 [redacted]

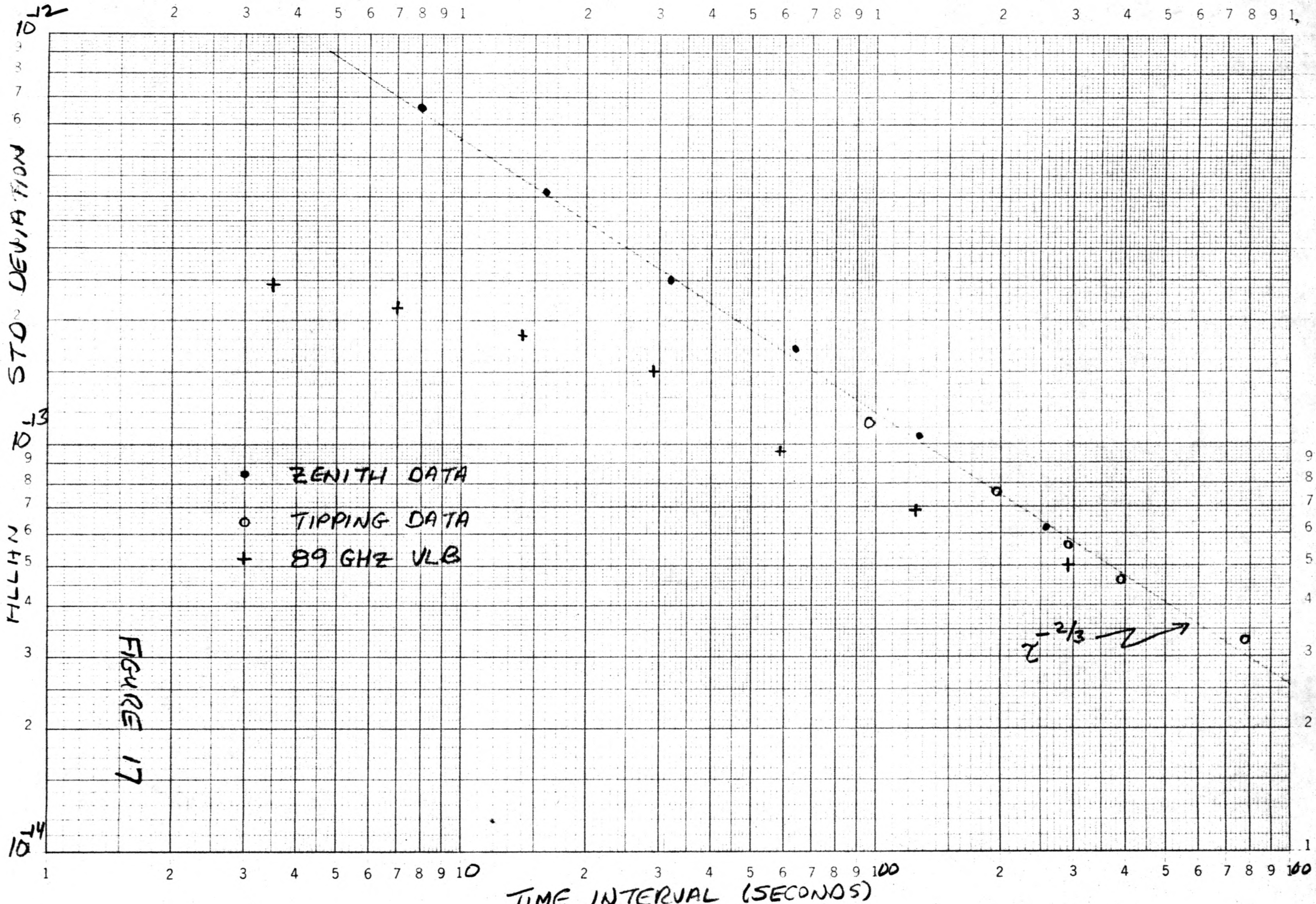


FIGURE 17