A STUDY OF THE WATER VAPOR FLUCTUATIONS AT SELECTED SITES IN HAWAII

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April 23, 1985

Summary

A water vapor radiometer was operated at five sites on the island of Hawaii during the period November 16, 1984 to January 25, 1985. The data were used to estimate the phase fluctuations that would have been experienced by a VLBA antenna operating at 22 GHz. All sites were found to be good, with the predicted single path fluctuation so small that the coherence over 500 seconds remains greater than 0.9 at least 60 percent of the time. All of the Hawaiian sites are better than the best site in Puerto Rico. The fluctuation data are not sufficient to enable sharp distinctions to be found among the Hawaiian sites. However, because of extinction, the relatively low total water vapor content found for the three high sites suggests that the antenna should be located at an elevation greater than 6000 feet.

Introduction. On the basis of coverage in the u-v plane the State of Hawaii is a critical location for an element of the Very Long Baseline Array. However, the state offers a wide range of sites, from near rain forest conditions to the superb optical/IR site at the peak of Mauna Kea. To get some guidance about the siting of the VLBA element, we undertook a series of observations with a water vapor radiometer, at selected sites on the island of Hawaii.

The water vapor radiometer used in the observations was the same unit used in the earlier experiments in Puerto Rico (VLB Array Memo 312). It was loaned to the NRAO by the Jet Propulsion Laboratory. In addition to the loan of the instrument, JPL personnel supervised the shipment of the instrument to and from Hawaii, and also moved the instrument from site to site in Hawaii.

Observations. The observations were made at five sites on the island of Hawaii.

Mauna Loa Observatory. This site is at 11 000 ft, on the northwest side of the mountain. We are grateful to the Director, Dr. Elmer Robinson, and to the National Oceanic and Atmospheric Administration for permission to use this site. The observations were made during the period November 16-December 4, 1984. Bruce Gary and Noboru Yamane of JPL installed the instrument at the Observatory, and brought it into operation. The subsequent care and feeding of the machine was undertaken by Dr. Charles Garcia, Superintendent of the High Altitude Observatory, and members of his observing group.

Hale Pohaku. This is the mid-level support facility of the Mauna Kea Observatory, operated by the Institute for Astronomy, University of Hawaii. It is of an elevation of 9200 feet. We are grateful to the Director, Dr. Donald Hall, for permission to use the site, and to the Superintendent, Mr. Tom Krieger, for his help in getting us set up. The observations were made during the period December 4-December 19, 1984, and were undertaken by Dr. Garcia and his observers.

Pohakuloa. The site was in the Endangered Species Project compound at the northeast edge of the Ahakuloa Military Camp, at an elevation of 6500 feet. The Project is operated by the Division of Forestry and Wildlife, Department of Land and Natural Resources, of the State of Hawaii. We thank the District Biologist, Mr. Ronald Bachman for permission to use the site, and for his help in getting us situated there. The observations were made during the period

December 19, 1984-January 3, 1985. The observations were made by Dr. Garcia's group, and by Dr. Duval of the Project Staff, who devoted considerable effort to the experiment when we ran into problems with our tapes.

Waimea. The observations were made at the Canada-France-Hawaii Telescope Corporation building in Waimea at an elevation of 2700 feet. We appreciate greatly the cooperation of the Director, Dr. G. Lelievre, and the Associate Director, Dr. R. McLaren, for allowing us to use their building. The observations were made between January 3 and January 17, 1985, by members of the CFH staff. In particular, we thank Dr. R. Link, who bore most of the burden.

Hilo. The observations were made at the Hilo airport, from the building occupied by the U.S. National Weather Service, and adjacent to the site from which the radiosondes are launched. The elevation of the site is essentially at sea level. The observations were made by Fred Soltis and Steve Guidero of JPL, for the period January 18-January 25, 1985.

The observing techniques were similar to, but not identical with those used in Puerto Rico. At each site we attempted to get 48 hours of data in which the radiometer continuously, performed tipping curves, yielding a measurement of the zenith temperatures every 100 seconds. These data were useful for studying the radiometer gain characteristics and the asymmetries in the water vapor distribution, since temperatures are measured at three zenith angles in addition to the zenith direction. The data (dubbed HITIP) are less satisfactory for specifying the site characteristics since they do not yield estimates directly either of the rms in phase or the coherence, though they do give estimates of the Allan standard deviation.

The rest of the time at each site was spent in the mode in which 88 seconds of each 10 minutes was spent doing a tipping curve, to provide radiometer calibration, and the rest of the time was used to obtain 128 measurements, with integration time 4 seconds, of the zenith brightness temperature. This mode (HILOS) was similar to that used in Puerto Rico, except that the frequency of the calibration was increased by a factor of two.

Our intention was to get one week of data for Hilo, for comparison with radiosonde data, and spend about two weeks at each of the other sites. Unfortunately, because of some problems at Hale Pohaku and Pohakuloa, our data have for these sites is somewhat smaller than planned.

Analysis

The gain of the system is calibrated from the tipping curve. 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 algorithms provided by Bruce Gary of JPL.

Let the antenna temperatures measured at 22.235 GHz and 31.4 GHz be T_1 and T_2, respectively. Then define T_1', T_2' by

$$T_1' = T_1 + {\frac{T_2-3}{21.2}}^{2} \quad , \quad T_2' = T_2 + {\frac{T_2-3}{21.2}}^{2} \quad .$$

From extensive calibrations at low altitude sites, B. Gary finds that the amount of precipitable water vapor, in gm cm^{-2} is, for the Hilo data,

$$V = -0.108 + 0.0656 * T_1' - 0.0335 * T_2' \ .$$

For high altitude sites the calibration is less certain because no work has been done before with these devices at altitude. By integration of model atmospheres Gary estimates that for the Mauna Loa observations

$$V = - 0.069 + 0.0436 * T_1' - 0.0222 * T_2'$$

The conversion relationships for sites at intermediate altitudes were obtained by interpolation between the relationships for Hilo and Mauna Loa. Finally, the inferred path delay is taken to be

$$L = 6.5 * V \text{ cm} .$$

The accuracy with which the path delay is retrieved from the measured antenna temperatures is difficult to estimate, and the values for the higher elevations may be particularly uncertain. However, the relative error between two measurements separated by only a few minutes will have much smaller uncertainty and will be limited by the noise and instability of the receiver.

As a test of the receiver performance, I have used data from Mauna Loa on November 17, when the water vapor content was low and apparently stable. Figure 1 shows the distribution of the observed antenna temperatures at the two frequencies for a period of 10 minutes. The rms values are a factor of about 2 higher than expected from the system noise, perhaps because there is a small drift with time. Figure 2 shows the variation in path length observed during six 10-minute scans. The mean value of the path length has been removed from each scan; the residuals are shown on the plot. The rms of the residuals is 0.17 radians at the nominal frequency of 22.2 GHz, and the distribution is nearly guassian, as is seen by comparison with the gaussian curve. If it is assumed that indeed the atmosphere was quite stable during this period, then the value $\Delta L \sim 0.17$ radian can be taken as a measure of the instrumental uncertainty.

The data from each site were reduced to yield estimates of the phase rms, the coherence, and the Allan standard deviation. All estimates assumed a frequency of 22.235 GHz. For the days in which only tipping observations were made (HITIP), only the Allan standard deviations could be calculated directly, and values of the coherence were inferred assuming as an approximation the case for white frequency noise (Rogers and Moran 1981). In the case where most of the data were taken in the zenith direction (HILOS) the rms, coherence and Allan standard deviation are all calculated directly. For the calculation of rms and coherence a linear phase drift is first removed.

Because the radiometer was essentially unattended, water could accumulate on the radome and would stay until it evaporated. In such cases the antenna temperatures are unreliable. I have therefore taken all cases where the antenna temperature at 31.4 GHz exceeded 70 K and recorded those hours as time lost. Because the observing periods at each site are so short, the fraction of time lost is highly variable, and may introduce a distortion in the statistics. I will show statistics both for total time, including time lost, and for only those times for which useable data were obtained.

Results. Figure 3 shows the fraction of all zenith data (HILOS) having an rms in phase averaged over 100 seconds less than a given value. For small values of rms the sites are ranked according to elevation, with Mauna Loa the best. However, all sites are good, with the rms less than 0.5 radians three-fourths of the time.

A more demanding test is the behavior over 500 seconds. Figure 4 shows the fraction of the time the coherence is greater than a given value, for all data (both HITIP and HILOS). Again all sites are good, with the coherence greater than 0.9 at least 70 percent of the time, except for Hilo.

Figures 5 and 6 show the fraction of the time that the Allan standard deviation is less than a given value, for lags of 100 seconds and 500 seconds respectively. In this case only the useable data from HILOS are HITIP are included, although the number of hours lost is noted on the plots. For reference, the similar quantities for Ramey, Puerto Rico are shown in Figure 5. All Hawaiian sites are much better. Also for reference the vertical line marked CO shows the value for which, at lag T and frequency ω, the Allan standard deviation $\sigma_y(T)$ is

$$\omega \; \sigma y(T) \; T \sim 1$$

which is a rule-of-thumb for significant loss (Rogers and Moran 1981). In the case of these observations, where

$$\sigma_y(T) \propto T^{-2/3}$$

this criterion corresponds to a loss of coherence of about 10 percent.

The most striking difference among the sites is in the total water vapor content, shown in Figure 7. These results must be treated with some caution, because the conversion algorithms for the high altitude sites are still being refined. However, it is clear that, as expected, the sites above 6000 ft elevation are much more suitable for observations above 20 GHz than are the two lower sites. As an example, a crude estimate using the curves in Waters (1976) suggests that the additional 2 cm of water at Hilo compared to Mauna Loa will cause an additional opacity of 0.5 dB at both 22.235 and 86 GHz.

Conclusion. The island of Hawaii appears to be a very promising site for a VLBA antenna. Because of the very limited time of observation, it is difficult on the basis of the path fluctuation data alone to specify a minimum elevation below which we should not site the antenna. However, consideration of the total water vapor content argues that we should seriously consider sites only above 6000 feet in elevation.

Acknowledgement. It is a pleasure to thank JPL for the generous loan of the water vapor radiometer, and Nob Yamane and the other JPL personnel for their considerable efforts on behalf of this experiment. Bruce Gary of JPL did all of the programming of the instrument, and provided invaluable advice about the interpretation of the data.

References

Rogers, A.E.E. and Moran, J. M., Jr. 1981, IEEE Trans. Instrum. Meas. Vol. IM-30, pp 283-286.

Waters, J. W. 1976, in Methods of Experimental Physics, M. L. Meeks ed., Vol. 12, Part B, pp. 142-176.

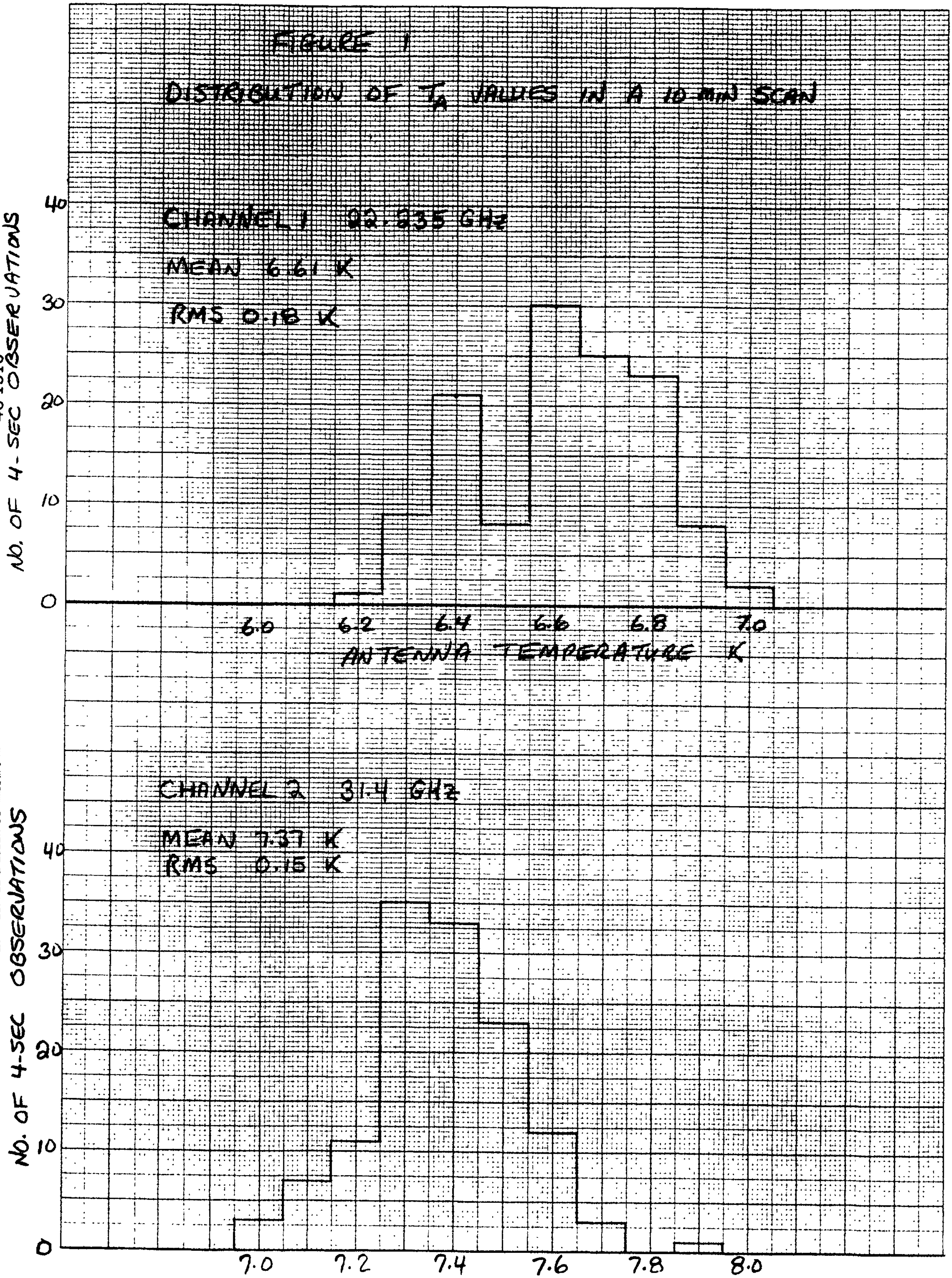


FIGURE 1
DISTRIBUTION OF T_A VALUES IN A 10-MIN SCAN

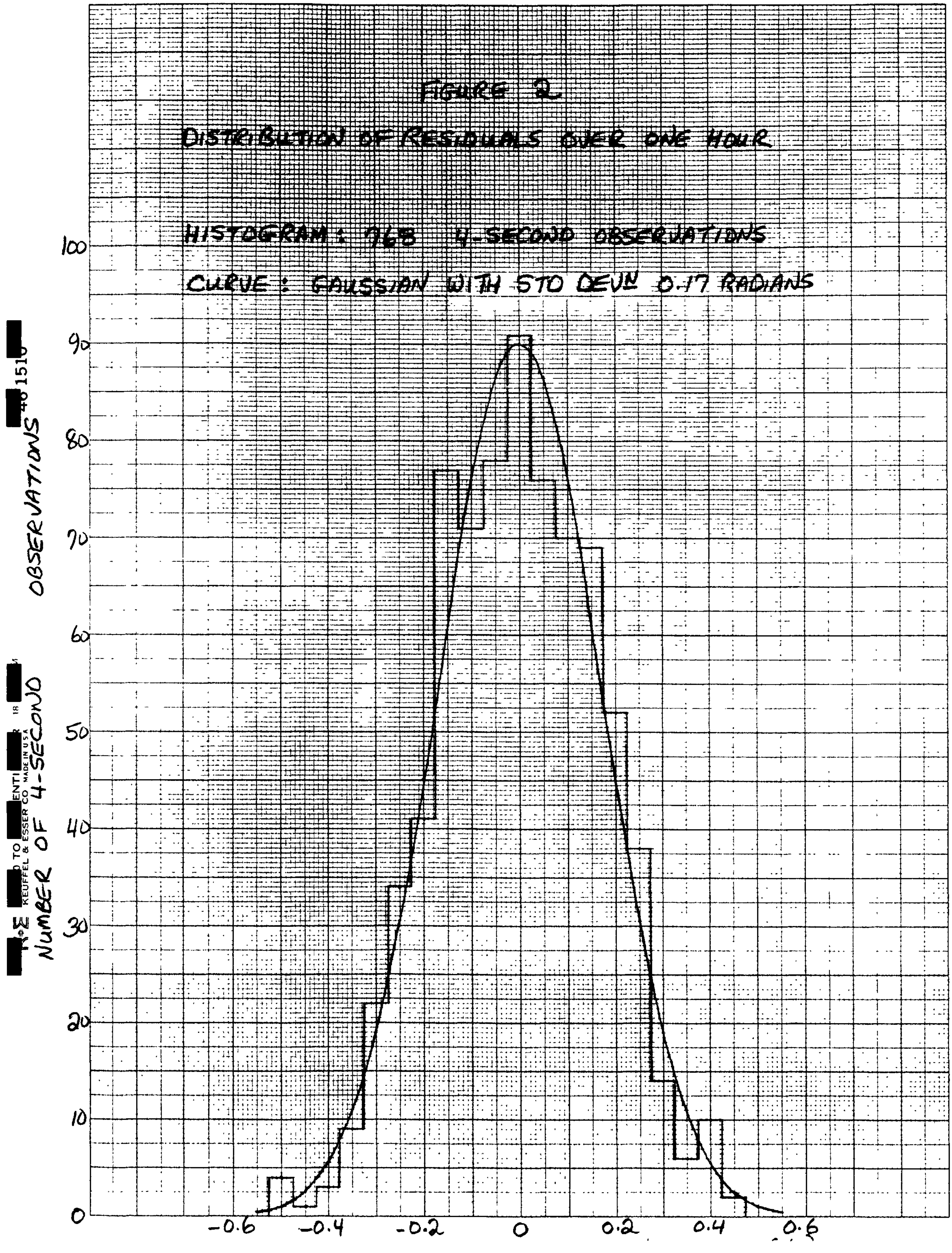
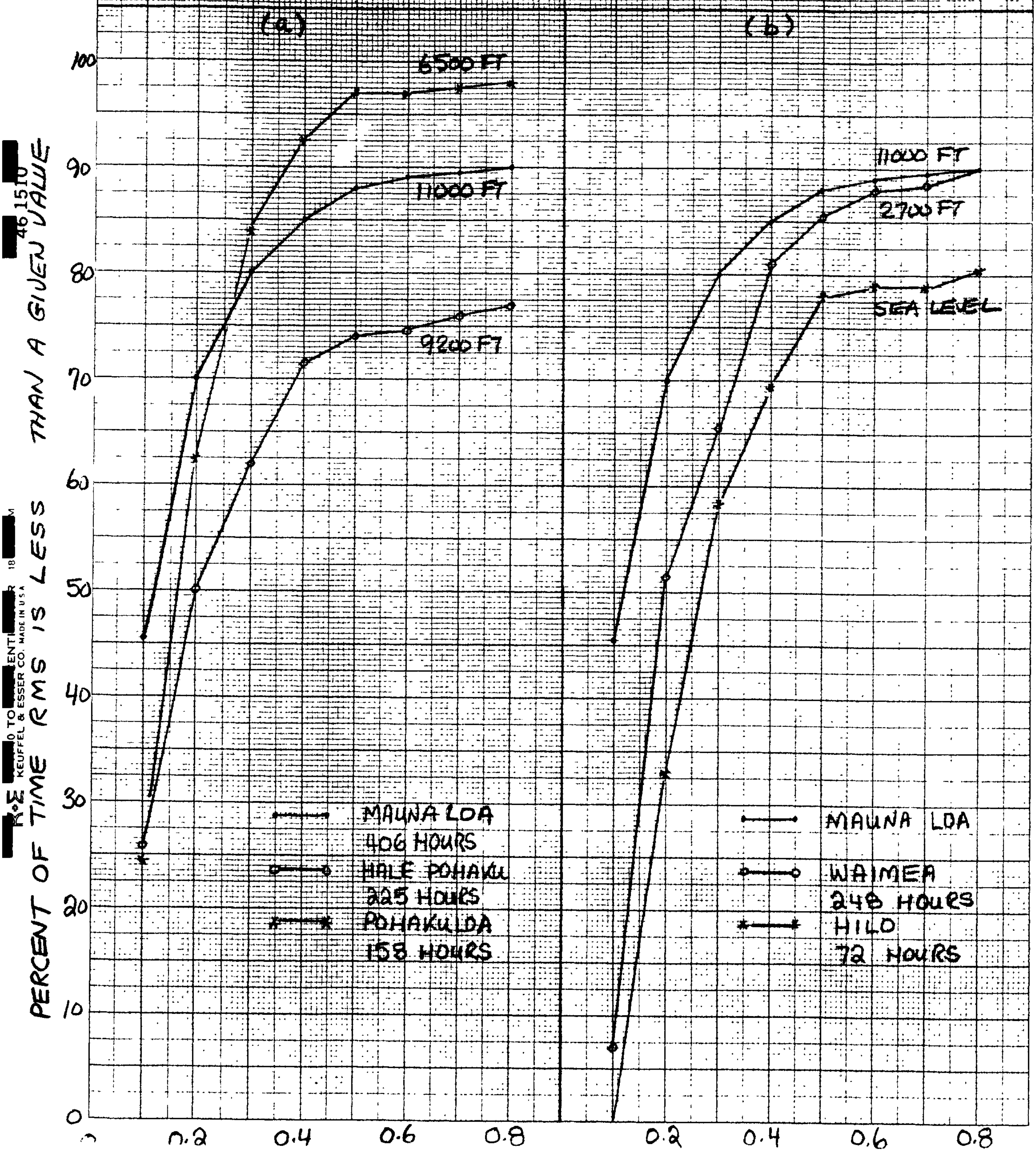


FIGURE 2
DISTRIBUTION OF RESIDUALS OVER ONE HOUR
HISTOGRAM: 768 4-SECOND OBSERVATIONS
CURVE: GAUSSIAN WITH STD DEVN 0.17 RADIANS
NUMBER OF 4-SECOND OBSERVATIONS
0
10
20
30
40
50
60
70
80
90
100
-0.6
-0.4
-0.2
0
0.2
0.4
0.6

FIGURE 3

RMS OF 22 GHz PHASE - 100 SEC AVERAGES



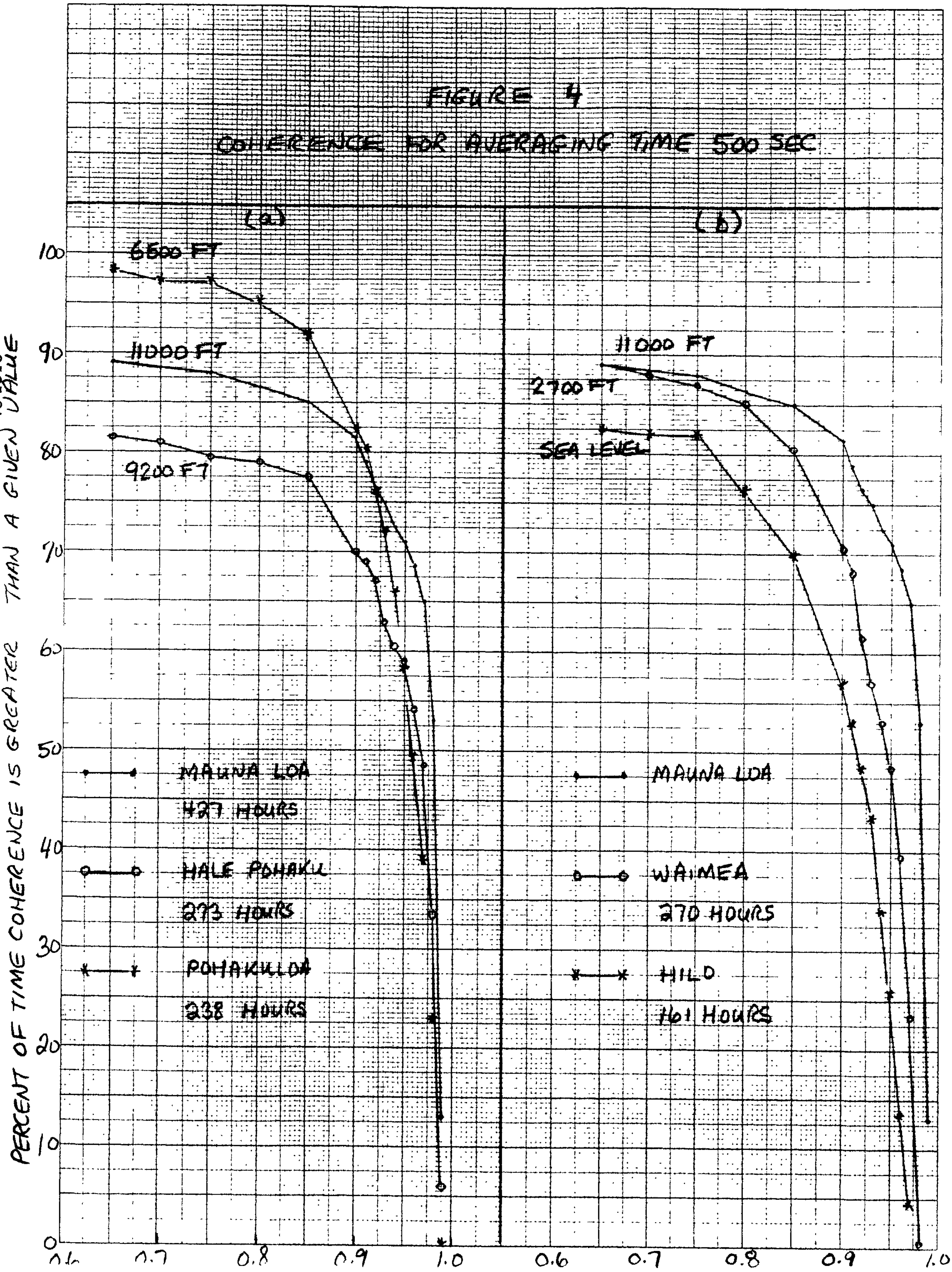
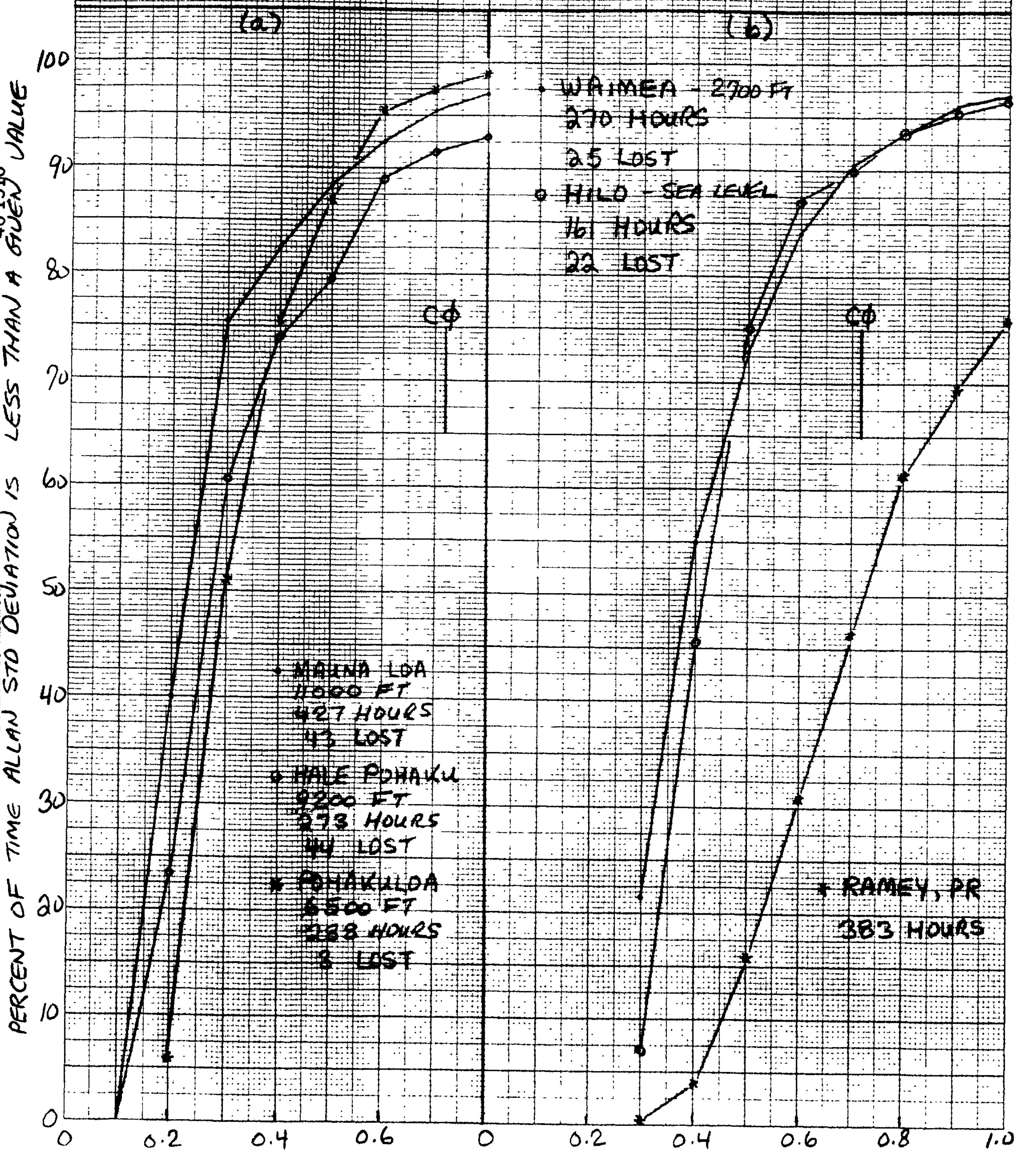


FIGURE 4
COHERENCE FOR AVERAGING TIME 500 SEC
(a)
(b)
6500 FT
11000 FT
9200 FT
11000 FT
2700 FT
SEA LEVEL
PERCENT OF TIME COHERENCE IS GREATER THAN A GIVEN VALUE
MAUNA LOA
427 HOURS
HALE POHAKU
273 HOURS
POHAKULOA
238 HOURS
MAUNA LOA
WAIMEA
270 HOURS
HILO
161 HOURS
0
10
20
30
40
50
60
70
80
90
100
0.7
0.8
0.9
1.0
0.6
0.7
0.8
0.9
1.0

FIGURE 5

ALLAN STD DEVIATION - 100 SEC LAG



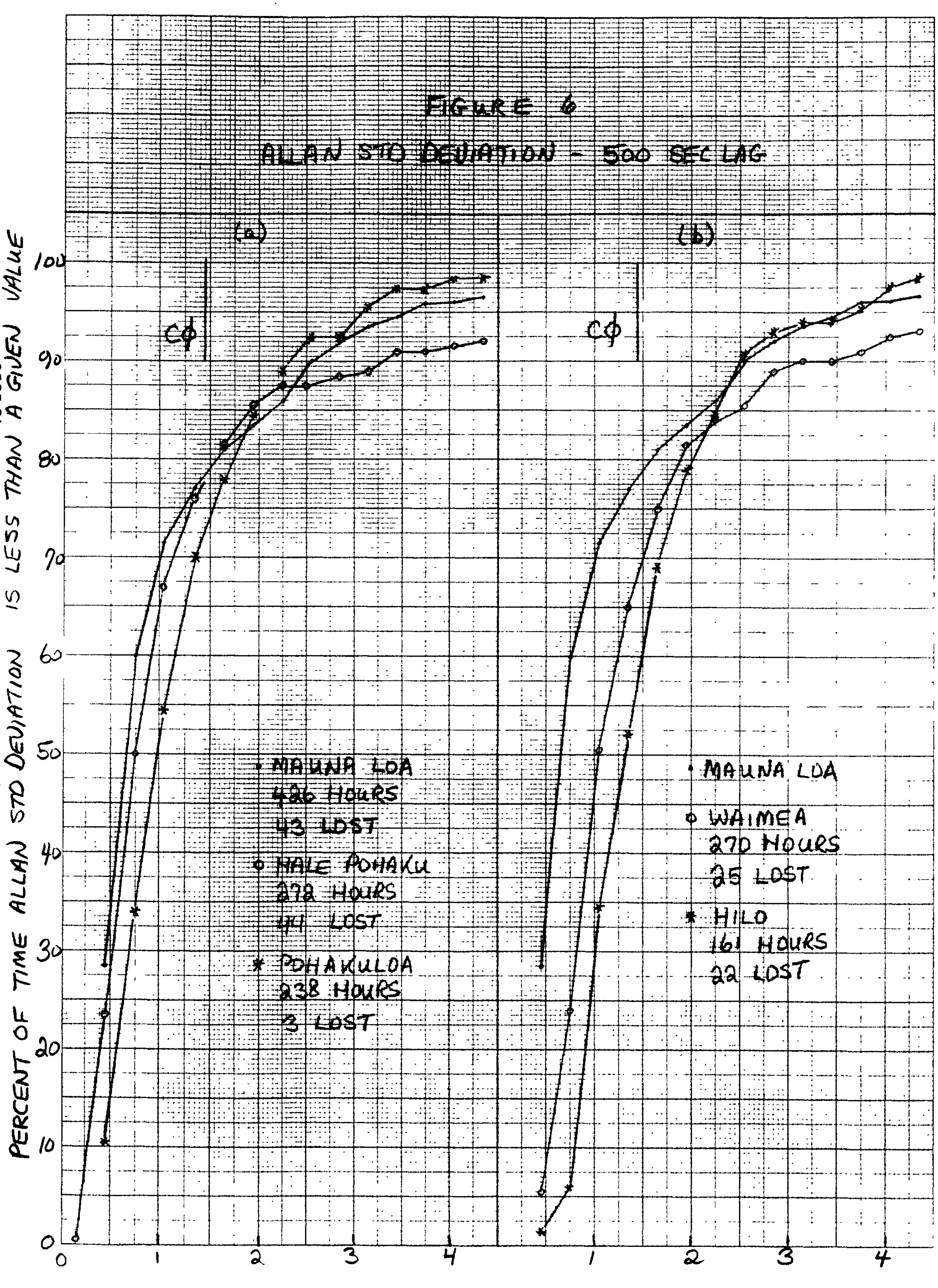


FIGURE 6
ALLAN STD DEVIATION - 500 SEC LAG
(a)
(b)
CΦ
CΦ
PERCENT OF TIME ALLAN STD DEVIATION IS LESS THAN A GIVEN VALUE
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
1
2
3
4
• MAUNA LOA
426 HOURS
43 LOST
○ HALE POHAKU
272 HOURS
44 LOST
* POHAKULOA
238 HOURS
3 LOST
• MAUNA LOA
○ WAIMEA
270 HOURS
25 LOST
* HILO
161 HOURS
22 LOST

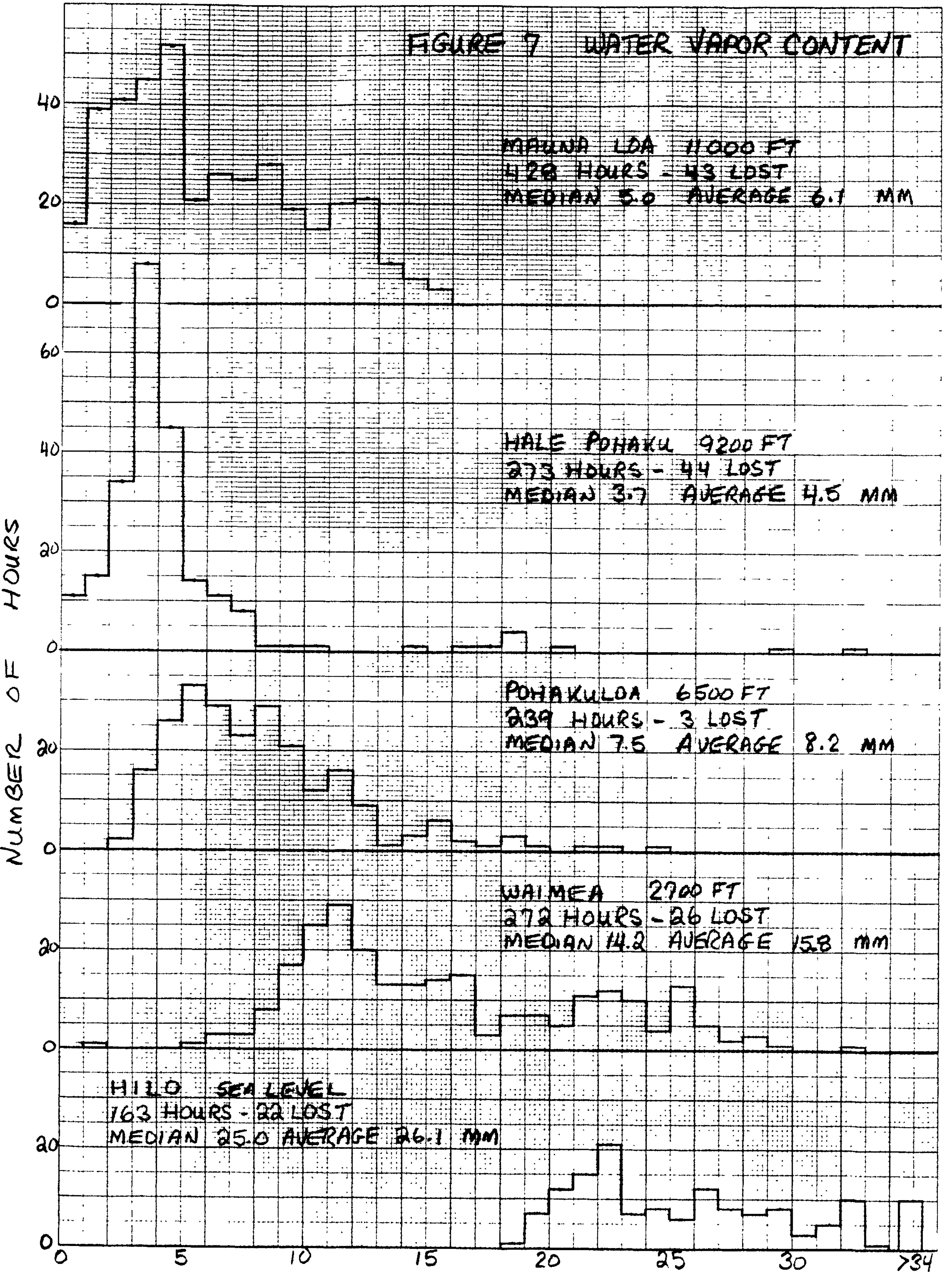


FIGURE 7 WATER VAPOR CONTENT
MAUNA LOA 11000 FT
428 HOURS - 43 LOST
MEDIAN 5.0 AVERAGE 6.1 MM
HALE POHAKU 9200 FT
273 HOURS - 44 LOST
MEDIAN 3.7 AVERAGE 4.5 MM
POHAKULOA 6500 FT
239 HOURS - 3 LOST
MEDIAN 7.5 AVERAGE 8.2 MM
WAIMEA 2700 FT
272 HOURS - 26 LOST
MEDIAN 14.2 AVERAGE 15.8 mm
HILO SEA LEVEL
163 HOURS - 22 LOST
MEDIAN 25.0 AVERAGE 26.1 MM
NUMBER OF HOURS
40
20
0
60
40
20
0
20
0
20
0
20
0
0
5
10
15
20
25
30
>34