MILLIMETER ARRAY
MEMO NO. 79

A Summary of the Data Obtained During the mmA Site Survey

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Abstract: A radiometer was developed in 1986 to test potential sites for the proposed Millimeter Array. The atmospheric transparency and the stability at three sites have now been evaluated using several of these devices. This report presents a summary of the data obtained.

Introduction: After the millimeter array concept had been explored and discussed with the scientific community, a project group was formed to develop the concept into a proposal which could be forwarded to the National Science Foundation. One of the critical questions concerned the possible site for the array. It was soon realized that it would be necessary to make accurate measurements of the atmospheric conditions at prospective sites in order to properly evaluate their potential for the mmA.

About ten years ago John Payne developed a radiometer operating at 225 GHz with the intention of using it to monitor the sky transparency at Kitt Peak, as a guide to observers at the 12 meter telescope. This design was modified and further developed in Charlottesville by S. Weinreb and Z-Y Liu, and four of the devices were built. After two years of observations (1986-1988), the devices were modified and upgraded by G. Petencin, and returned to service in the fall of 1989. Data are available for the Magdalena Mountains (also called South Baldy) and the VLA Site from the earlier period, for the Magdalena site and Mauna Kea for 1989-1991, and for Springerville for 1990-1991.

This report will present the data in sufficient detail that interested readers will be able to develop a good feel for the uncertainties involved in the measurements. A few graphs will be used to summarize the data, but the comparative analysis will be given elsewhere. Some studies based on the earlier data have been given by McKinnon (1987), Hogg, Owen, and McKinnon (1988), Owen and Hogg (1990), Schwab, Hogg, and Owen (1990), and Owen (1991).

The Instrument: The detailed technical description of the basic radiometer system is given by Liu (1987), and a more general discussion of the instrument, operation, and tipping-scan data analysis is found in McKinnon (1987). Briefly, the receiver uses a room temperature Schottky mixer operating at 225 GHz as the primary element. The LO is derived from a 75 GHz Gunn using a tripler. The rf and if components are maintained in a small temperature-controlled box. The signal is received by a small primary mirror located outside the box, and is directed into the mixer through a chopper wheel by means of a secondary mirror. The primary mirror can be rotated through 360 degrees in elevation, enabling the sampling of the atmosphere over a wide range of zenith angle. The chopper wheel alternates the receiver input between the sky, a load at 45 C, and a load at 65 C. The two stable temperature loads permit internal calibration of the system gain.

As originally designed the units operated from line power, and required periodic visits to retrieve the data stored on a local disk. During the course of the site tests extensive developments were made by G. Petencin, to the point that the Springerville unit operated remotely on solar power and the data were retrieved by interrogation using a cellular phone.

During the first two years the units were used only to estimate the zenith opacity at 225 GHz using a tipping technique which measured the sky temperature at a series of zenith angles. During the later trials the units also measured the atmospheric stability by recording the sky temperature fluctuations at the zenith over the course of a hour, such samples being taken every fifth hour.

Anemometers were installed at the Magdalena Mountain and Springerville sites during the course of the later trials, thus giving a limited sampling of the wind statistics for these places.

Operations and Data Archival: The operations and data processing for the entire site survey was under the supervision of F. Owen. During the first period, from November 1986 to June 1988 the operations and initial data retrieval and analysis were conducted by M. McKinnon (McKinnon 1987). For the second period the systems were extensively upgraded by G. Petencin, who also looked after their operations. The introduction of the sky fluctuation measurements, and the data retrieval, was done by a number of students working for F. Owen. The archiving of the data was done primarily by Theresa Calavini.

It is important to note that the observations at the Magdalena Mountains and at Springerville were made near the center of the proposed array site and should therefore be representative of the conditions that the array might operate under. In contrast, the observations at Mauna Kea were conducted in cooperation with the Smithsonian Astrophysical Observatory and the California Institute of Technology at the CSO site in the "millimeter valley." At 4080 m, this site is 355 m higher than the potential array site, which lies near the VLBA site. If the scale height of water vapor is 2000 m at high altitudes on Mauna Kea, the opacity (for small values) at the potential array site would be about 20 percent greater than the value measured at the summit. The effect on the radio path length inferred may be greater than this by another factor which is difficult to estimate but which also depends on opacity. The total water vapor may be systematically underestimated, since the opacity caused by a given amount of water vapor will be less at the higher altitude because of the smaller pressure broadening.

The Zenith Opacity Data: The measurement of the zenith opacity consisted of a series of 11 observations taken over zenith angles between 7 and 70 degrees corresponding to airmasses between one and three. Here the opacity tau is defined so that the fractional atmospheric attenuation is given by exp(-A*tau), where A is the airmass normalized to unity at the zenith. The details of the algorithms used for the extraction of tau from the tipping scans are given by McKinnon (1987).

During the first period a tipping measurement was made every ten minutes, twenty-four hours per day. The tipping runs for each hour were reduced to give the opacity, and the median value of the six runs was defined to be the opacity value characteristic of that hour. In the second period the tipping runs were interrupted every fifth hour in order to make a stability run, as will be described in the next section.

In general the data required little editing. There were of course times when the tipper was broken. Occasionally, perhaps following a storm, the tipper gave unreasonably small values for the zenith opacity, indicating that there was little change in sky temperature,* presumably because there was a layer of snow or moisture on the primary mirror. Such times were assigned either to the category "broken" or to the category "high opacity" if the occurrence was short-lived and was surrounded by valid measurements showing high opacity.

All of the hourly medians for the three sites sampled in the second period are given in Figure 1. A striking feature of the continental sites is the almost periodic fluctuation of the opacity on a time scale of a few days. On each site there are long periods during which the zenith opacity at 225 GHz is low (i.e., below 0.1). It is evident that the number of such periods is greater for the Magdalena Mountains than it is at the Springerville site. The data for Mauna Kea show less regular structure, and the site has more periods of low opacity than either of the continental sites.

In order to make quantitative evaluations of the sites, the data have been analyzed to show the frequency of occurrence of a given value of the zenith opacity. Figure 2 gives a summary of all such data for the three sites from the second period, with the data grouped by three months, for brevity. Also shown for completeness are the data from the Magdalena Mountains for the first period.

An abstract of the data from the last period is given in Figure 3. Displayed for each of the three sites are contours giving the fraction of the time the opacity lies below certain selected values, as a function of time. All sites have significant amounts of time during which the zenith opacity at 225 GHz lies below 0.1, though Mauna Kea has the most such time and Springerville the least.

Figure 4 compares the opacities that obtain for 25 percent of the time and for 50 percent of the time at the three sites.

The Zenith Fluctuation Data: Every fifth hour the 225 GHz radiometers were directed towards the zenith, and the total power was sampled every 3.51 seconds. The fluctuations thus observed are characterized by the Allan standard deviation (ASD), calculated for lags between 3.5 sec and 898 sec, in steps of a factor of two.

Included in the Allan standard deviation are components of the variation due to sky fluctuation and due to radiometer instability. To separate these effects, every fifth fluctuation run was taken with the primary mirror directed toward the ground, rather than toward the zenith. These reference measurements were plotted as a function of time, and a value for the instrumental fluctuation at each lag was estimated from the lower envelope of the plotted values. This procedure probably results in a slight overestimate of the instrumental contribution, since the total system temperature is higher when pointed at the ground, and indeed the resultant Allan variance is occasionally negative, especially for small values of lag where the instrumental term is a much greater fraction of the observed fluctuations. However, for the larger lag values the procedure appears to be satisfactory.

Intuitively, it is clear that the lower the fluctuations the better the site will be for interferometry. However, to make the distinction quantitative is a difficult task, because it involves knowledge of the wind and a model of the atmosphere. These considerations are reviewed and a preliminary analysis of selected fluctuation data is given in the recent report by M. Holdaway (1991).

The fluctuation data are summarized in Figure 5, which shows for each site the fraction of the time that the ASD lies below a given value. For brevity, the data are grouped into intervals of three months. The quality of the data in general was high and needed little editing. However, the data for the last ten weeks at Mauna Kea are inconsistent with earlier observations, and perhaps should be discarded even though the radiometer was apparently working. Note that the negative values are included in the frequency-of-occurrence statistics, since these are probably times when the ASD is the smallest, even though the precise value was not accurately measured.

As Holdaway (1991) notes, a crucial parameter of the fluctuation study is the dependency of the magnitude of the ASD on the value of the lag. To illustrate the data, we have grouped the ASD values for the Magdalena Mountains by the value of the ASD at a lag of 56 seconds. Figure 6 shows the value of the ASD as a function of lag for three groups of data. Also shown is plus and minus one standard deviation in the mean. The groups have $0.04 < ASD56 < 0.08$; $0.16 < ASD56 < 0.20$; and $0.28 < ASD56 < 0.32$. The points at lags of 3.5 sec and, to a lesser extent at 7.0 sec are seriously influenced by the instrumental term. The points at a lag of 898 sec are poorly determined, since the lag is one-fourth of the total duration of the observation. With these caveats, the spectrum of the ASD appears to be similar over the range of ASD(56 sec) chosen for the analysis. The spectrum is somewhat steeper than the value 0.33 expected for very long lags, but is consistent with a random power spectrum in the phase fluctuation (Holdaway 1991).

It is also of interest to examine the spectra of the three sites, to see if the vastly differing terrain has had an influence on the atmospheric structure. Figure 7 compares the spectra for two different selections of the ASD at 56 seconds. The spectra for the three sites appear to be similar at the times of the large fluctuations, but the spectrum of the fluctuations at Springerville is steeper at the longer lags during periods of low fluctuation.

In order to compare the nature of the fluctuations at the three sites, we show in Figure 8 the fraction of the time that the fluctuations at the sites are less than two selected values, as a function of time. Very crudely, the ASD(56 sec) of 0.04 corresponds to a phase fluctuation on the longer baselines of the mmA of 8 degrees, and the ASD(56) of 0.20 to 40 degrees. In general, Mauna Kea has the greatest fraction of the time with low fluctuations, and Springerville has the lowest incidence of low fluctuations.

Finally, it is of interest to explore the atmospheric transparency during times of good phase stability. Figure 9 shows the distribution of the zenith opacities for all times at the three sites for which the Allan standard deviation at 56 seconds was less than 0.1 K. As might be expected, such periods are characterized by superior transparency. It should be noted that the observations at Mauna Kea and the Magdalena Mtns spanned nearly two years, while only one year's worth of data were obtained at Springerville.

The Wind Data: Wind data were recorded for possible use in the interpretation of the fluctuation data. However, since they may also be of value in the design of the telescope as well as in the planning of operations, we present a summary of the data for the Magdalena Mountains and for Springerville. No data were obtained for Mauna Kea.

Figure 10 gives the frequency of occurrence of wind values for each site. The data have been grouped into intervals of three months. The winds at the Magdalena site are often higher than at the Springerville site, and occasionally exceeded 70 mph. The winds at Springerville are relatively light.

Acknowledgement: The program of site evaluation was developed and led by Frazer Owen. He performed the initial calibration of the devices as they were received from the Central Development Lab, and supervised the surveys conducted at the VLA and Magdalena Mountains between 1986 and 1988. He then evaluated the performance of the devices, and, with G Petencin, undertook a program of rebuilding and upgrade which materially improved the reliability and stability of the systems. Finally, he supervised the survey from 1989 to 1991, the results of which are compiled in this report.

References

Hogg, D. E., Owen, F. N., and McKinnon, M. 1988, MMA Memo No. 45

Holdaway, M. A. 1991, MMA Memo No. 68

Liu, Z-Y. 1987, MMA Memo No. 41 (EDIR No. 271).

McKinnon, M. 1987, MMA Memo No. 40

Owen, F. N. 1991, in Radio Interferometry: Theory, Techniques, and Applications, ed. T. J. Cornwell and R. A. Perley, IAU Colloq. No. 151, p 124.

Owen, F. N. and Hogg, D. E. 1990, in URSI/IAU Symp. on Radio Astronomical Seeing, ed. Wang Shoguan and Yang Ti-Pei, Chinese Acad. Sci., Beijing, p 42.

Schwab, F. R., Hogg, D. E., and Owen, F. N. 1990, ibid, p 116.

Figure Captions

Figure 1. Observations of the zenith opacity at 225 GHz as a function of time. Plotted are all valid measurements of the hourly median which were obtained during the survey 1989-1991.
(a) Magdalena Mountains (South Baldy). (b) Mauna Kea.
(c) Springerville.

Figure 2. Frequency of occurrence of opacity values, averaged over intervals of three months. Values obtained at the Magdalena Mountain site between 1986 and 1988 are also shown.
(a) Magdalena Mountains. (b) Mauna Kea. (c) Springerville.

Figure 3. Frequency of occurrence of selected values of zenith opacity as a function of the time of year.
(a) Magdalena Mountains. (b) Mauna Kea. (c) Springerville.

Figure 4. A comparison of opacity values at the three sites as a function of the time of year.
(a) Opacities are lower than indicated value 25 percent of the time. (b) Opacities are lower than indicated value half the time.

Figure 5. The fraction of the time the Allan standard deviation (ASD) is less than a given value. The data have been grouped in intervals of three months.
(a) Magdalena Mountains. (b) Mauna Kea. (c) Springerville.

Figure 6. A comparison of the variation of the Allan standard deviation (ASD) with lag. The data have been selected for three ranges of the ASD at a lag of 56 seconds. Only data from the Magdalena Mountains taken when the zenith opacity was less than 0.2 are included in this figure.

Figure 7. The spectrum of the Allan standard deviation at the three survey sites, for two ranges of the ASD at 56 seconds.

Figure 8. A comparison of the atmospheric fluctuations at three sites. The lines show the fraction of the time the Allan standard deviation is less than a given value.
Upper: ASD at 56 seconds less than or equal to 0.20 K.
Lower: ASD at 56 seconds less than or equal to 0.07 K.

Figure 9. The distribution of values of the zenith opacity during times of low fluctuations for the three sites.

Figure 10. The wind at the two continental sites. Shown is the fraction of the time the wind speed is less than a given value, for data grouped in intervals of three months.
(a) Magdalena Mountains. (b) Springerville.

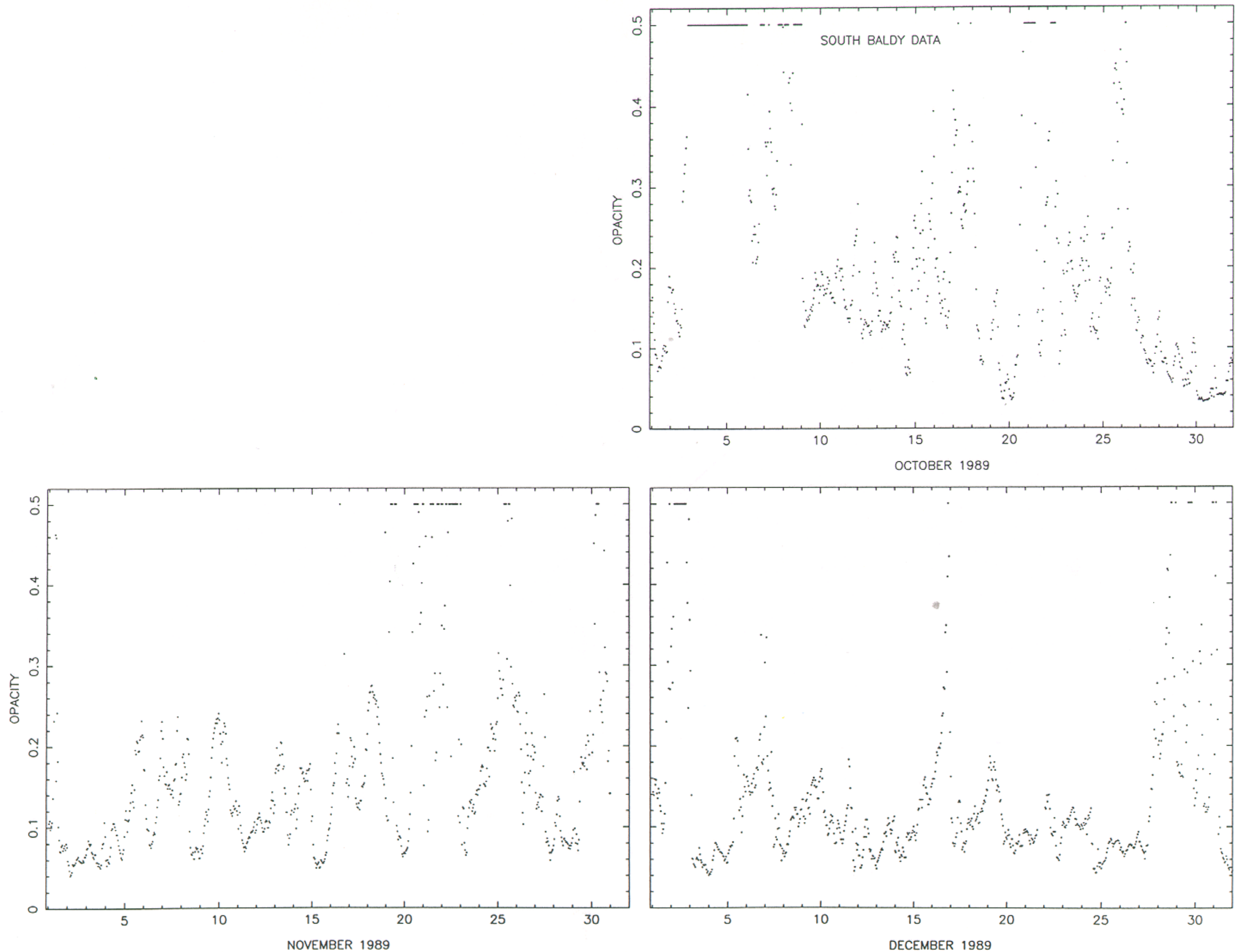

SOUTH BALDY DATA
OPACITY
0
0.1
0.2
0.3
0.4
0.5
5
10
15
20
25
30
OCTOBER 1989
NOVEMBER 1989
DECEMBER 1989

Figure 1a

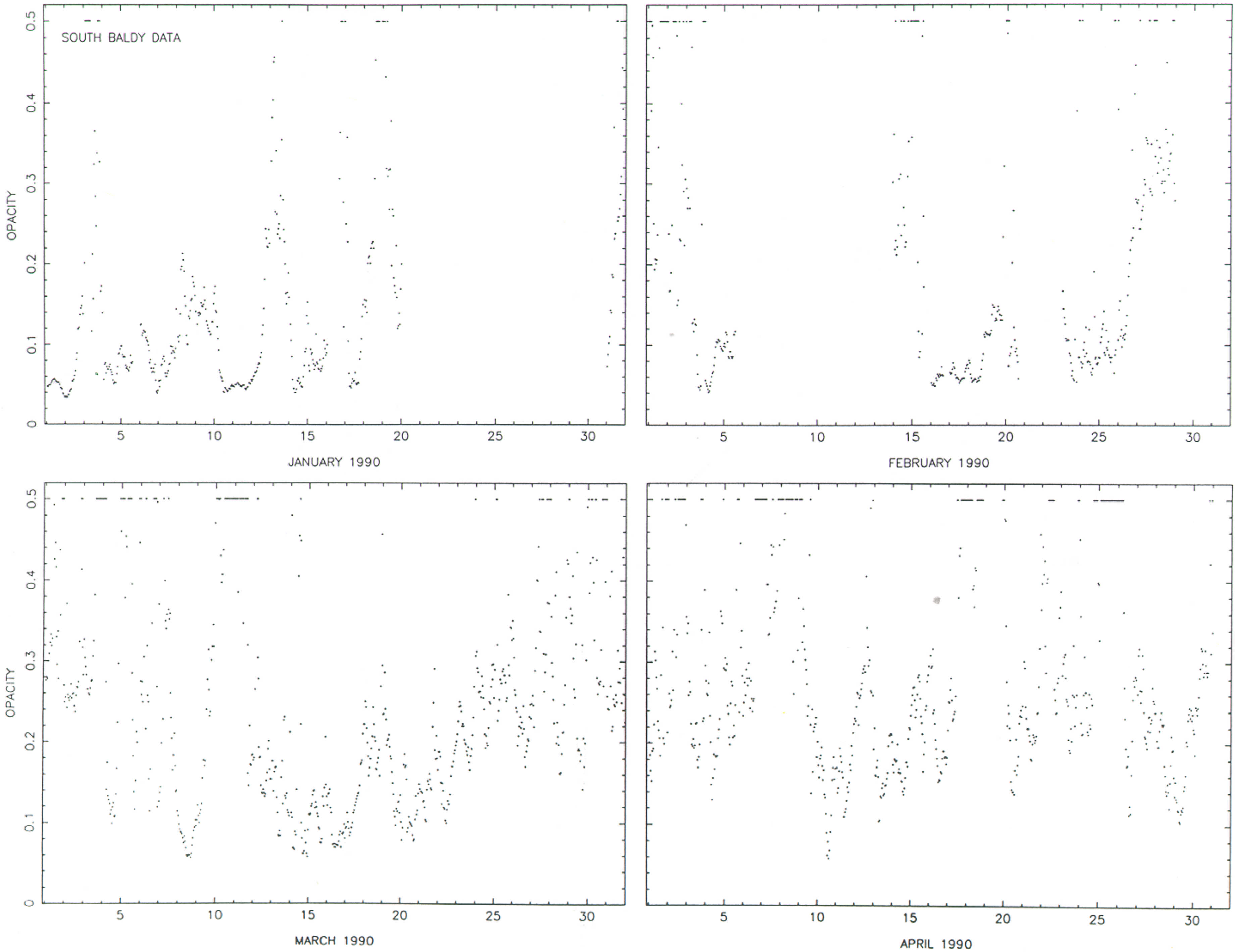
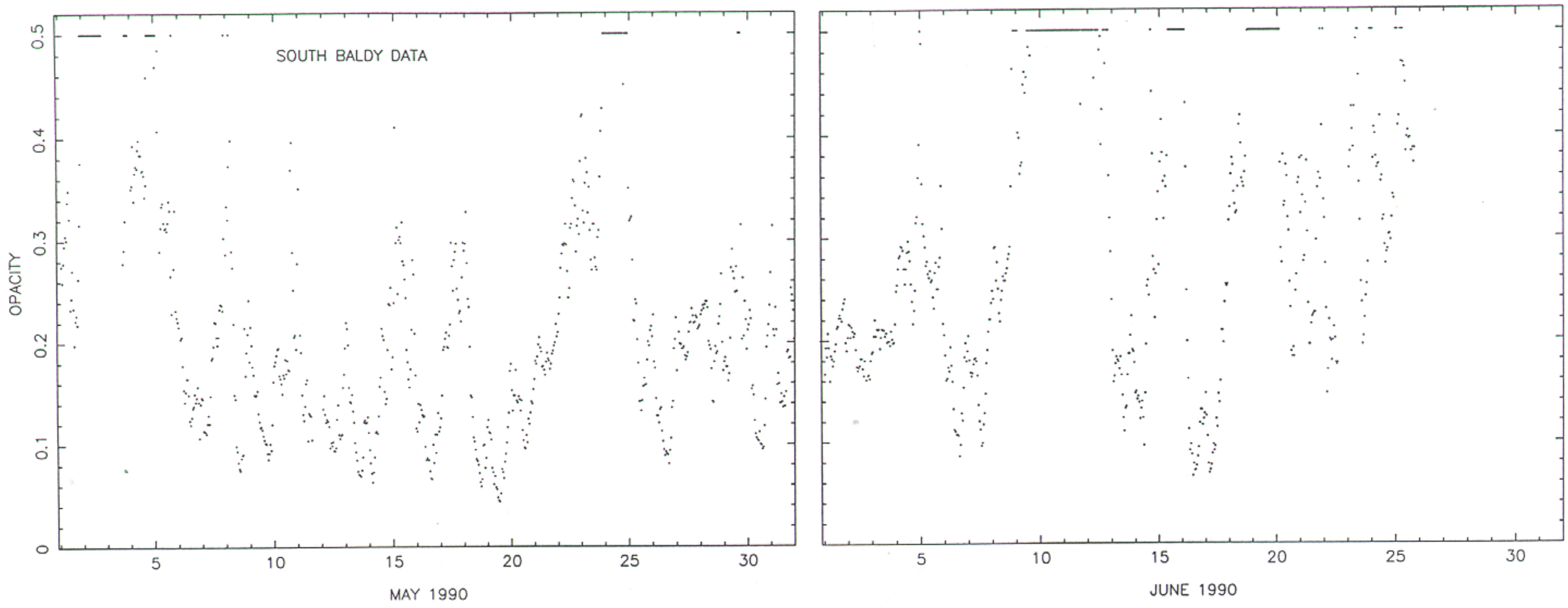

SOUTH BALDY DATA
OPACITY
JANUARY 1990
FEBRUARY 1990
MARCH 1990
APRIL 1990

Figure 1a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OPACITY
0
0.1
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0.3
0.4
0.5
5
10
15
20
25
30
MAY 1990
JUNE 1990

Figure 1a

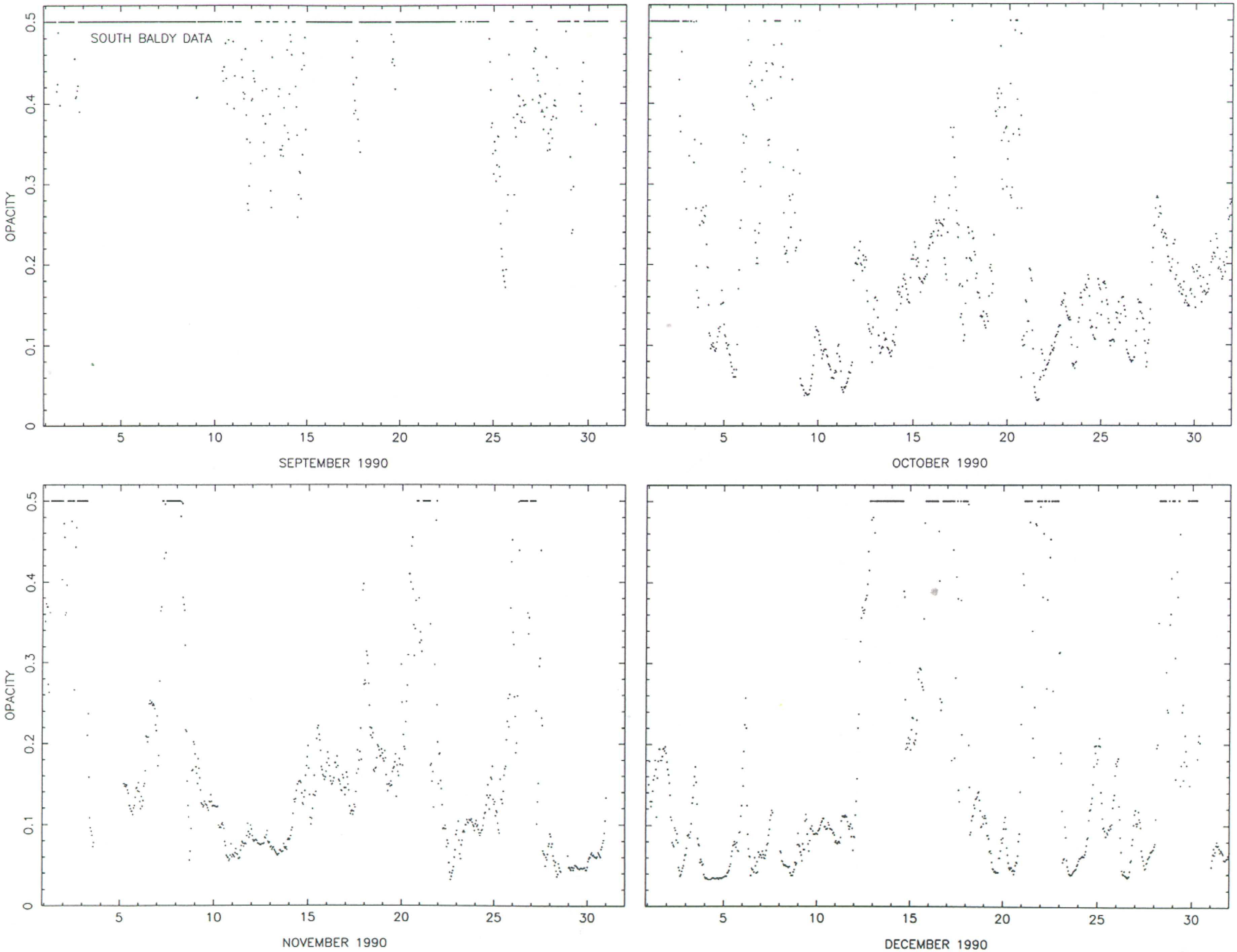
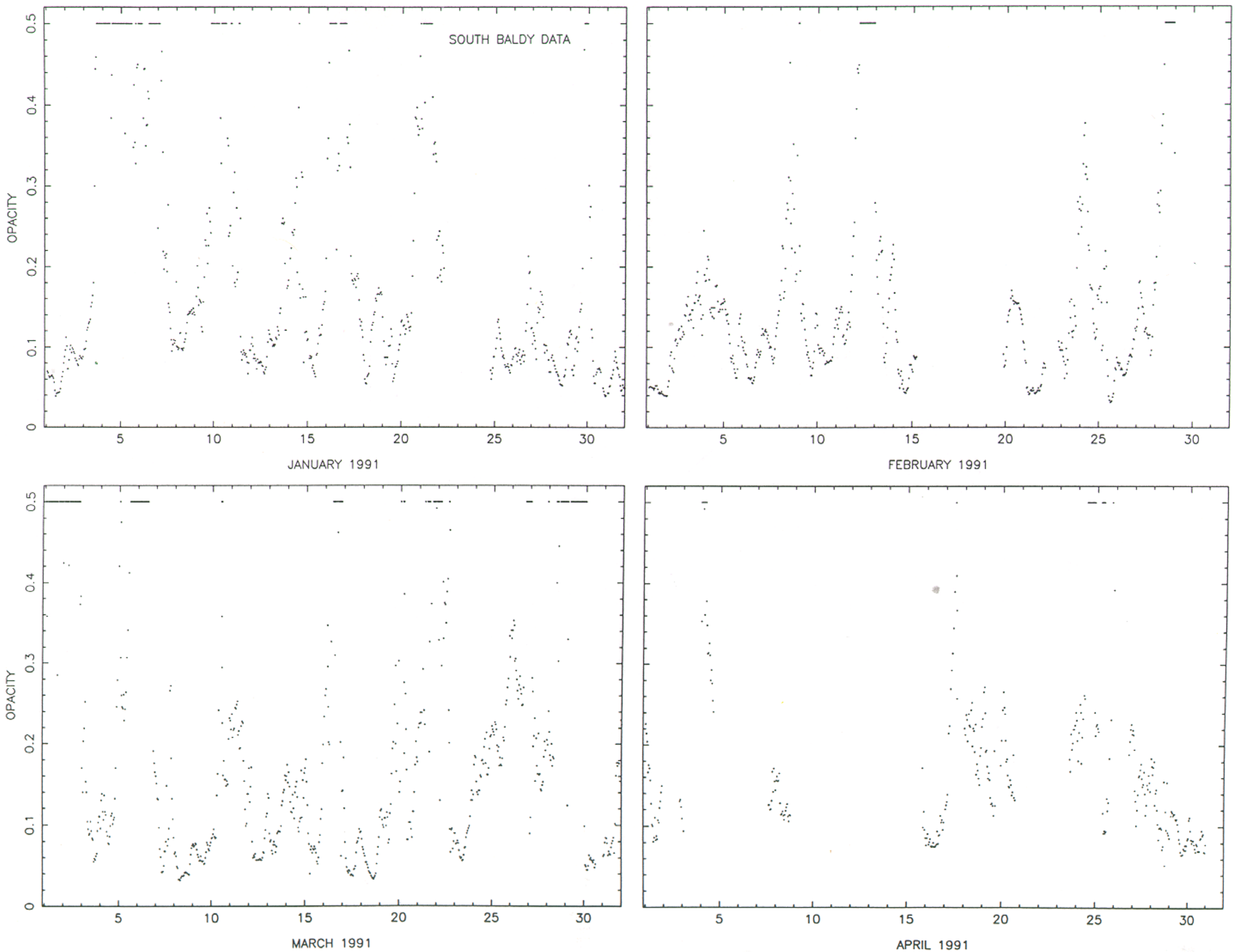

SOUTH BALDY DATA
OPACITY
SEPTEMBER 1990
OCTOBER 1990
NOVEMBER 1990
DECEMBER 1990

Figure 1a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OPACITY
0
0.1
0.2
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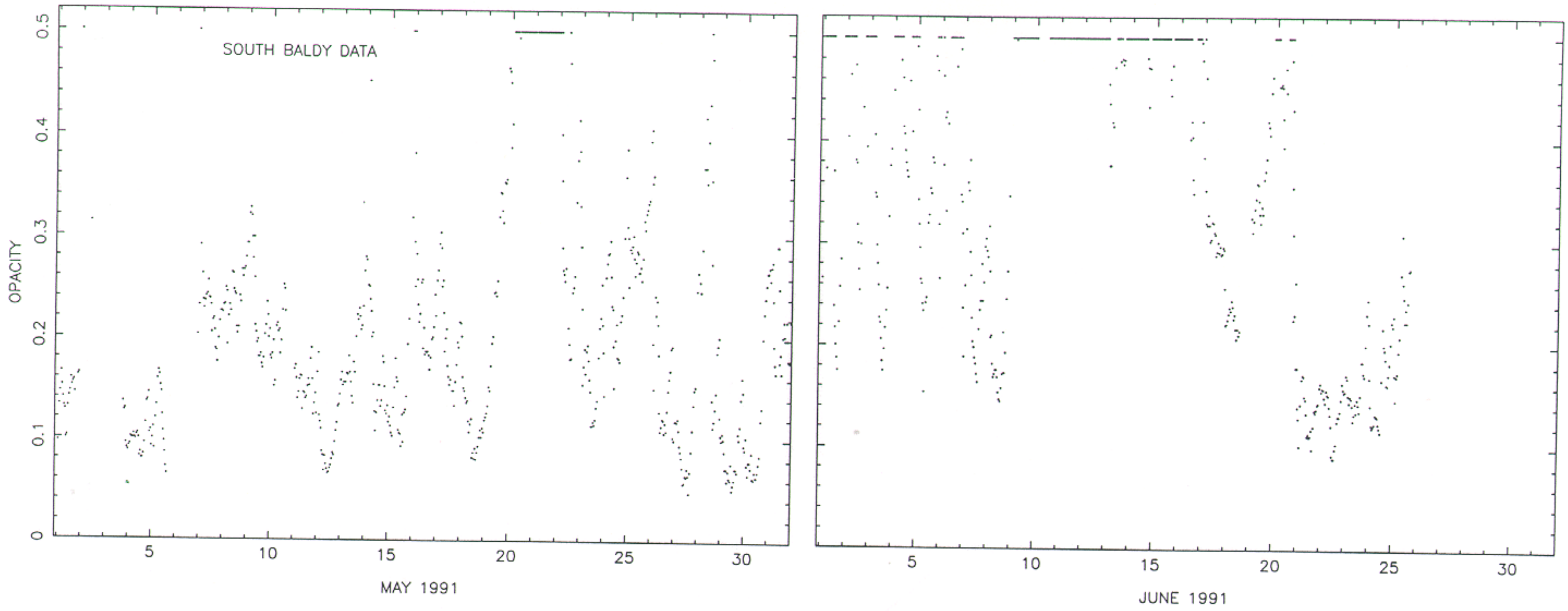
0.4
0.5
5
10
15
20
25
30
JANUARY 1991
FEBRUARY 1991
MARCH 1991
APRIL 1991

Figure 1a


SOUTH BALDY DATA
OPACITY
0
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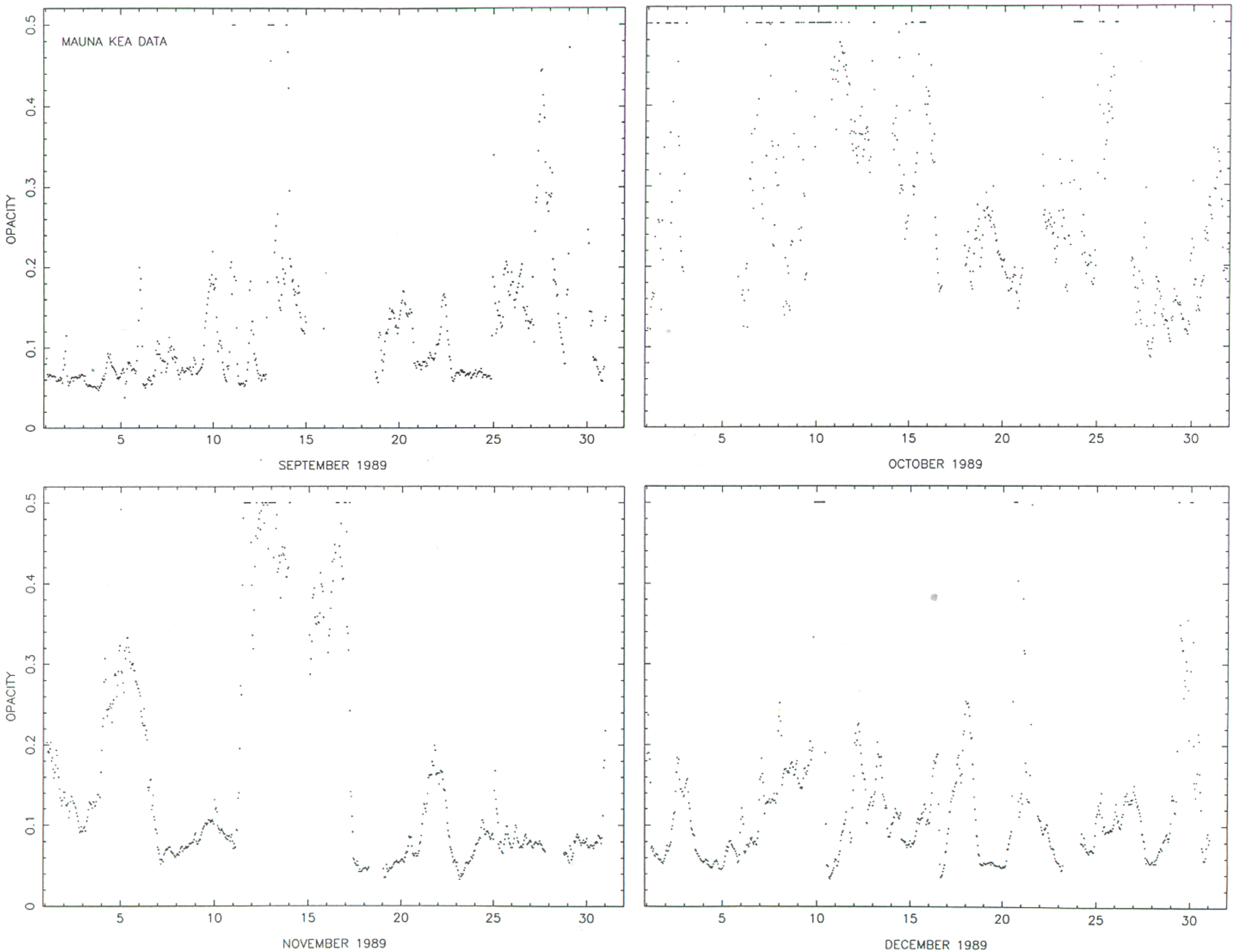
0.3
0.4
0.5
5
10
15
20
25
30
MAY 1991
JUNE 1991

Figure 1a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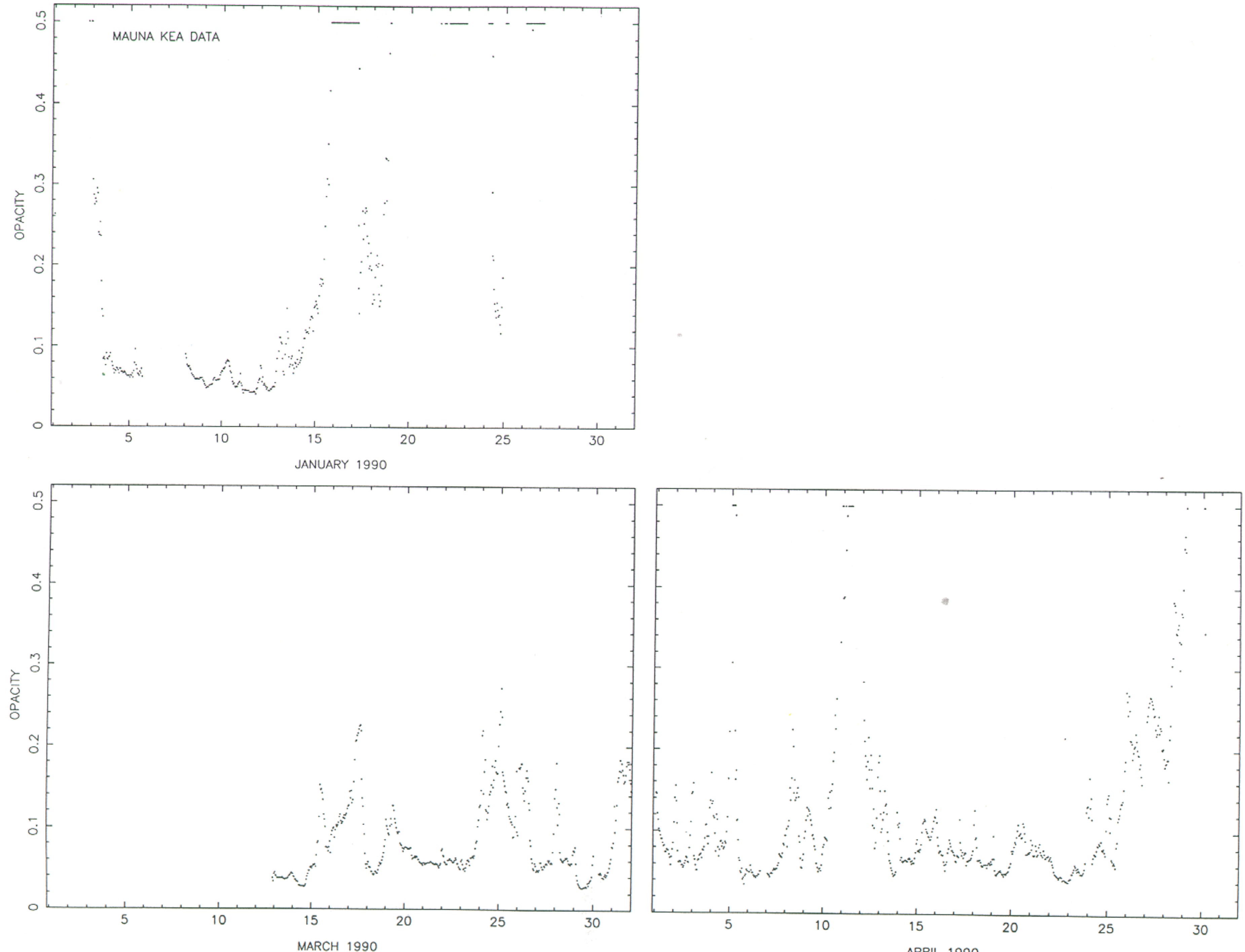
SEPTEMBER 1989
OCTOBER 1989
NOVEMBER 1989
DECEMBER 1989

Figure 1b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OPACITY
0.5
0.4
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0.1
0
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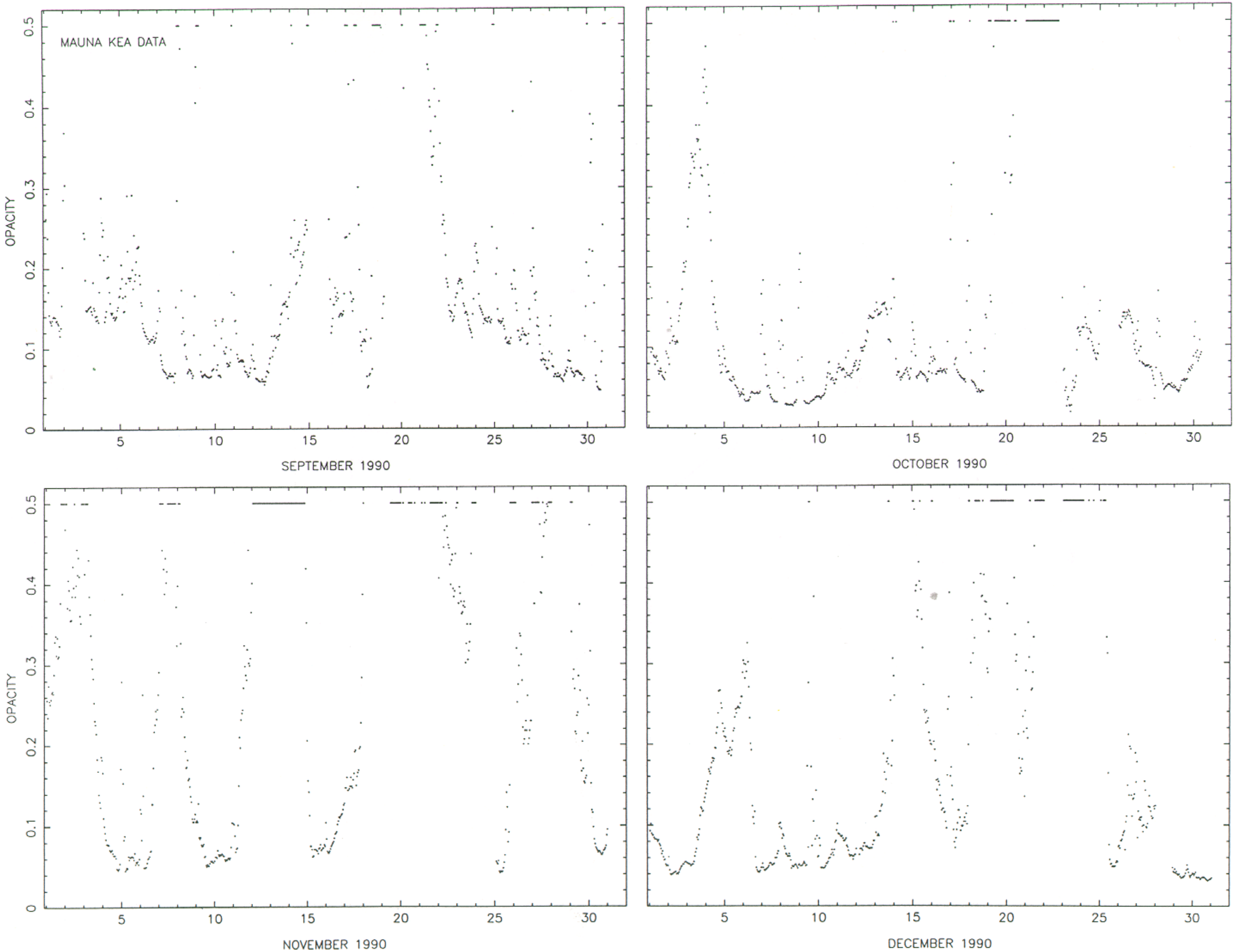
10
15
20
25
30
JANUARY 1990
MARCH 1990
APRIL 1990

Figure 1b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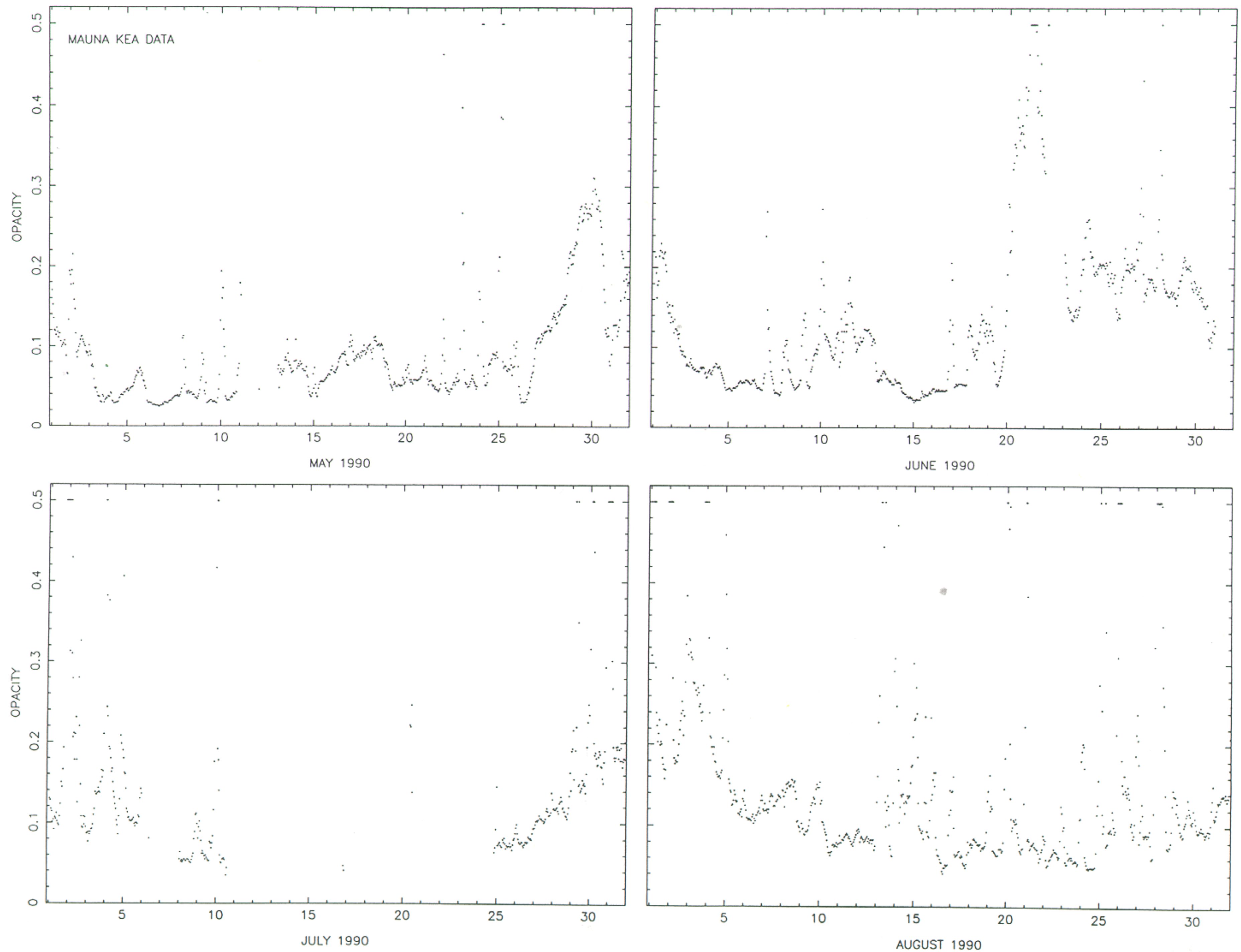
NOVEMBER 1990
DECEMBER 1990

Figure 1b



MAUNA KEA DATA
OPACITY
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0.1
0.2
0.3
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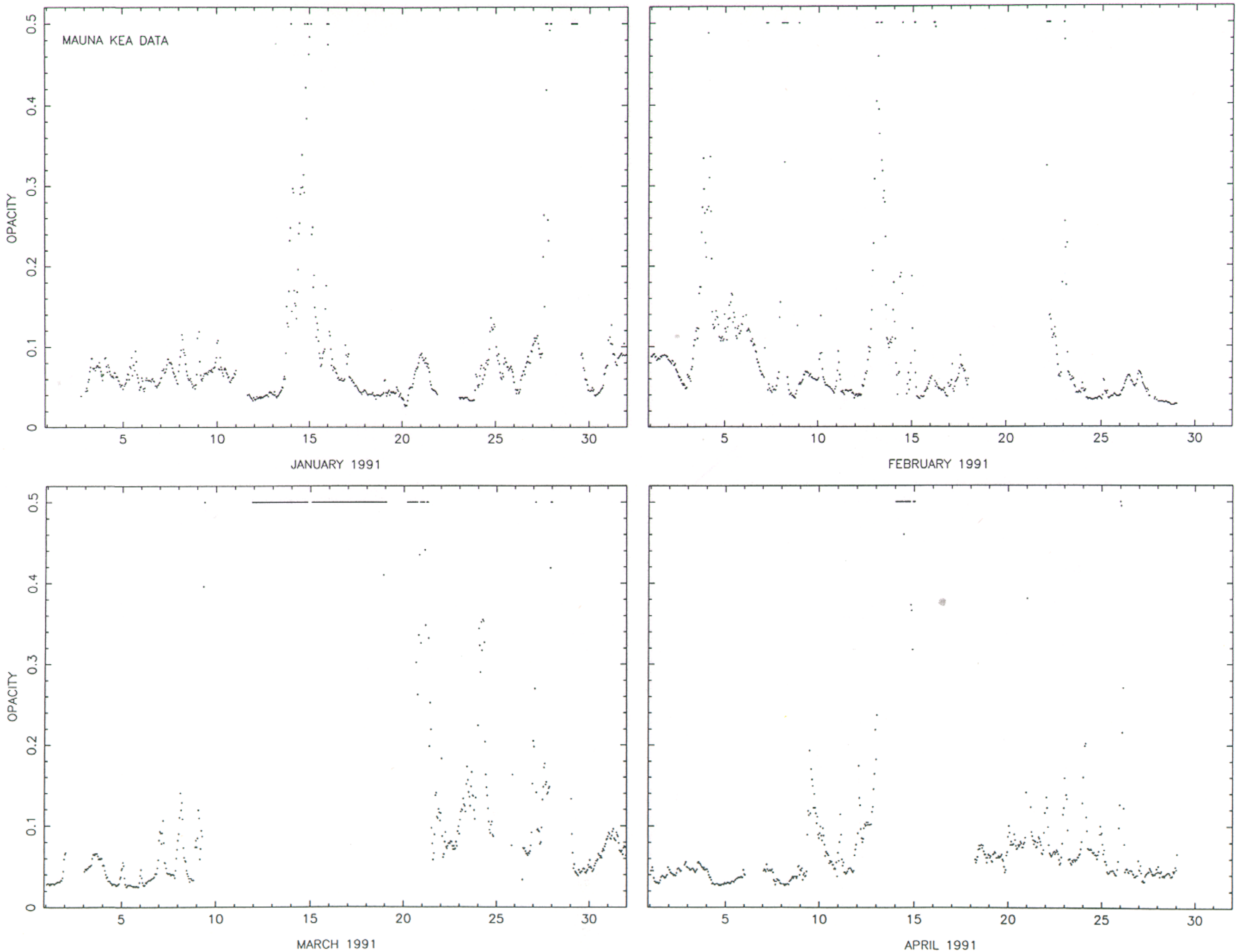
5
10
15
20
25
30
MAY 1990
JUNE 1990
JULY 1990
AUGUST 1990

Figure 1b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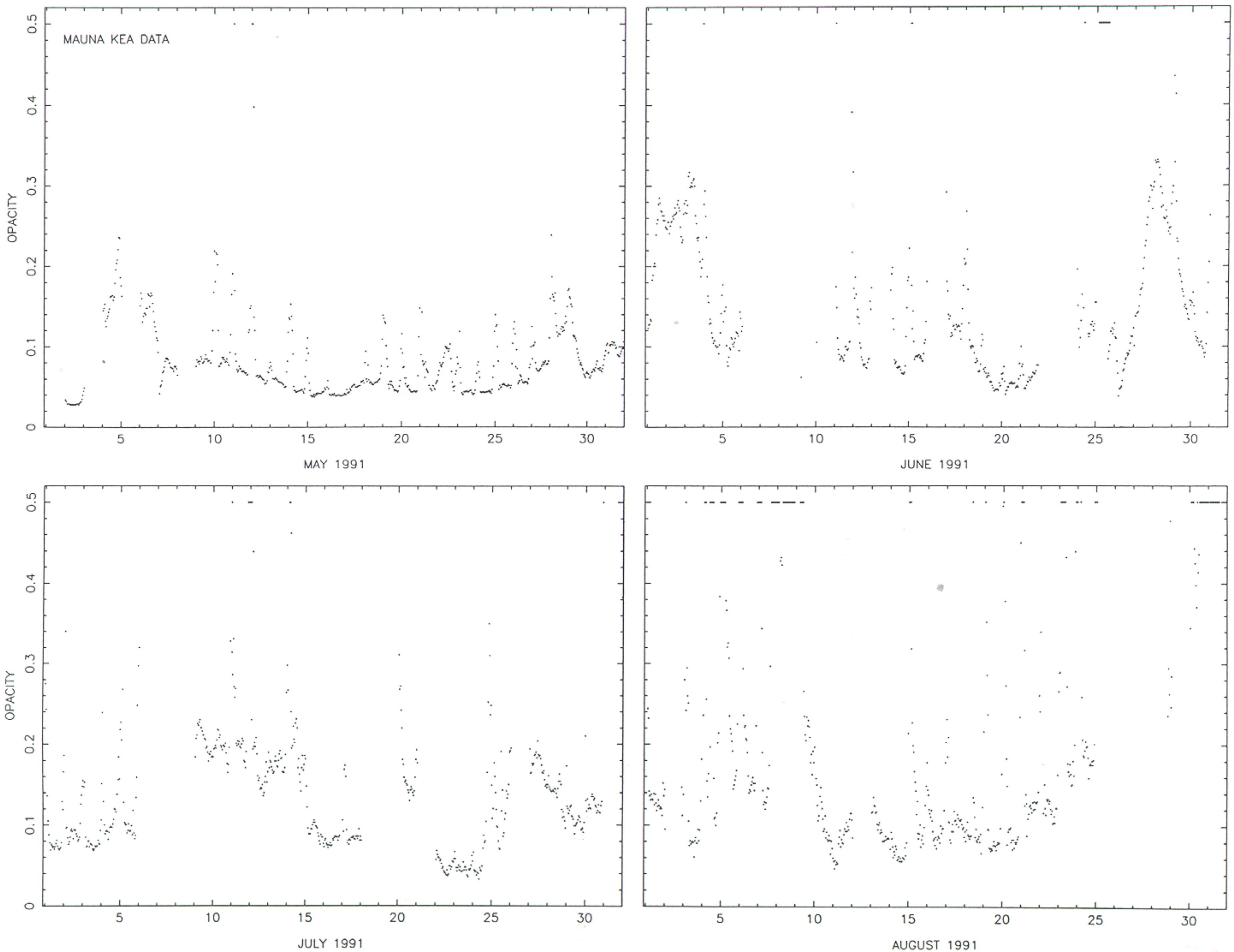
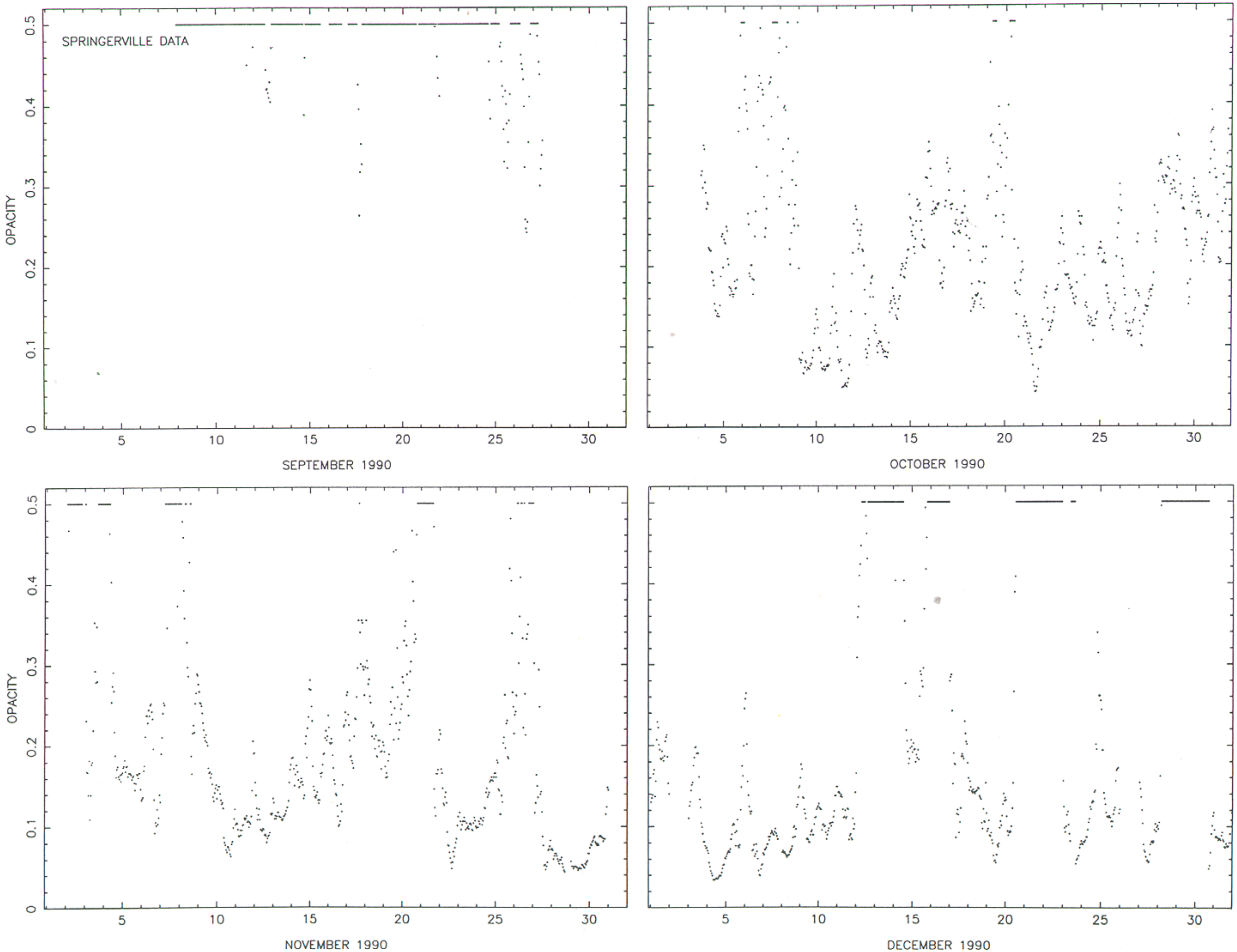
APRIL 1991

Figure 1b


MAUNA KEA DATA
OPACITY
MAY 1991
JUNE 1991
JULY 1991
AUGUST 1991
Figure 1b



SPRINGERVILLE DATA
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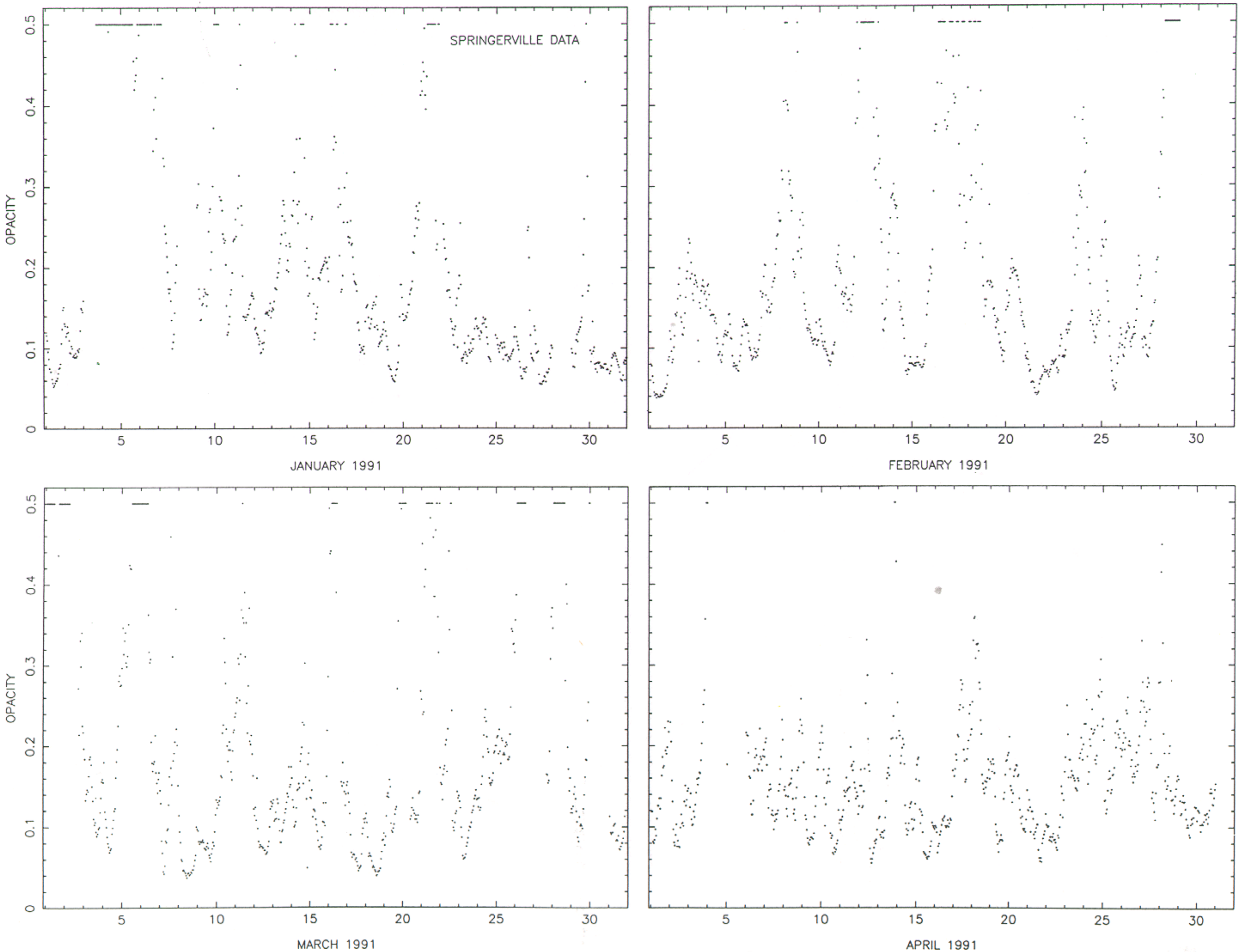
DECEMBER 1990

Figure 1c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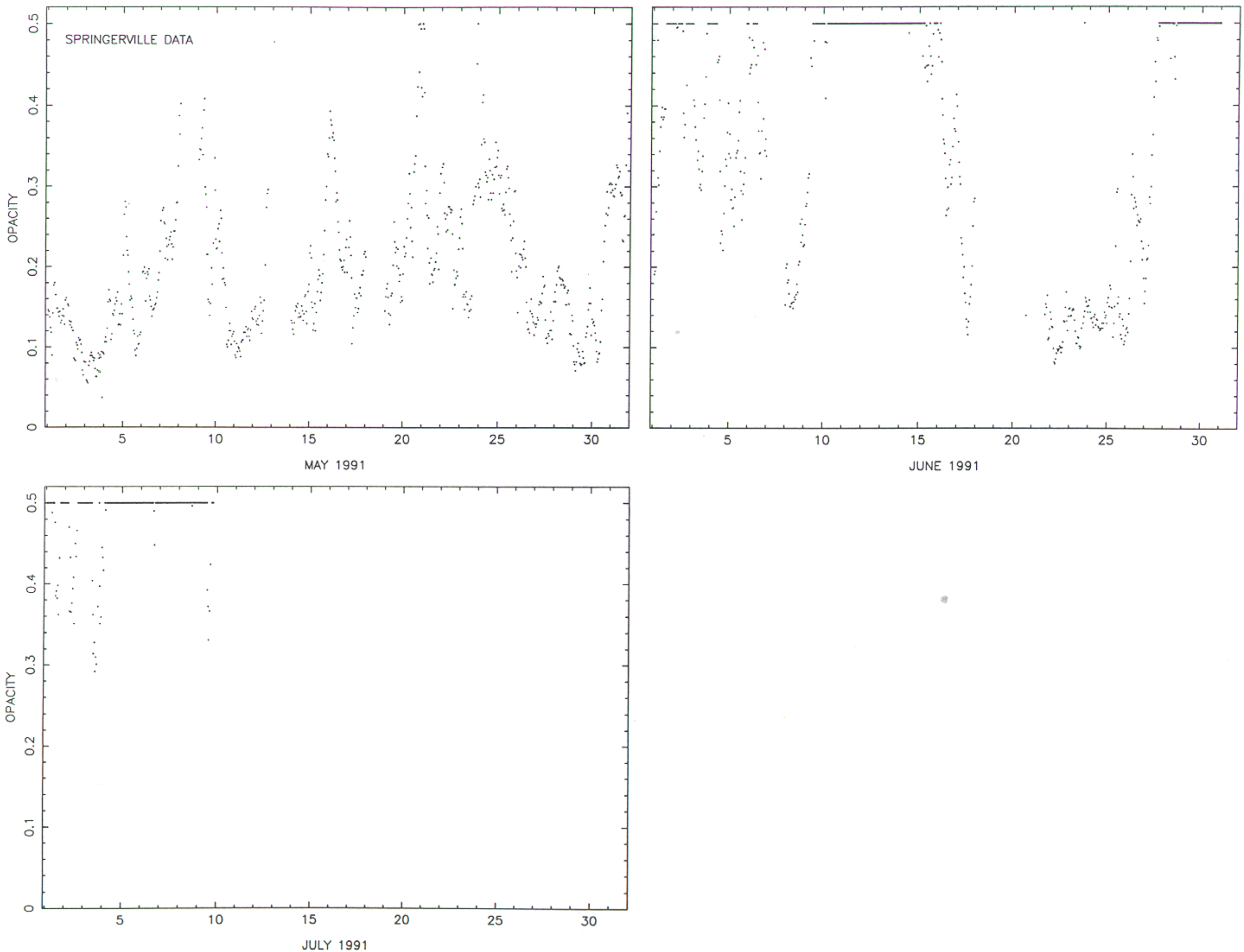
MARCH 1991
APRIL 1991

Figure 1c


SPRINGERVILLE DATA
OPACITY
0
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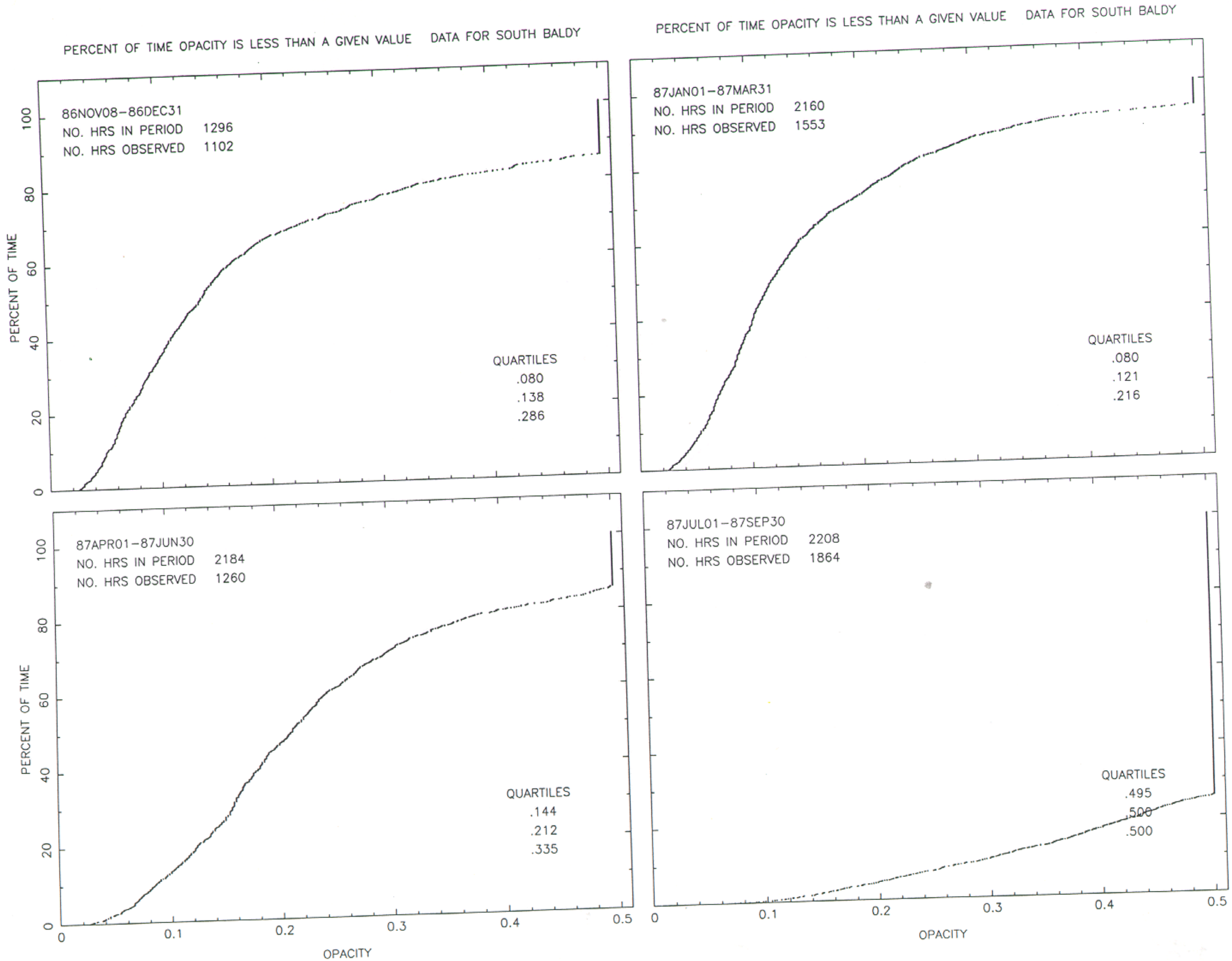
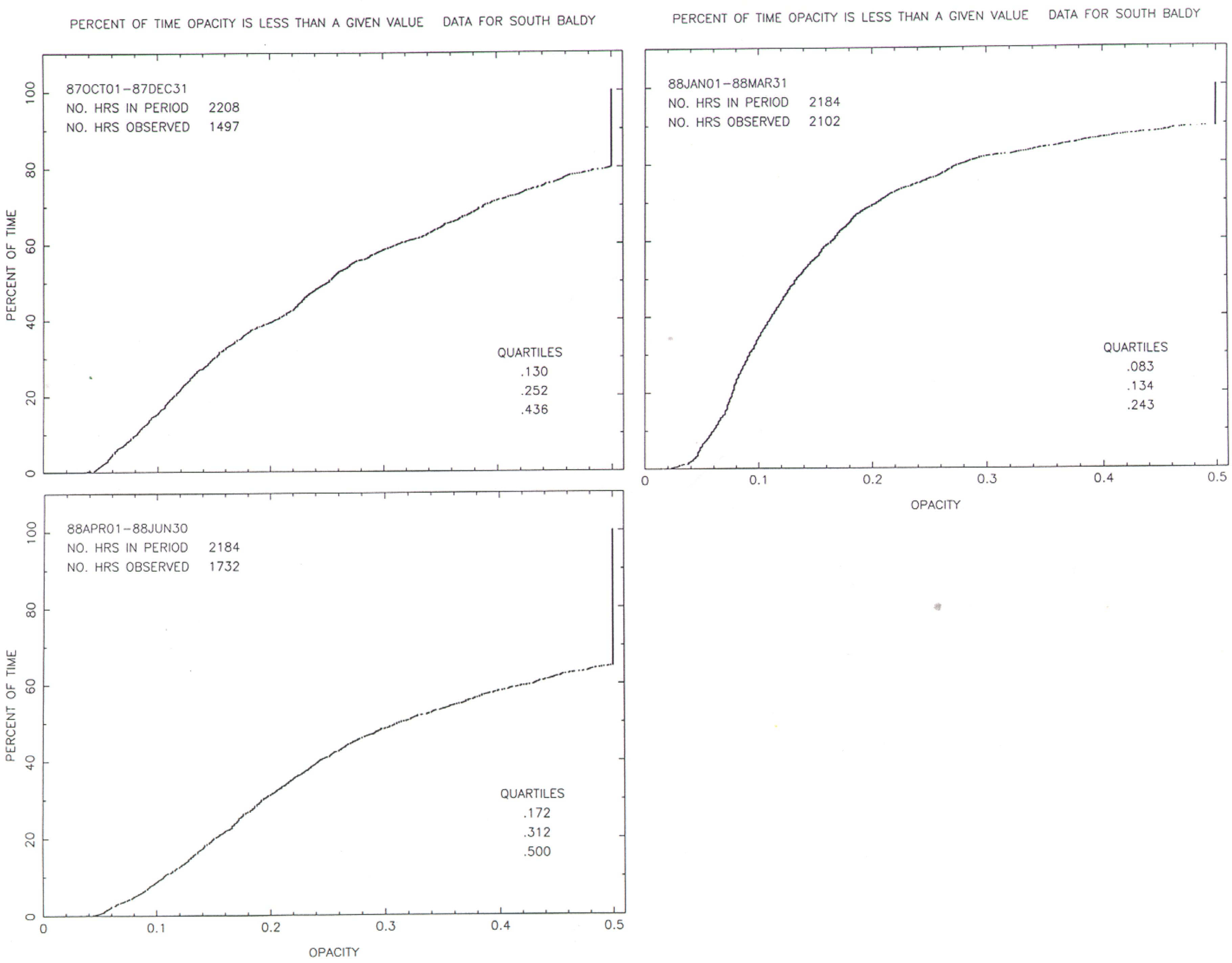
0.2
0.3
0.4
0.5
5
10
15
20
25
30
MAY 1991
JUNE 1991
JULY 1991

Figure 1c



PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SOUTH BALDY
86NOV08-86DEC31
NO. HRS IN PERIOD 1296
NO. HRS OBSERVED 1102
QUARTILES
.080
.138
.286
PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SOUTH BALDY
87JAN01-87MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 1553
QUARTILES
.080
.121
.216
87APR01-87JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1260
QUARTILES
.144
.212
.335
87JUL01-87SEP30
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 1864
QUARTILES
.495
.500
.500
PERCENT OF TIME
OPACITY

Figure 2a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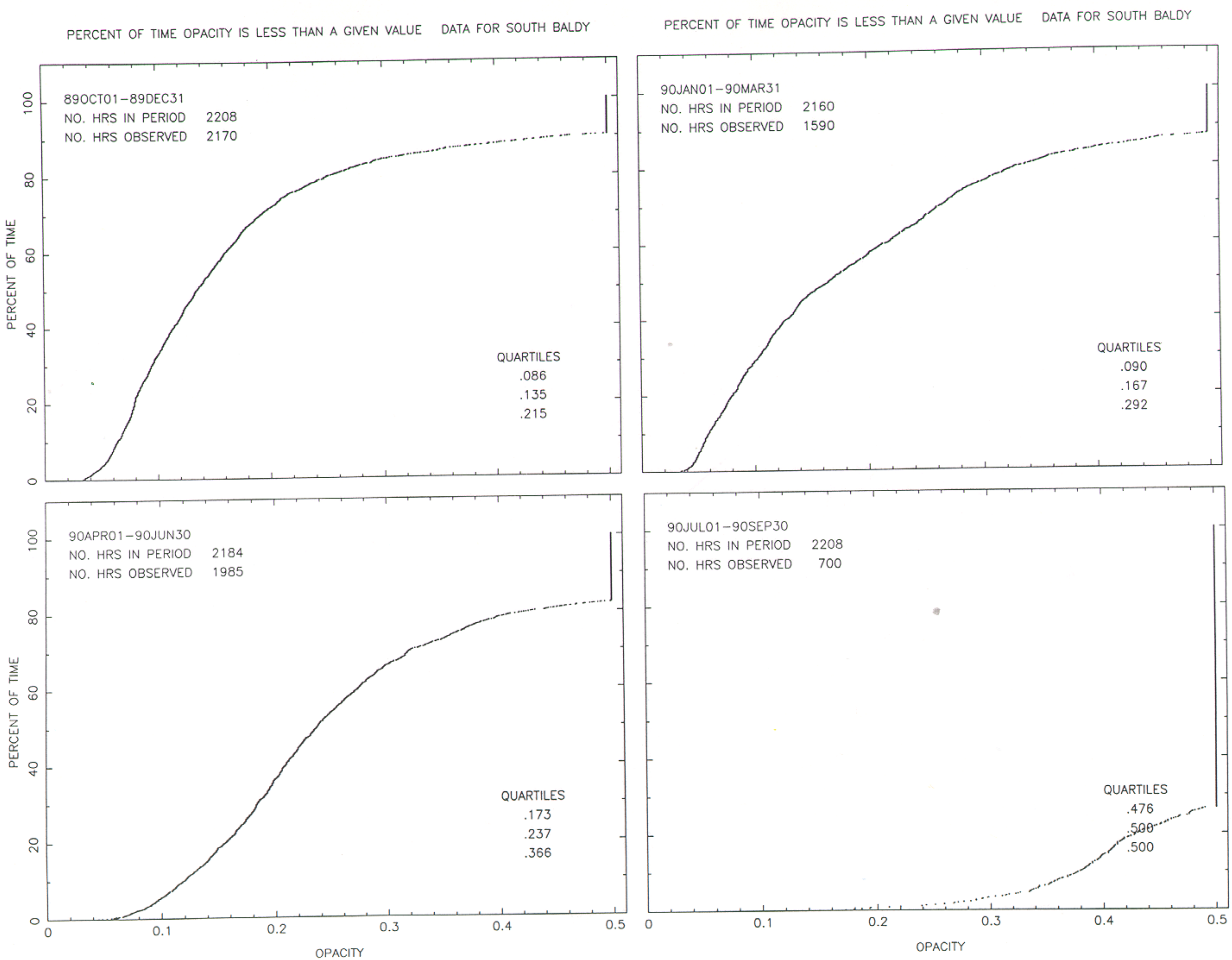
NO. HRS OBSERVED 1497
QUARTILES
.130
.252
.436
PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SOUTH BALDY
88JAN01-88MAR31
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 2102
QUARTILES
.083
.134
.243
88APR01-88JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1732
QUARTILES
.172
.312
.500
PERCENT OF TIME
OPACITY
0
20
40
60
80
100
0.1
0.2
0.3
0.4
0.5

Figure 2a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89OCT01-89DEC31
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 2170
QUARTILES
.086
.135
.215
PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SOUTH BALDY
90JAN01-90MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 1590
QUARTILES
.090
.167
.292
90APR01-90JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1985
QUARTILES
.173
.237
.366
90JUL01-90SEP30
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 700
QUARTILES
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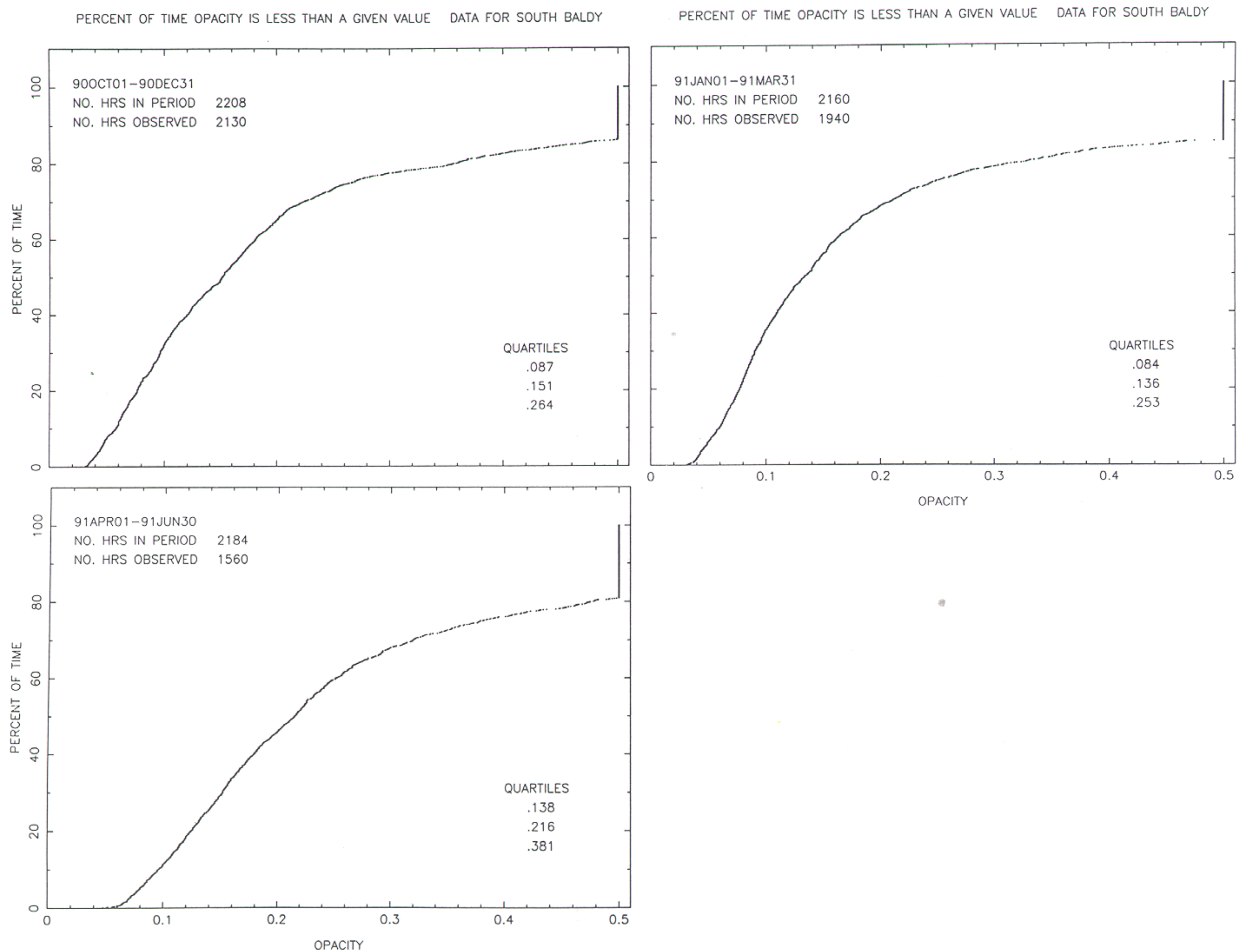
.500
.500
PERCENT OF TIME
OPACITY

Figure 2a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NO. HRS OBSERVED 2130
QUARTILES
.087
.151
.264
PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SOUTH BALDY
91JAN01-91MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 1940
QUARTILES
.084
.136
.253
91APR01-91JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1560
QUARTILES
.138
.216
.381
PERCENT OF TIME
OPACITY

Figure 2a

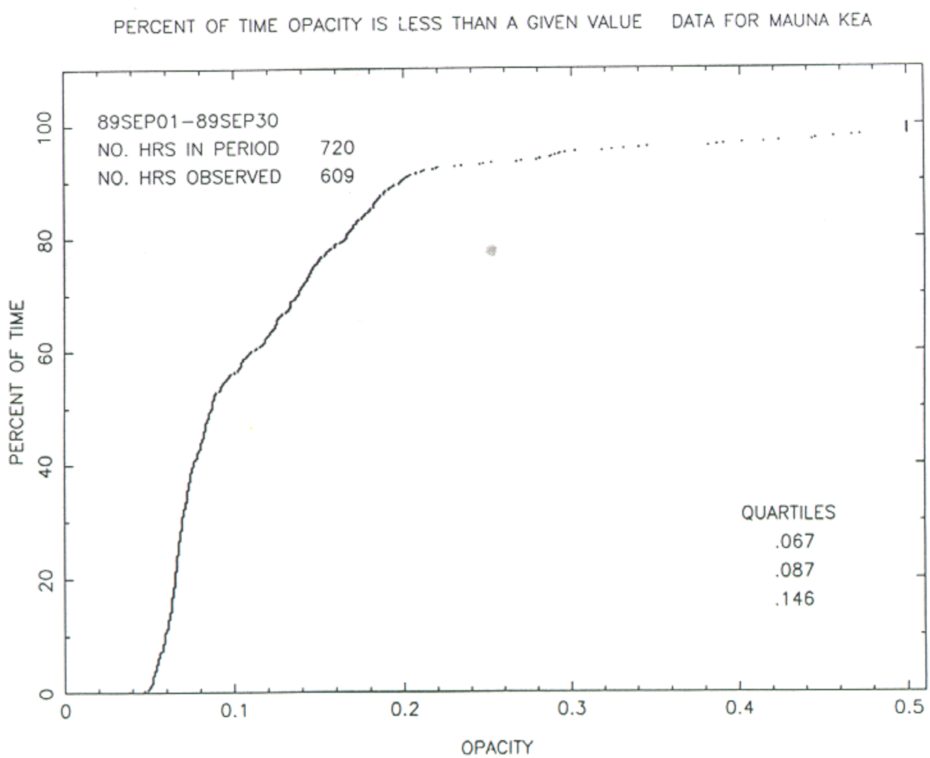

PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
89SEP01–89SEP30
NO. HRS IN PERIOD 720
NO. HRS OBSERVED 609
QUARTILES
.067
.087
.146
PERCENT OF TIME
0
20
40
60
80
100
0
0.1
0.2
0.3
0.4
0.5
OPACITY

Figure 2b

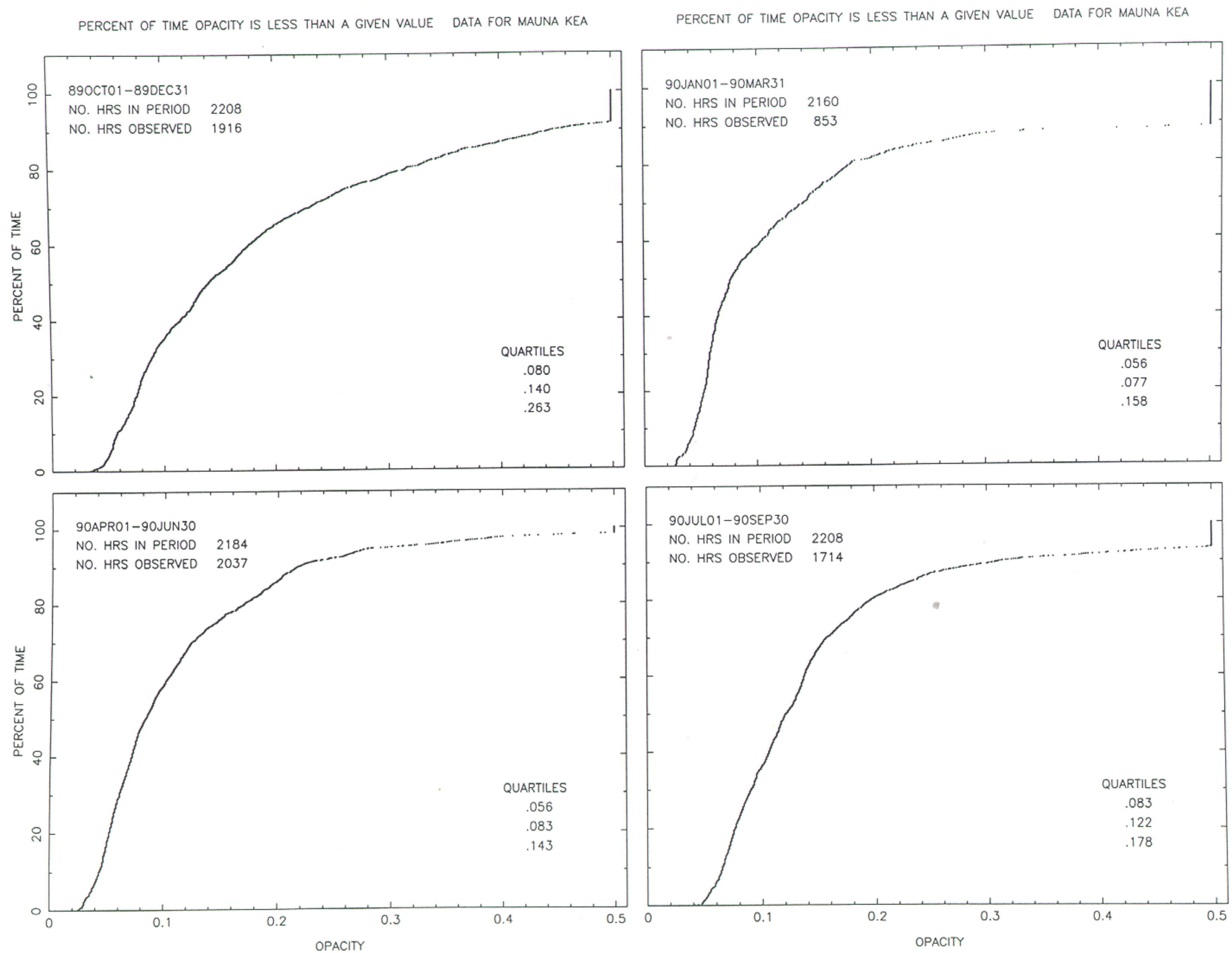

PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE   DATA FOR MAUNA KEA
89OCT01-89DEC31
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 1916
QUARTILES
.080
.140
.263
PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE   DATA FOR MAUNA KEA
90JAN01-90MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 853
QUARTILES
.056
.077
.158
90APR01-90JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 2037
QUARTILES
.056
.083
.143
90JUL01-90SEP30
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 1714
QUARTILES
.083
.122
.178
PERCENT OF TIME
OPACITY
0
20
40
60
80
100
0.1
0.2
0.3
0.4
0.5

Figure 2b

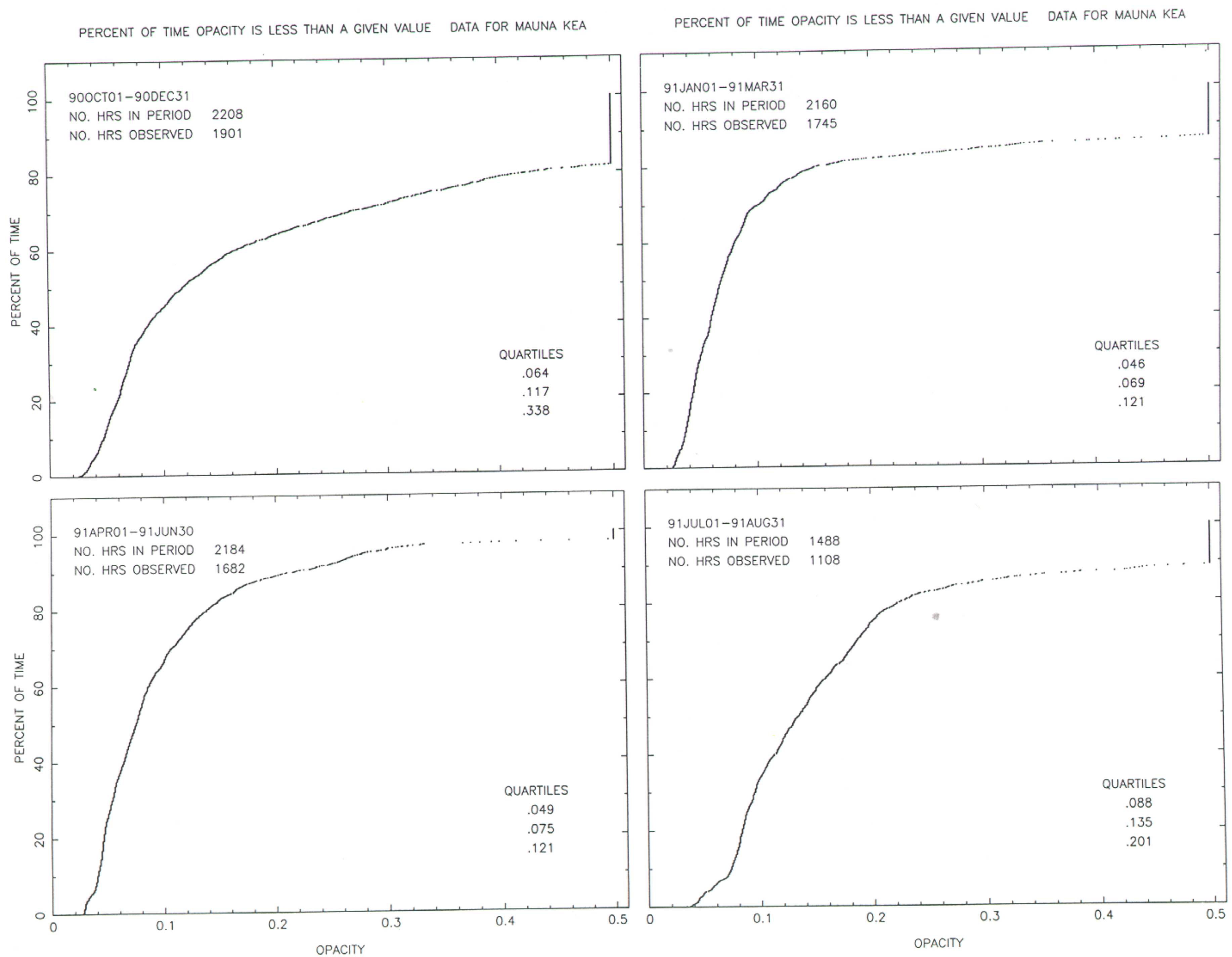
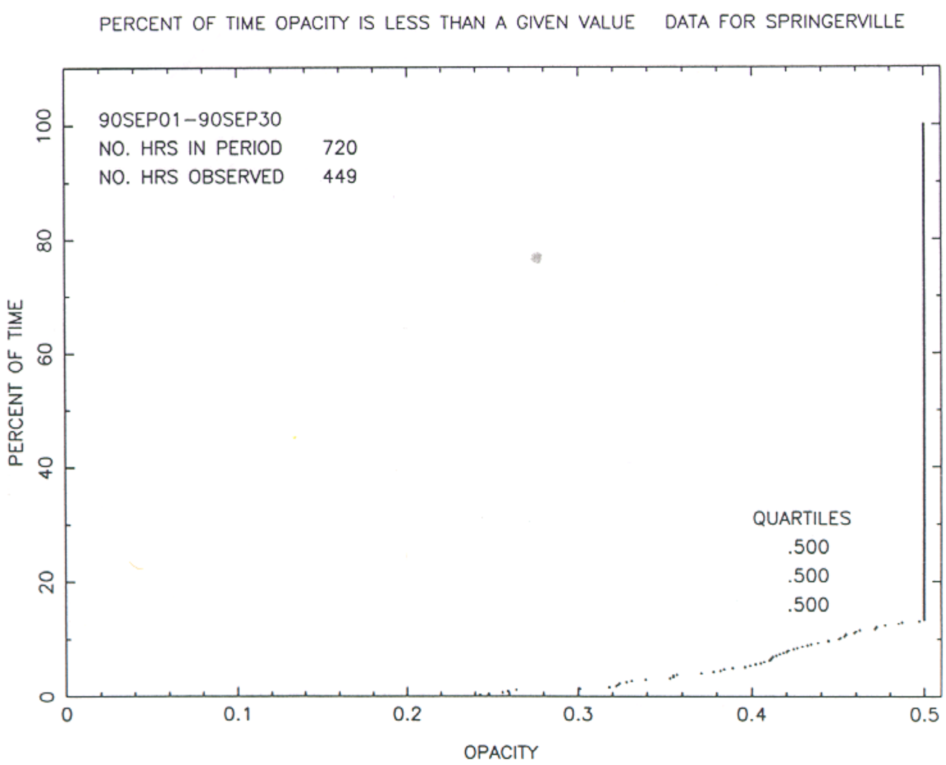

PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
90OCT01–90DEC31
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 1901
QUARTILES
.064
.117
.338
91JAN01–91MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 1745
QUARTILES
.046
.069
.121
91APR01–91JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1682
QUARTILES
.049
.075
.121
91JUL01–91AUG31
NO. HRS IN PERIOD 1488
NO. HRS OBSERVED 1108
QUARTILES
.088
.135
.201
PERCENT OF TIME
OPACITY

Figure 2b



PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
90SEP01-90SEP30
NO. HRS IN PERIOD 720
NO. HRS OBSERVED 449
QUARTILES
.500
.500
.500
PERCENT OF TIME
OPACITY

Figure 2c

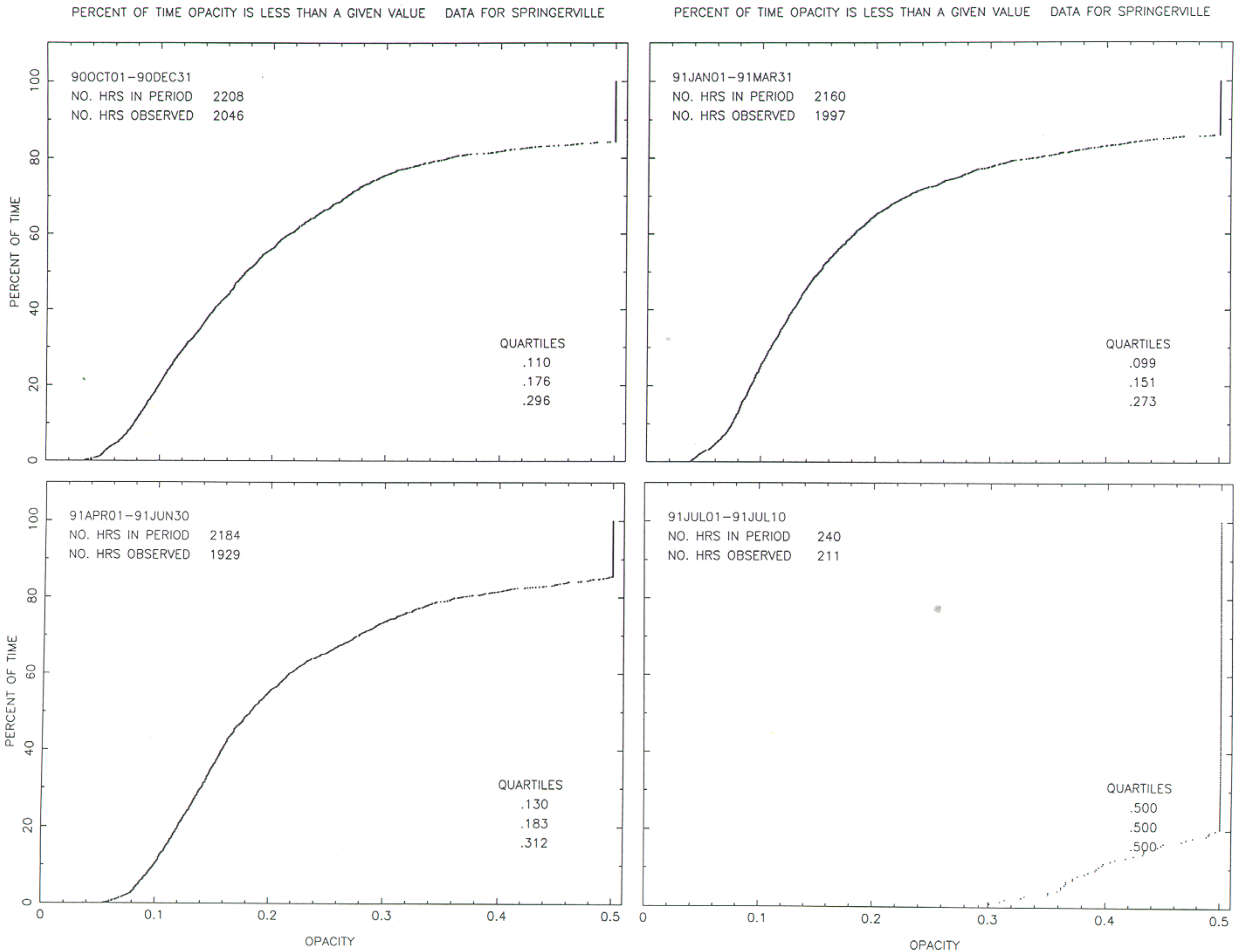

PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
90OCT01–90DEC31
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 2046
QUARTILES
.110
.176
.296
PERCENT OF TIME OPACITY IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
91JAN01–91MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 1997
QUARTILES
.099
.151
.273
91APR01–91JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1929
QUARTILES
.130
.183
.312
91JUL01–91JUL10
NO. HRS IN PERIOD 240
NO. HRS OBSERVED 211
QUARTILES
.500
.500
.500
PERCENT OF TIME
OPACITY
0
20
40
60
80
100
0.1
0.2
0.3
0.4
0.5

Figure 2c

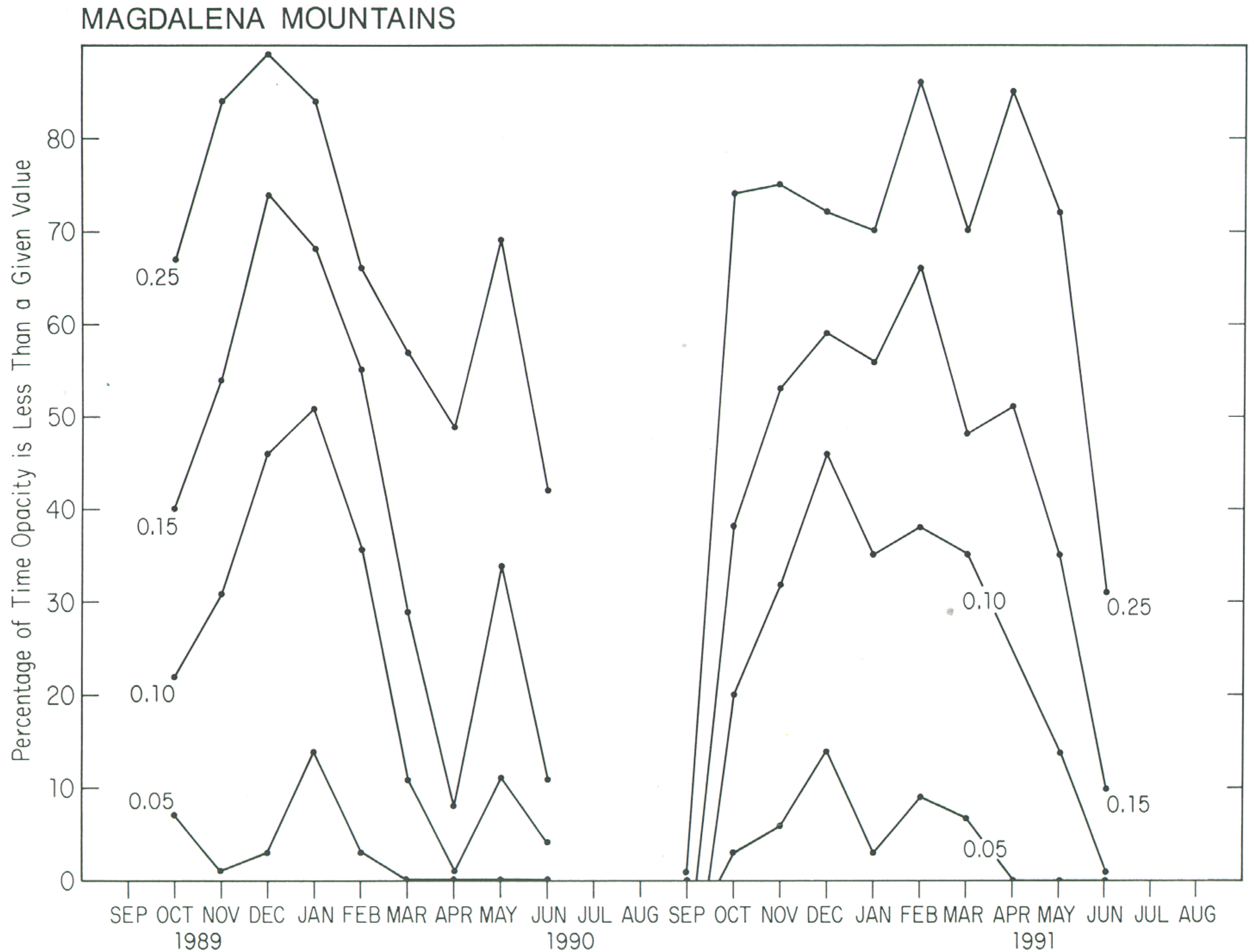

MAGDALENA MOUNTAINS
Percentage of Time Opacity is Less Than a Given Value
0
10
20
30
40
50
60
70
80
0.25
0.15
0.10
0.05
SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG
1989
1990
1991

Figure 3a

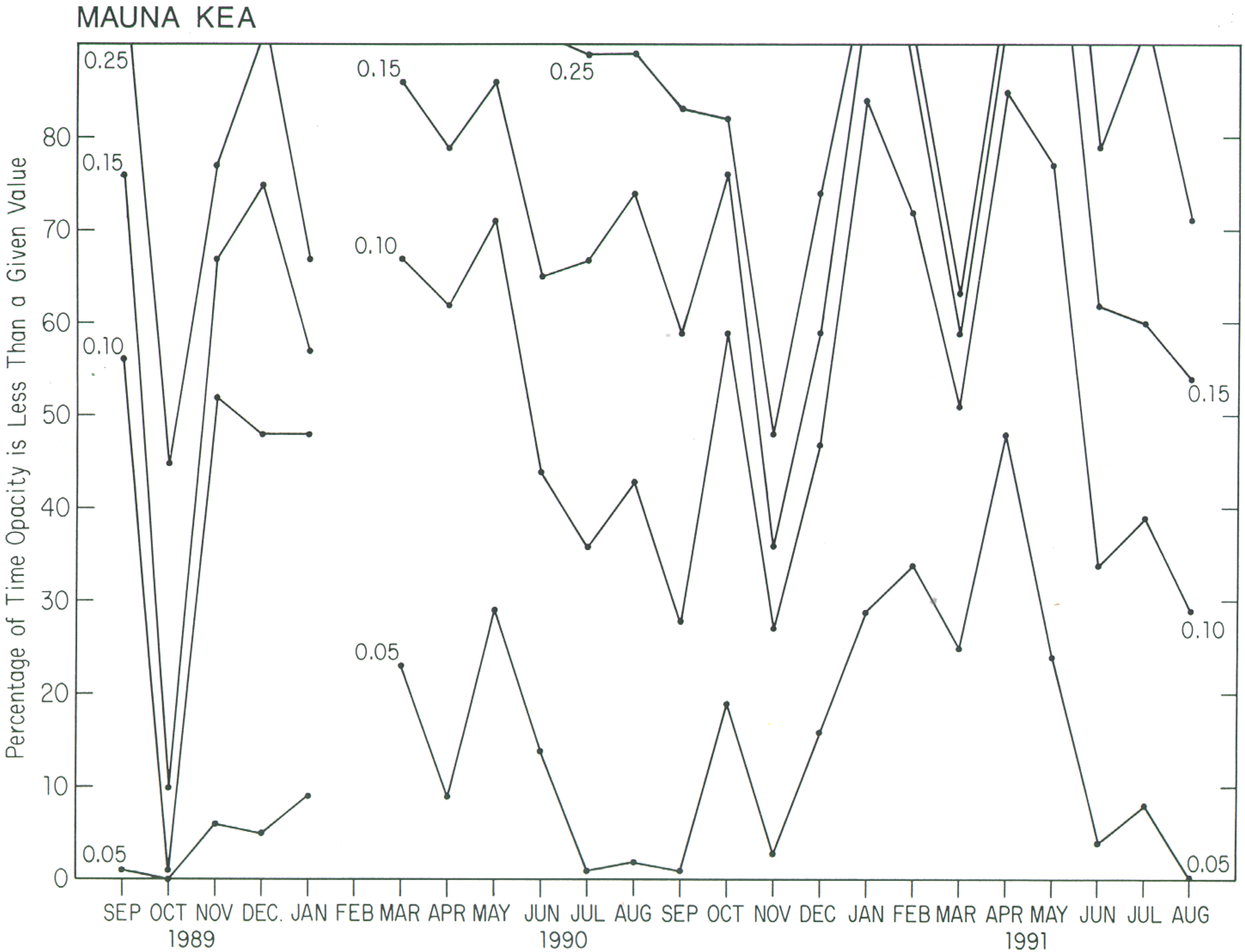

MAUNA KEA
Percentage of Time Opacity is Less Than a Given Value
0
10
20
30
40
50
60
70
80
0.25
0.15
0.10
0.05
0.15
0.10
0.05
0.25
0.15
0.10
0.05
SEP OCT NOV DEC. JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG
1989
1990
1991

Figure 3b

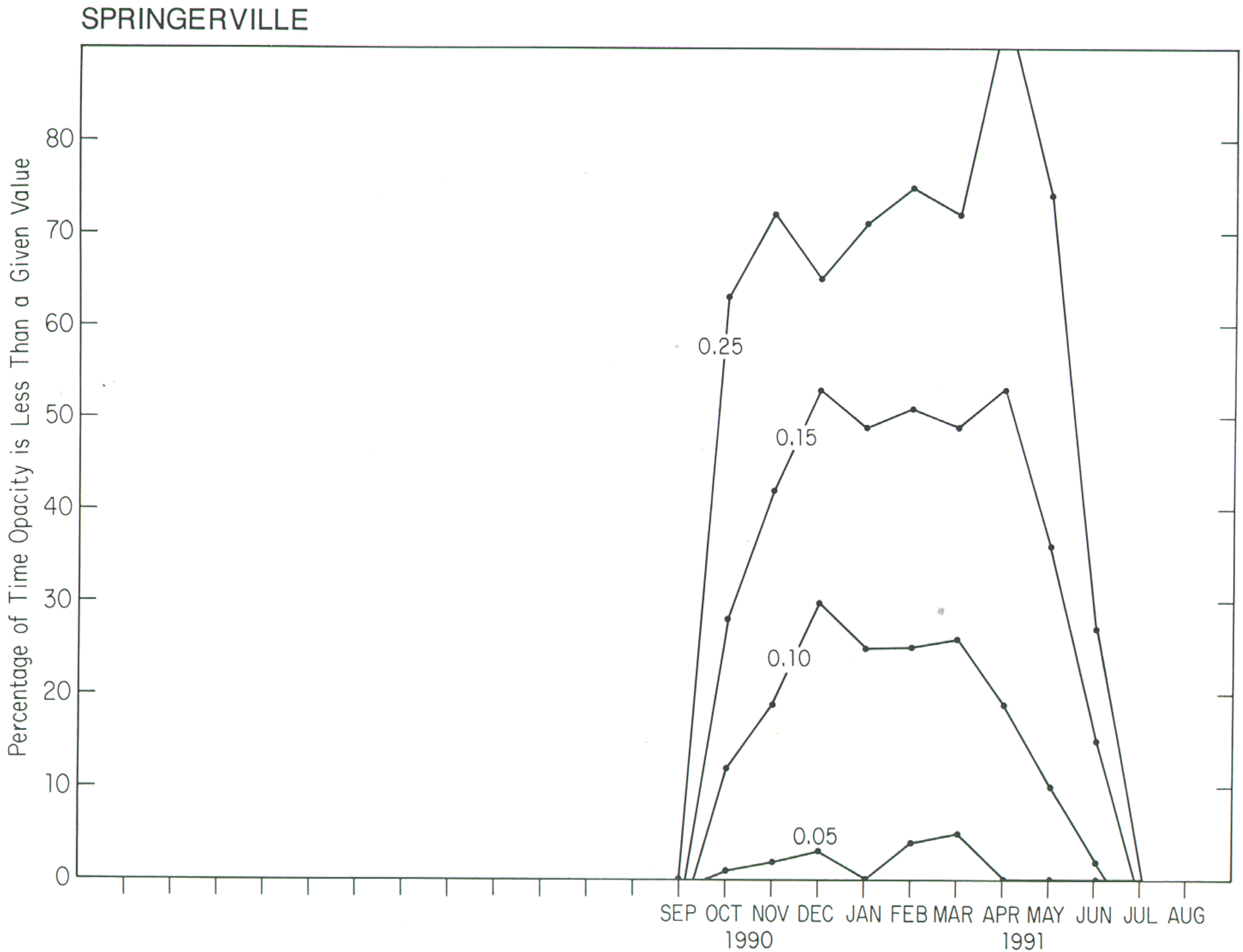

SPRINGERVILLE
Percentage of Time Opacity is Less Than a Given Value
80
70
60
50
40
30
20
10
0
0.25
0.15
0.10
0.05
SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG
1990
1991

Figure 3c

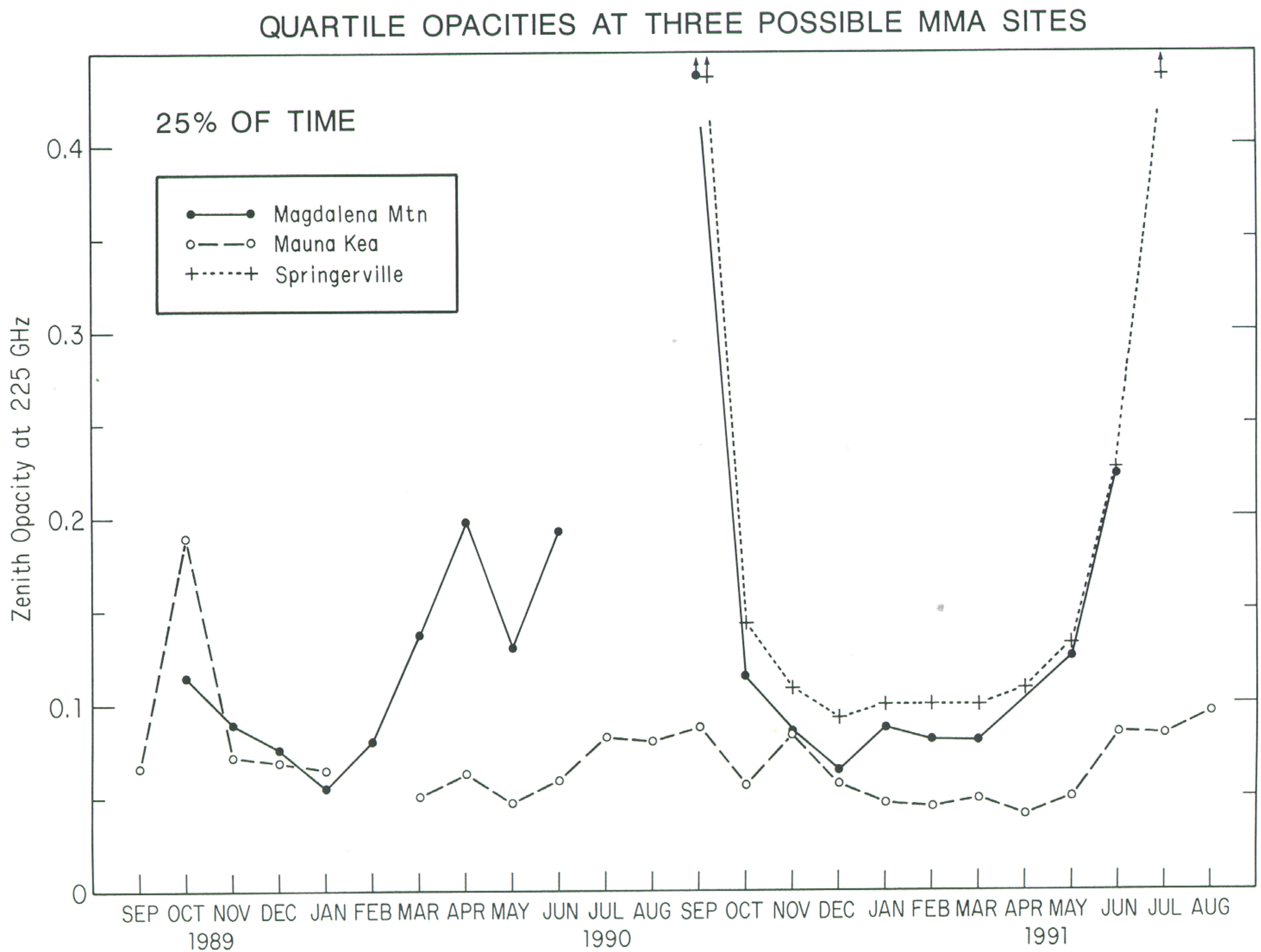

QUARTILE OPACITIES AT THREE POSSIBLE MMA SITES
25% OF TIME
Magdalena Mtn
Mauna Kea
Springerville
Zenith Opacity at 225 GHz
0
0.1
0.2
0.3
0.4
SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG
1989
1990
1991

Figure 4a

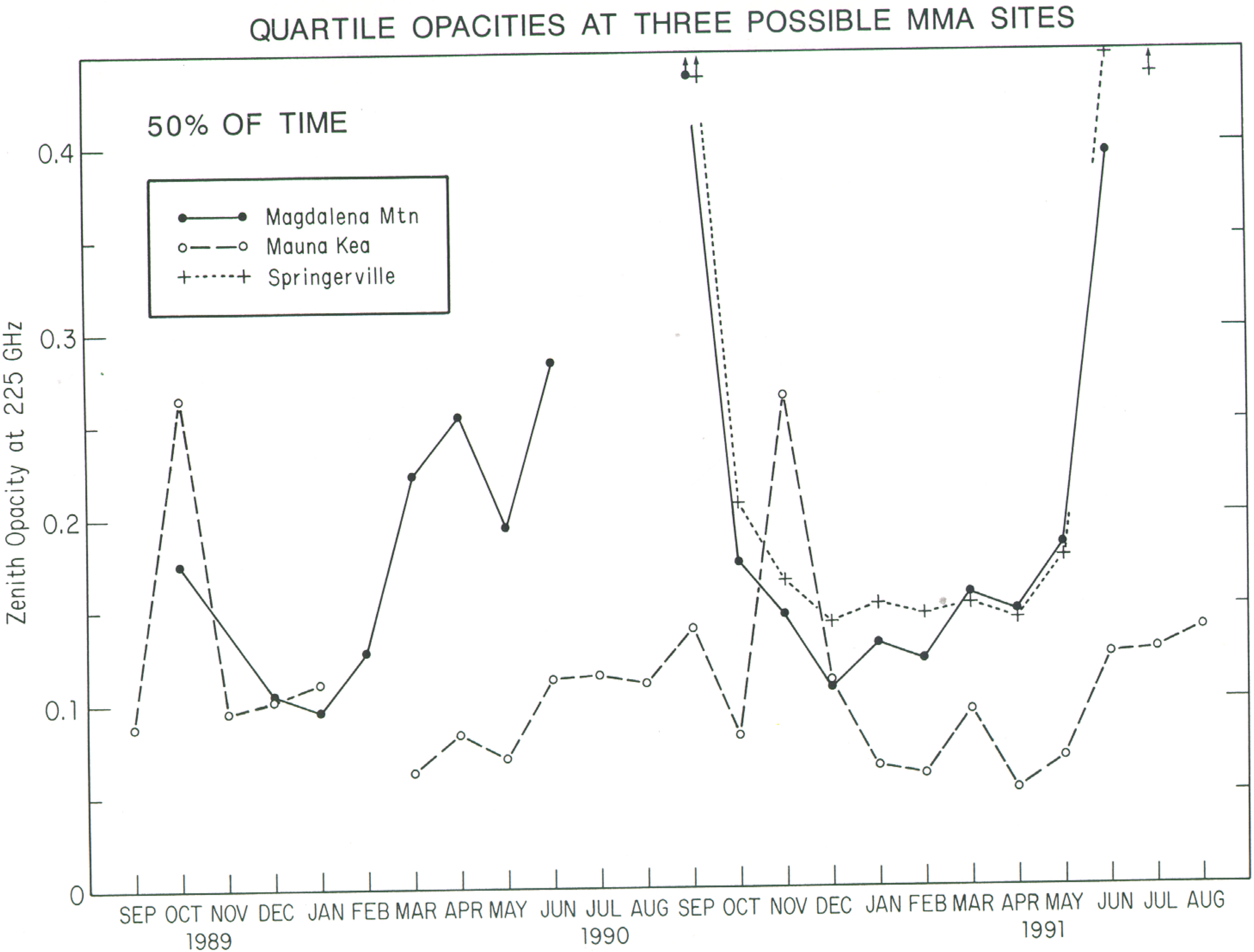

QUARTILE OPACITIES AT THREE POSSIBLE MMA SITES
50% OF TIME
Magdalena Mtn
Mauna Kea
Springerville
Zenith Opacity at 225 GHz
0
0.1
0.2
0.3
0.4
SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG
1989
1990
1991

Figure 4b

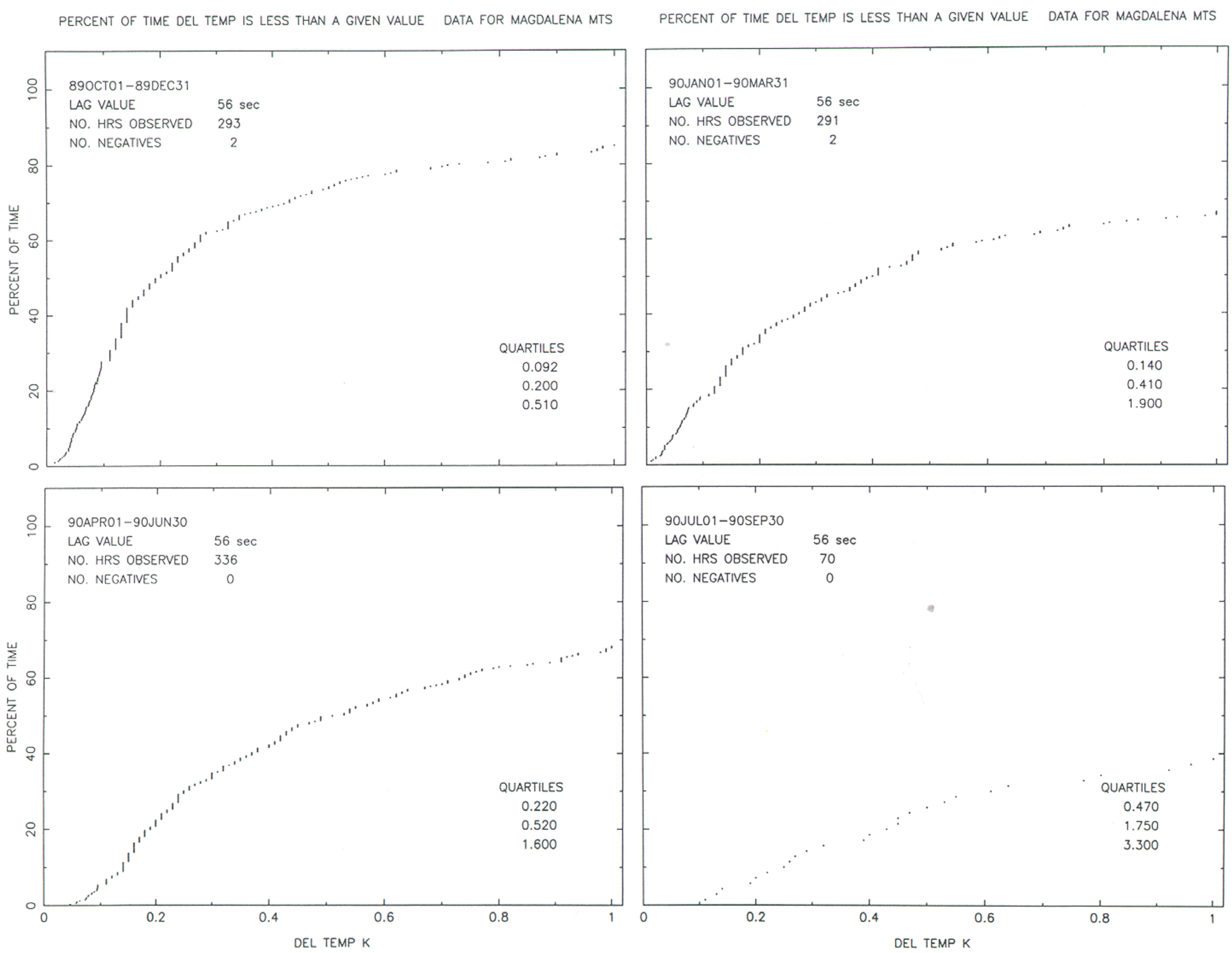
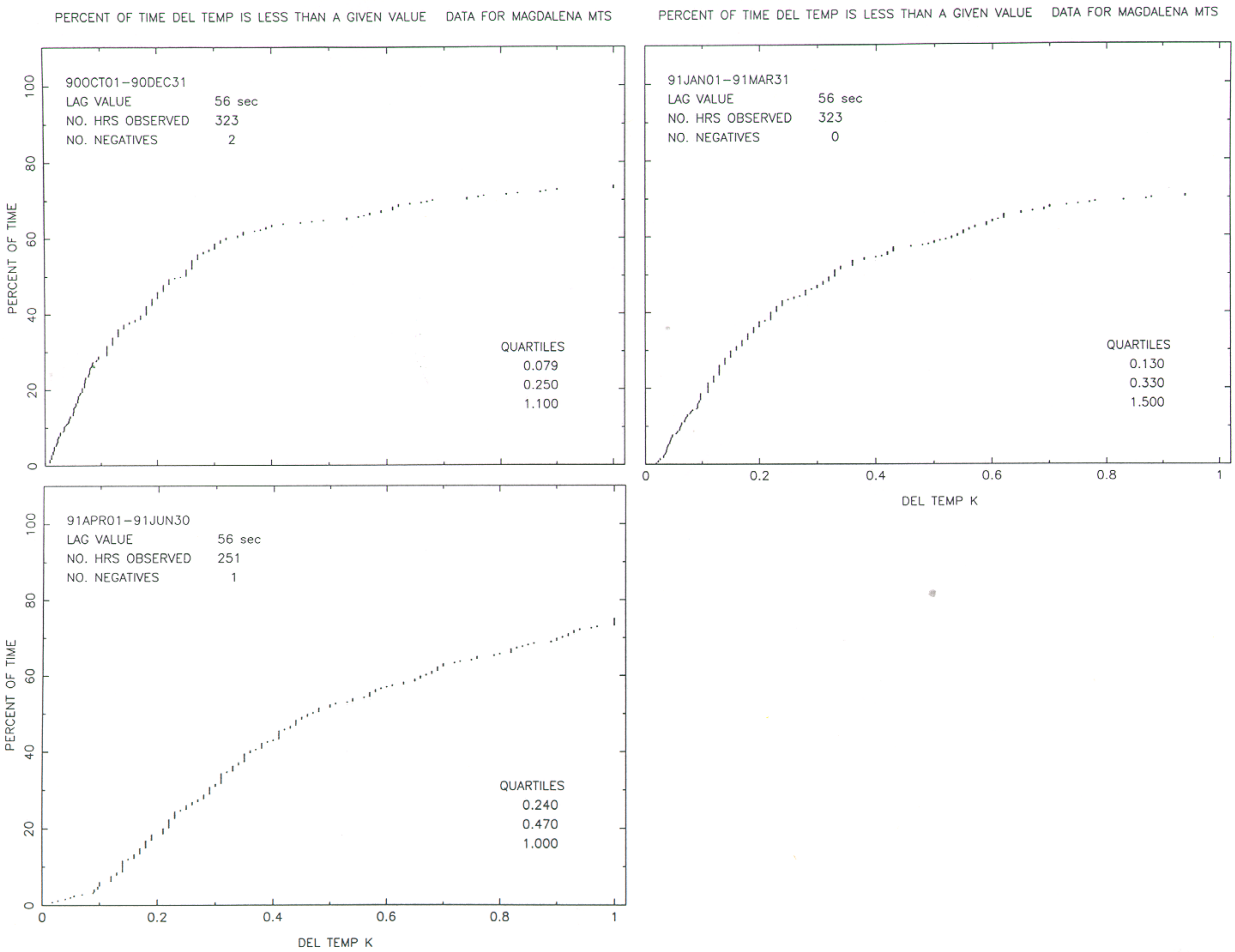

PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAGDALENA MTS
89OCT01-89DEC31
LAG VALUE 56 sec
NO. HRS OBSERVED 293
NO. NEGATIVES 2
QUARTILES
0.092
0.200
0.510
PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAGDALENA MTS
90JAN01-90MAR31
LAG VALUE 56 sec
NO. HRS OBSERVED 291
NO. NEGATIVES 2
QUARTILES
0.140
0.410
1.900
90APR01-90JUN30
LAG VALUE 56 sec
NO. HRS OBSERVED 336
NO. NEGATIVES 0
QUARTILES
0.220
0.520
1.600
90JUL01-90SEP30
LAG VALUE 56 sec
NO. HRS OBSERVED 70
NO. NEGATIVES 0
QUARTILES
0.470
1.750
3.300
PERCENT OF TIME
DEL TEMP K

Figure 5a



PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAGDALENA MTS
90OCT01-90DEC31
LAG VALUE 56 sec
NO. HRS OBSERVED 323
NO. NEGATIVES 2
QUARTILES
0.079
0.250
1.100
PERCENT OF TIME
PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAGDALENA MTS
91JAN01-91MAR31
LAG VALUE 56 sec
NO. HRS OBSERVED 323
NO. NEGATIVES 0
QUARTILES
0.130
0.330
1.500
DEL TEMP K
91APR01-91JUN30
LAG VALUE 56 sec
NO. HRS OBSERVED 251
NO. NEGATIVES 1
QUARTILES
0.240
0.470
1.000
PERCENT OF TIME
DEL TEMP K

Figure 5a

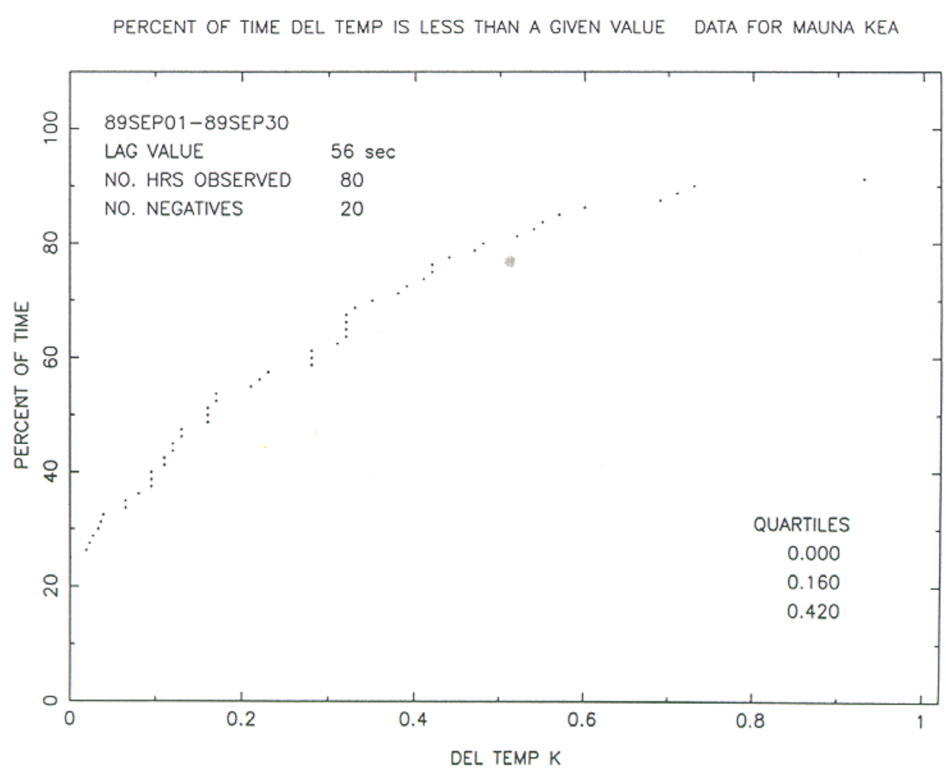
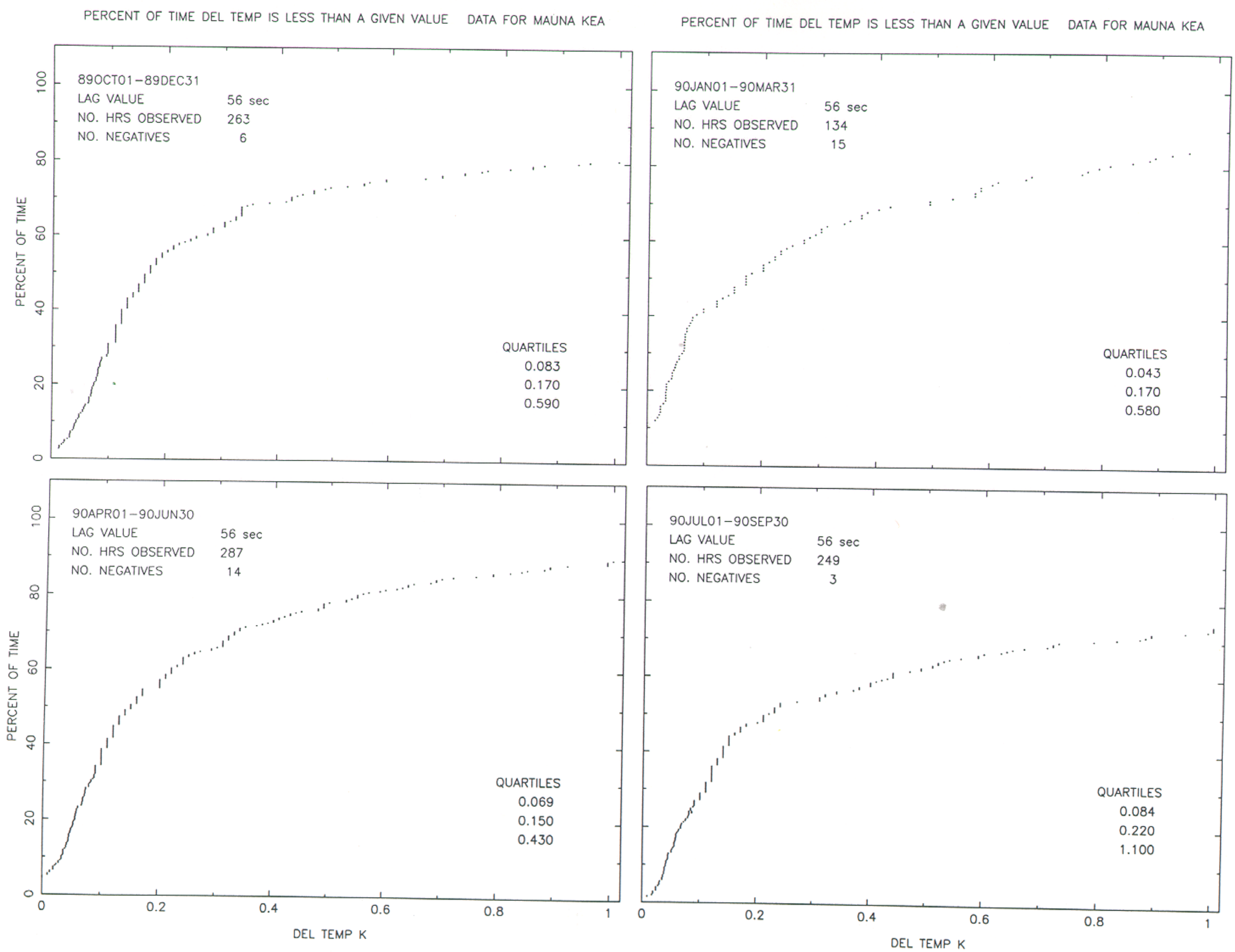

PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
89SEP01–89SEP30
LAG VALUE 56 sec
NO. HRS OBSERVED 80
NO. NEGATIVES 20
QUARTILES
0.000
0.160
0.420
PERCENT OF TIME
0
20
40
60
80
100
DEL TEMP K
0
0.2
0.4
0.6
0.8
1

Figure 5b



PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
89OCT01-89DEC31
LAG VALUE 56 sec
NO. HRS OBSERVED 263
NO. NEGATIVES 6
QUARTILES
0.083
0.170
0.590
90JAN01-90MAR31
LAG VALUE 56 sec
NO. HRS OBSERVED 134
NO. NEGATIVES 15
QUARTILES
0.043
0.170
0.580
90APR01-90JUN30
LAG VALUE 56 sec
NO. HRS OBSERVED 287
NO. NEGATIVES 14
QUARTILES
0.069
0.150
0.430
90JUL01-90SEP30
LAG VALUE 56 sec
NO. HRS OBSERVED 249
NO. NEGATIVES 3
QUARTILES
0.084
0.220
1.100
PERCENT OF TIME
0
20
40
60
80
100
DEL TEMP K
0
0.2
0.4
0.6
0.8
1

Figure 5b

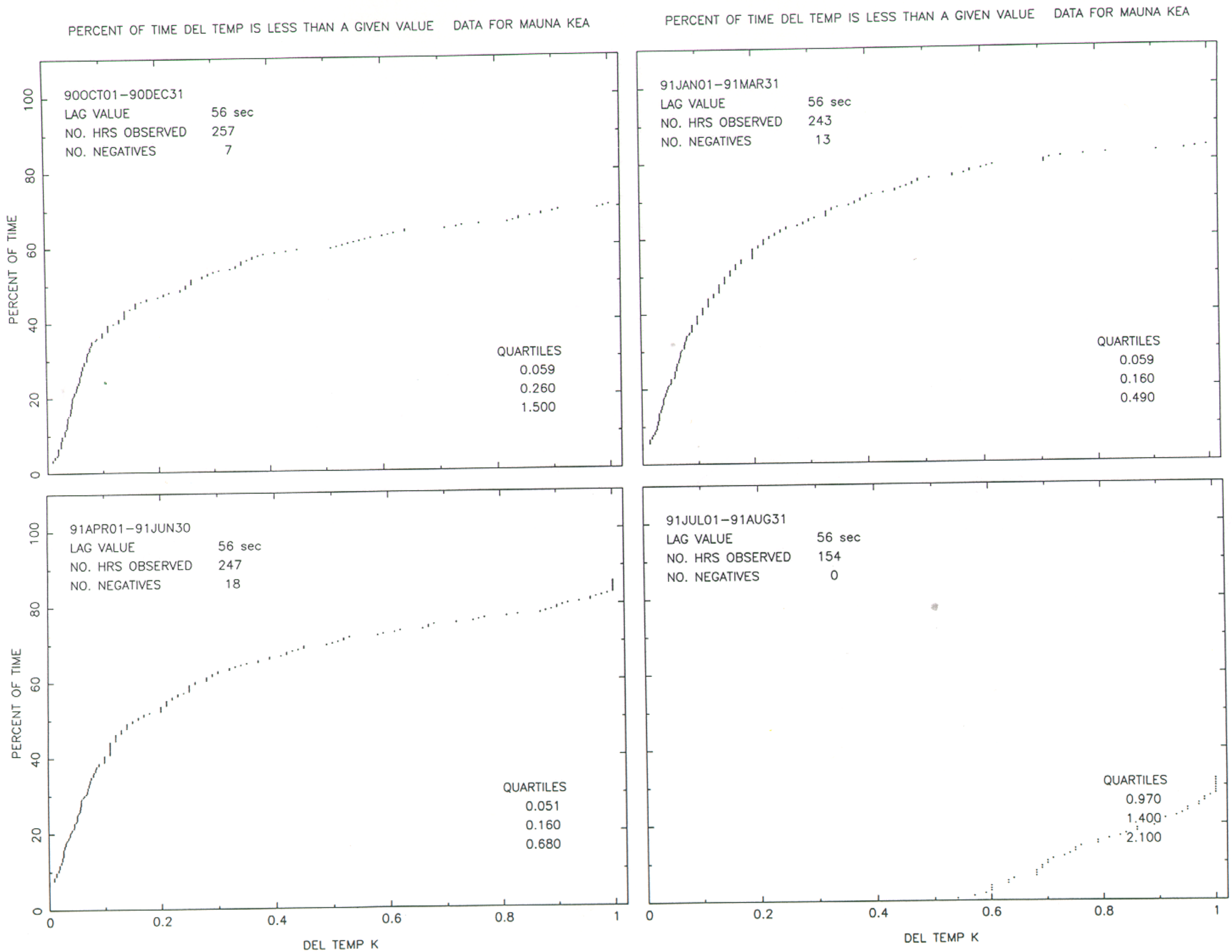

PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
90OCT01-90DEC31
LAG VALUE 56 sec
NO. HRS OBSERVED 257
NO. NEGATIVES 7
QUARTILES
0.059
0.260
1.500
PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR MAUNA KEA
91JAN01-91MAR31
LAG VALUE 56 sec
NO. HRS OBSERVED 243
NO. NEGATIVES 13
QUARTILES
0.059
0.160
0.490
91APR01-91JUN30
LAG VALUE 56 sec
NO. HRS OBSERVED 247
NO. NEGATIVES 18
QUARTILES
0.051
0.160
0.680
91JUL01-91AUG31
LAG VALUE 56 sec
NO. HRS OBSERVED 154
NO. NEGATIVES 0
QUARTILES
0.970
1.400
2.100
PERCENT OF TIME
DEL TEMP K

Figure 5b

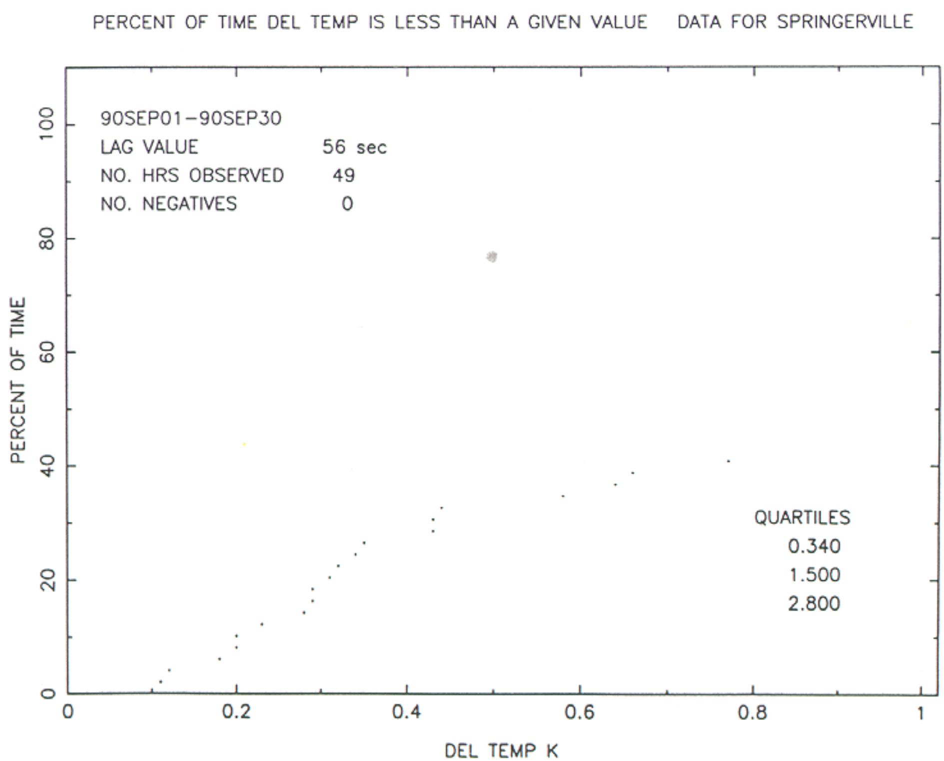

PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
90SEP01-90SEP30
LAG VALUE 56 sec
NO. HRS OBSERVED 49
NO. NEGATIVES 0
QUARTILES
0.340
1.500
2.800
PERCENT OF TIME
DEL TEMP K
0
20
40
60
80
100
0
0.2
0.4
0.6
0.8
1

Figure 5c

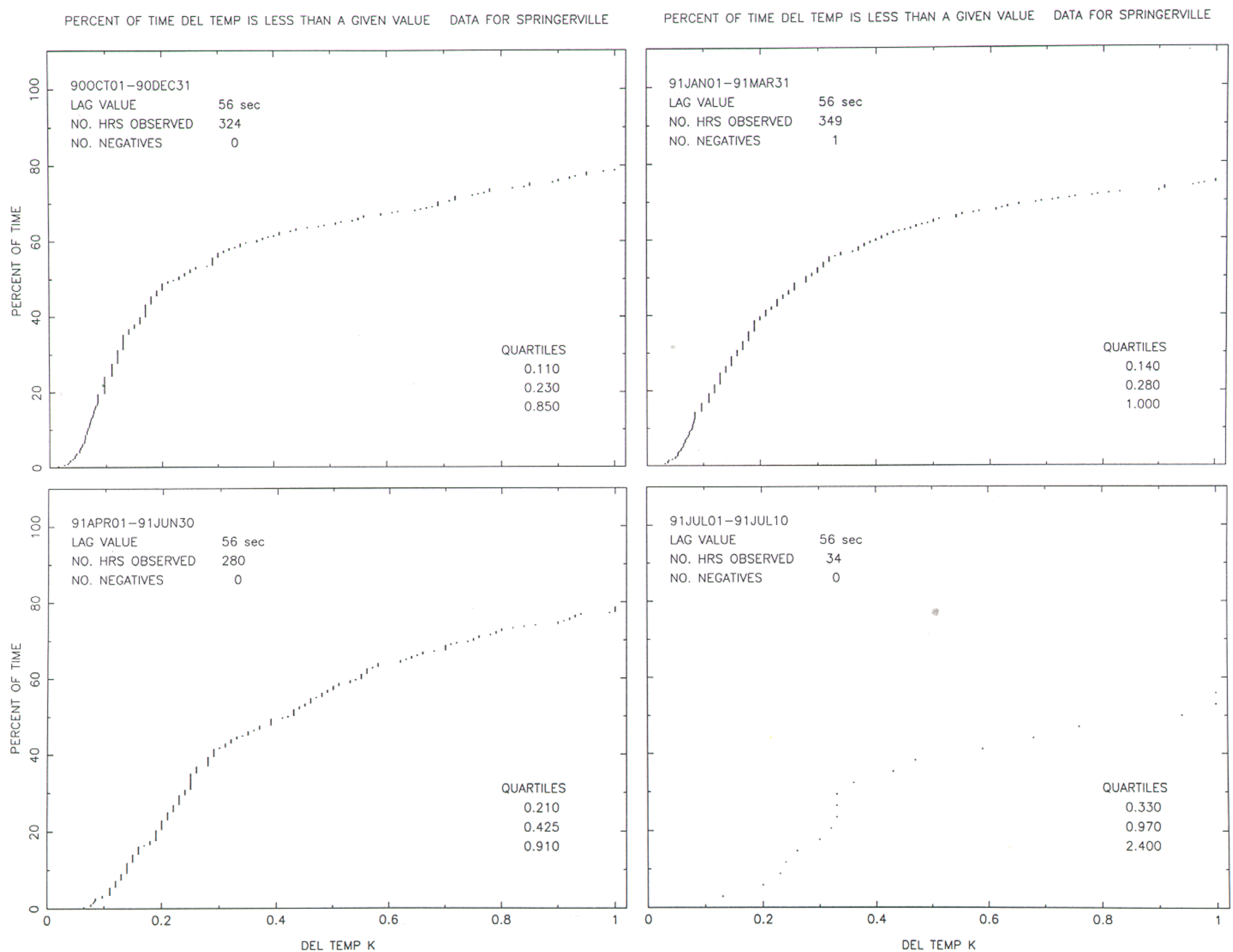

PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
90OCT01-90DEC31
LAG VALUE 56 sec
NO. HRS OBSERVED 324
NO. NEGATIVES 0
QUARTILES
0.110
0.230
0.850
PERCENT OF TIME DEL TEMP IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
91JAN01-91MAR31
LAG VALUE 56 sec
NO. HRS OBSERVED 349
NO. NEGATIVES 1
QUARTILES
0.140
0.280
1.000
91APR01-91JUN30
LAG VALUE 56 sec
NO. HRS OBSERVED 280
NO. NEGATIVES 0
QUARTILES
0.210
0.425
0.910
91JUL01-91JUL10
LAG VALUE 56 sec
NO. HRS OBSERVED 34
NO. NEGATIVES 0
QUARTILES
0.330
0.970
2.400
PERCENT OF TIME
DEL TEMP K

Figure 5c

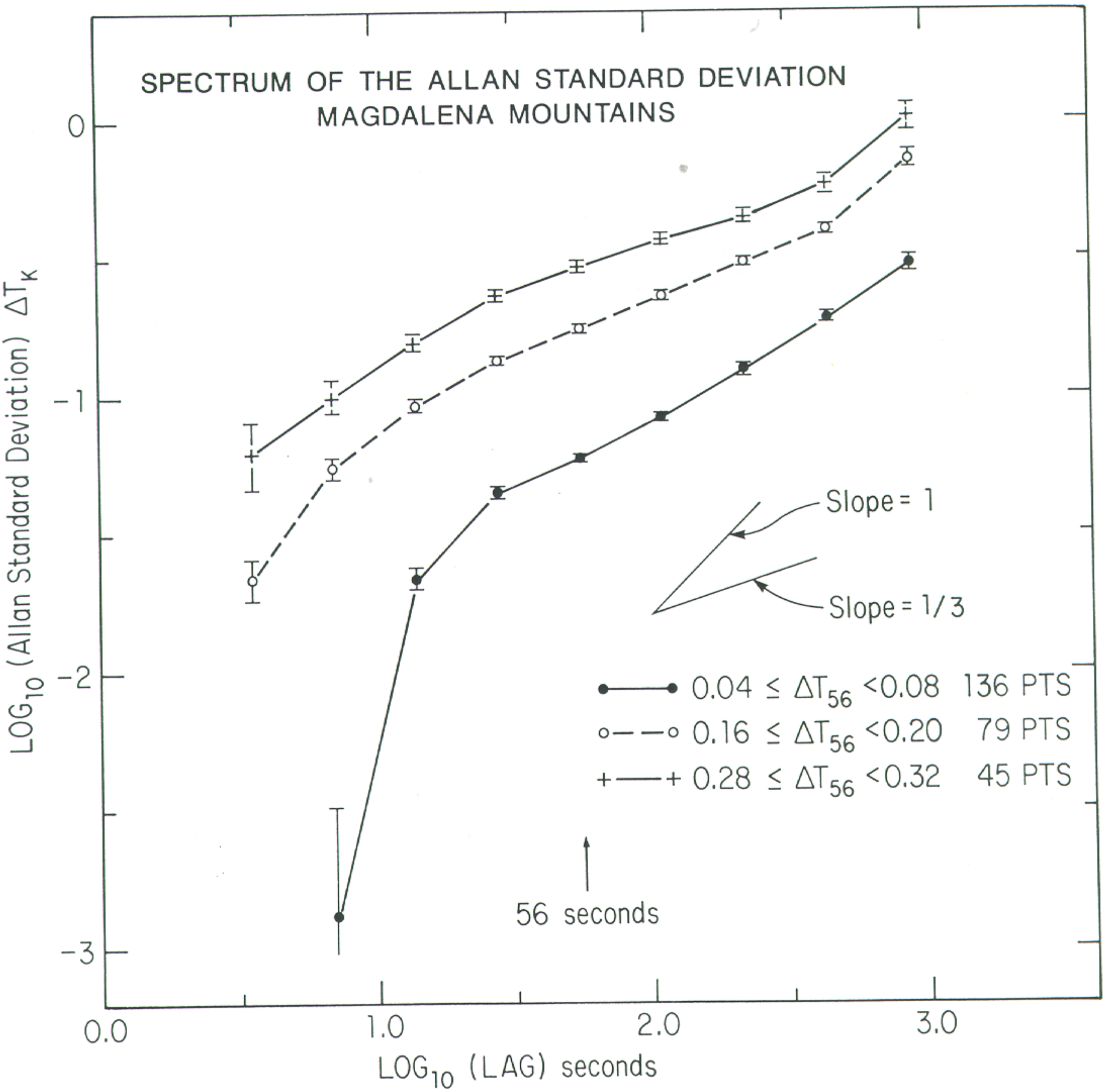
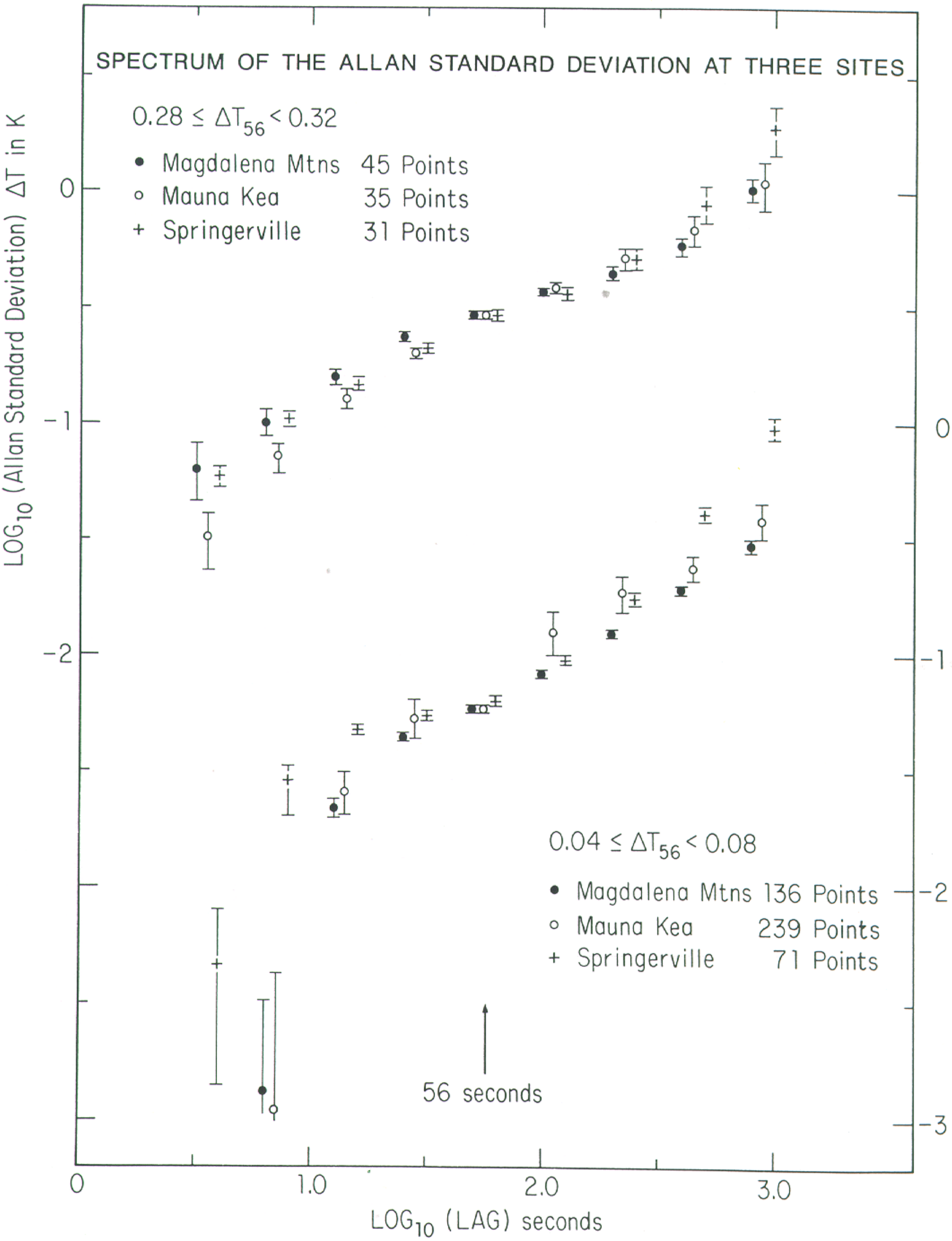

SPECTRUM OF THE ALLAN STANDARD DEVIATION
MAGDALENA MOUNTAINS
LOG10 (Allan Standard Deviation) ΔTK
0
−1
−2
−3
0.0
1.0
2.0
3.0
LOG10 (LAG) seconds
Slope = 1
Slope = 1/3
0.04 ≤ ΔT56 <0.08 136 PTS
0.16 ≤ ΔT56 <0.20 79 PTS
0.28 ≤ ΔT56 <0.32 45 PTS
56 seconds

Figure 6



SPECTRUM OF THE ALLAN STANDARD DEVIATION AT THREE SITES
0.28 ≤ ΔT56 < 0.32
• Magdalena Mtns 45 Points
○ Mauna Kea 35 Points
+ Springerville 31 Points
0.04 ≤ ΔT56 < 0.08
• Magdalena Mtns 136 Points
○ Mauna Kea 239 Points
+ Springerville 71 Points
56 seconds
LOG10 (Allan Standard Deviation) ΔT in K
LOG10 (LAG) seconds
0
1.0
2.0
3.0
0
−1
−2
−3

Figure 7

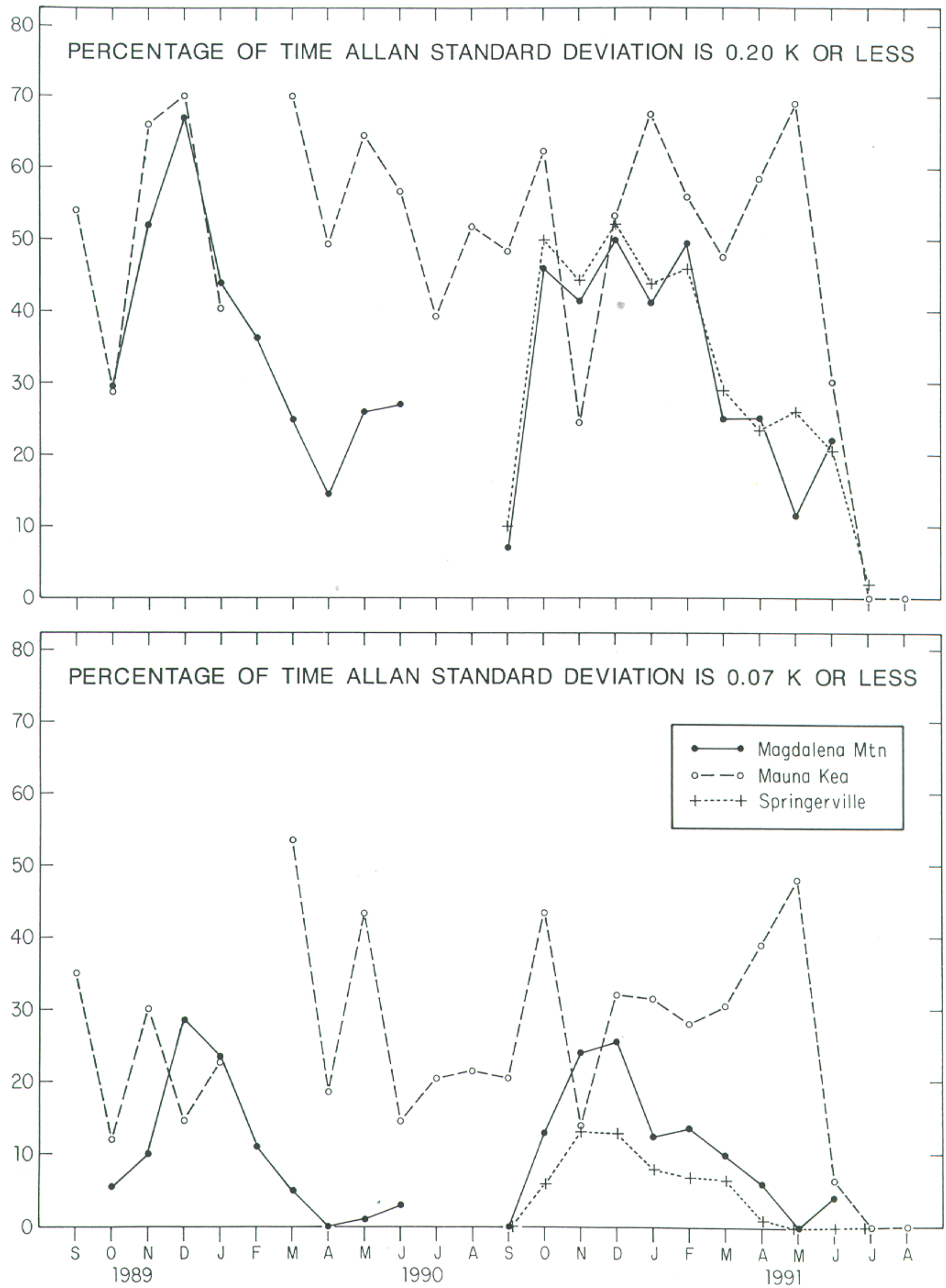

PERCENTAGE OF TIME ALLAN STANDARD DEVIATION IS 0.20 K OR LESS
PERCENTAGE OF TIME ALLAN STANDARD DEVIATION IS 0.07 K OR LESS
Magdalena Mtn
Mauna Kea
Springerville
0
10
20
30
40
50
60
70
80
S O N D J F M A M J J A S O N D J F M A M J J A
1989
1990
1991

Figure 8

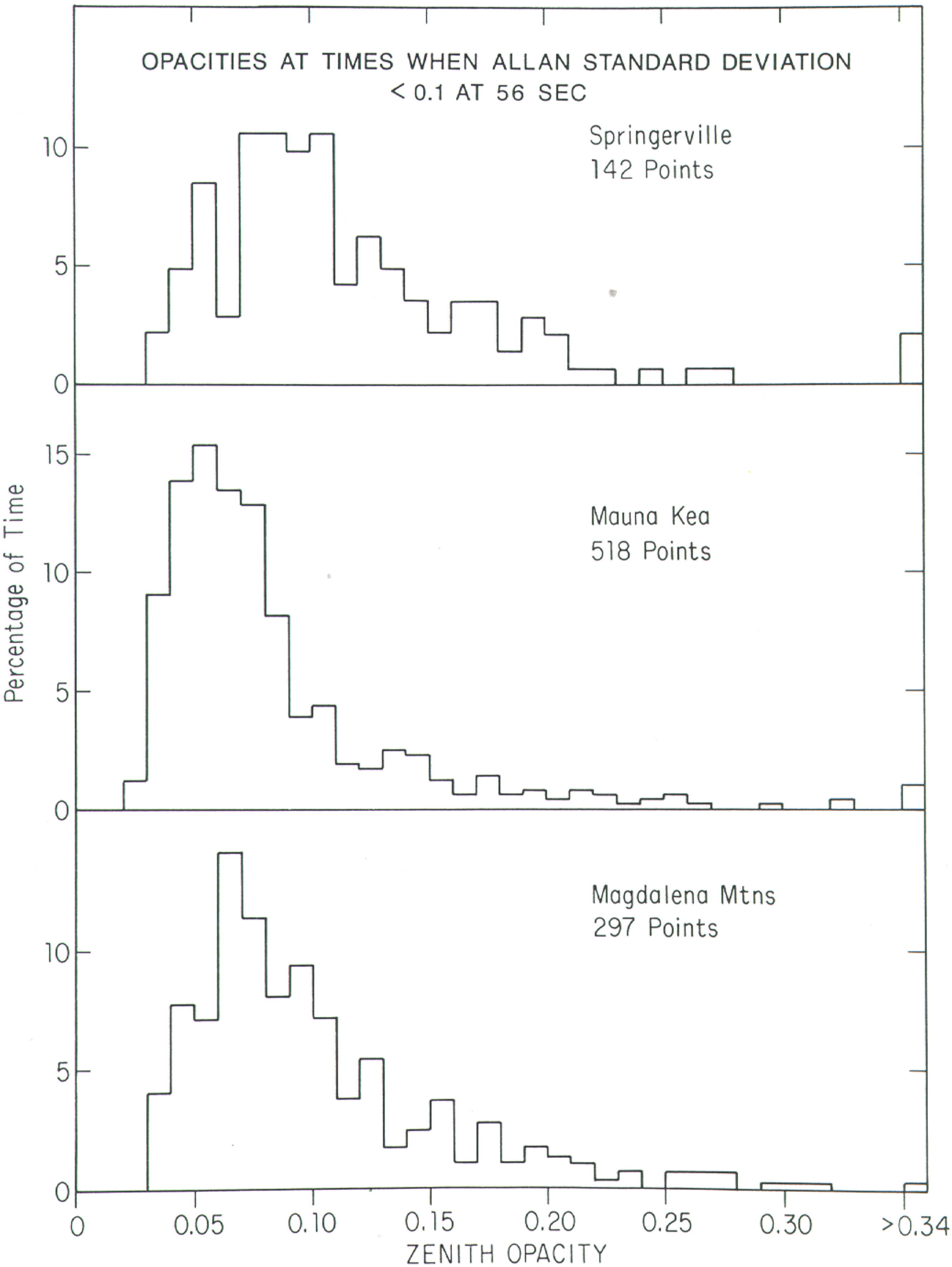

OPACITIES AT TIMES WHEN ALLAN STANDARD DEVIATION
< 0.1 AT 56 SEC
Springerville
142 Points
Mauna Kea
518 Points
Magdalena Mtns
297 Points
Percentage of Time
ZENITH OPACITY
0
5
10
15
0.05
0.10
0.15
0.20
0.25
0.30
>0.34

Figure 9

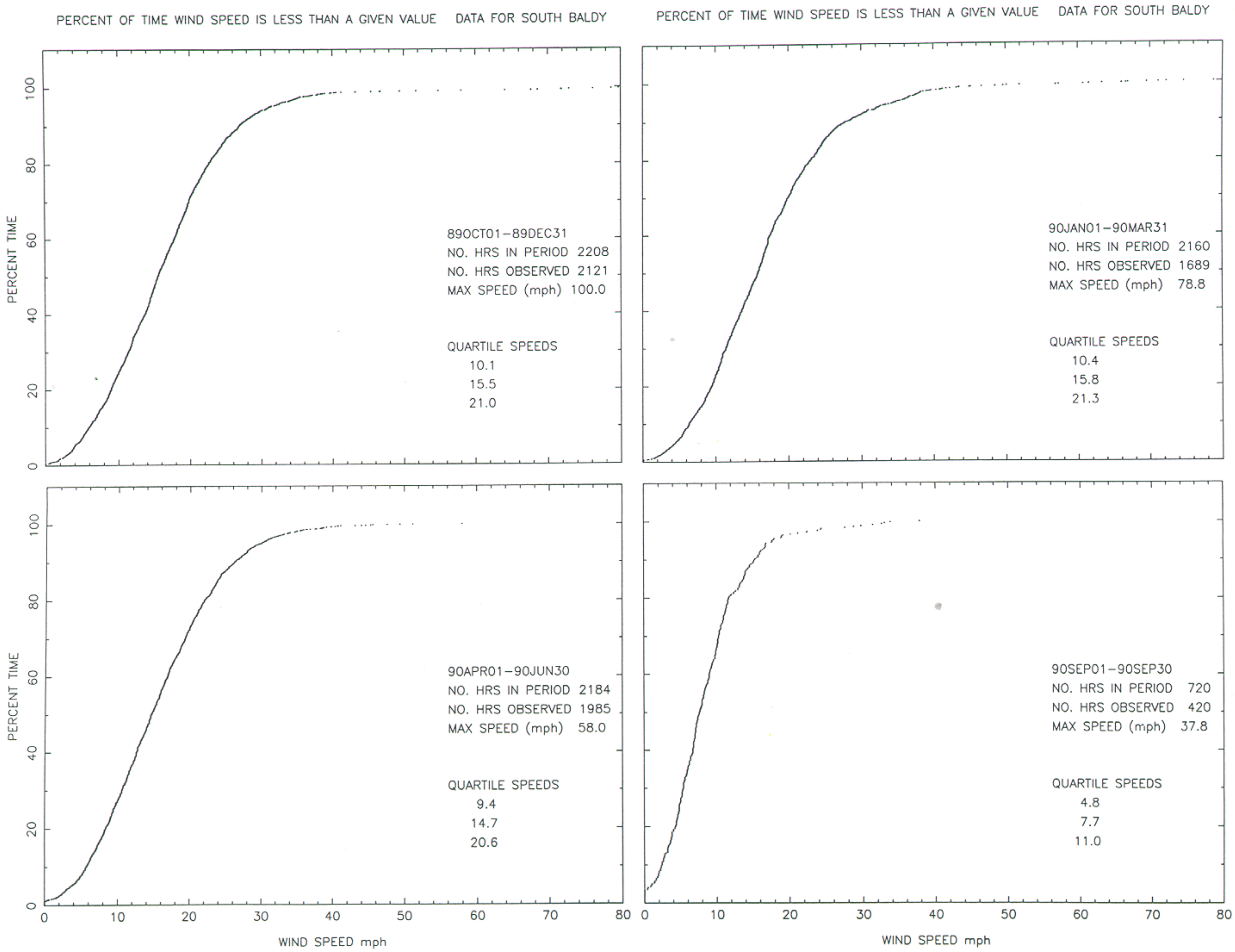

PERCENT OF TIME WIND SPEED IS LESS THAN A GIVEN VALUE
DATA FOR SOUTH BALDY
PERCENT TIME
89OCT01-89DEC31
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 2121
MAX SPEED (mph) 100.0
QUARTILE SPEEDS
10.1
15.5
21.0
PERCENT OF TIME WIND SPEED IS LESS THAN A GIVEN VALUE
DATA FOR SOUTH BALDY
90JAN01-90MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 1689
MAX SPEED (mph) 78.8
QUARTILE SPEEDS
10.4
15.8
21.3
PERCENT TIME
90APR01-90JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1985
MAX SPEED (mph) 58.0
QUARTILE SPEEDS
9.4
14.7
20.6
WIND SPEED mph
90SEP01-90SEP30
NO. HRS IN PERIOD 720
NO. HRS OBSERVED 420
MAX SPEED (mph) 37.8
QUARTILE SPEEDS
4.8
7.7
11.0
WIND SPEED mph

Figure 10a

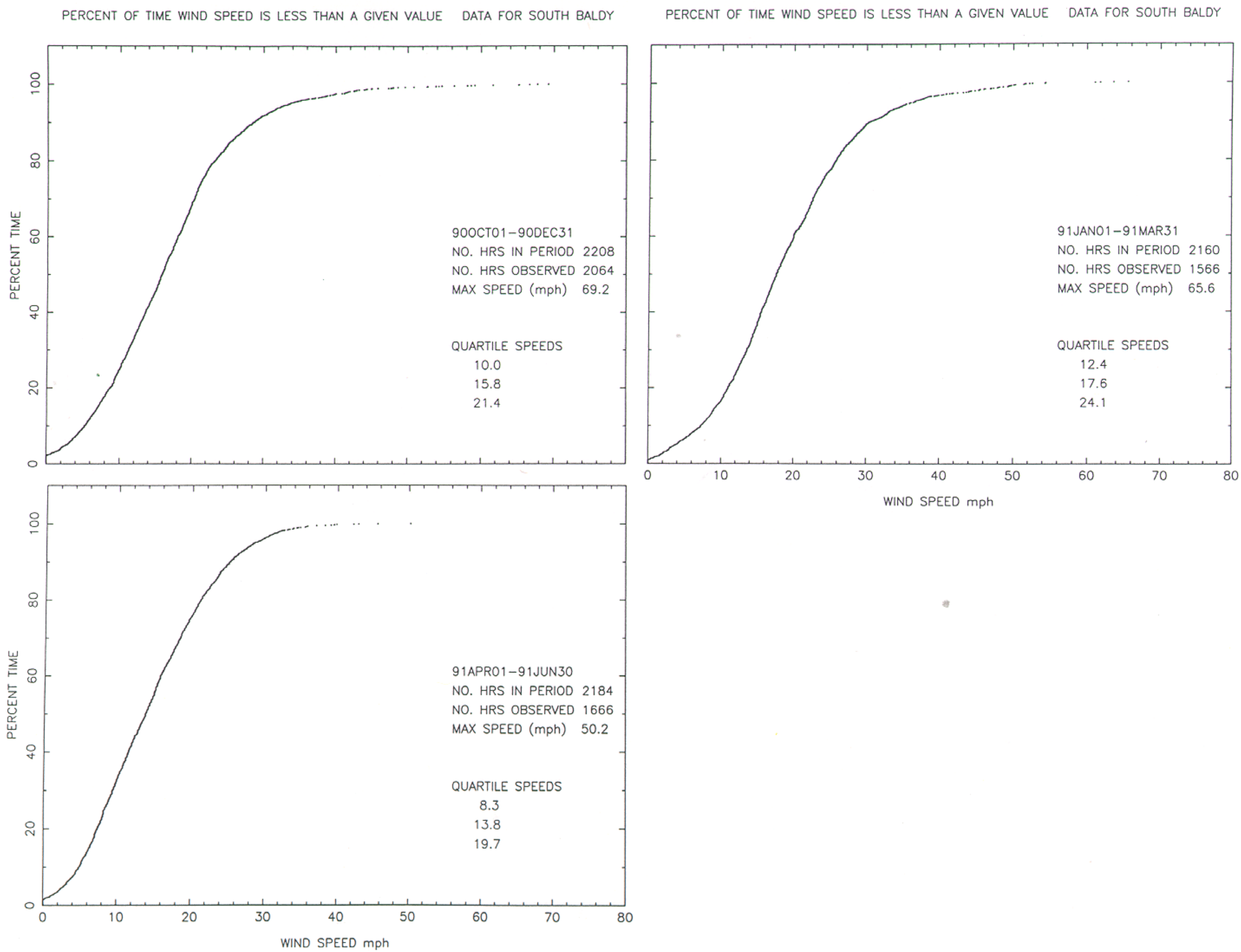

PERCENT OF TIME WIND SPEED IS LESS THAN A GIVEN VALUE DATA FOR SOUTH BALDY
PERCENT TIME
90OCT01-90DEC31
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 2064
MAX SPEED (mph) 69.2
QUARTILE SPEEDS
10.0
15.8
21.4
PERCENT OF TIME WIND SPEED IS LESS THAN A GIVEN VALUE DATA FOR SOUTH BALDY
91JAN01-91MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 1566
MAX SPEED (mph) 65.6
QUARTILE SPEEDS
12.4
17.6
24.1
WIND SPEED mph
PERCENT TIME
91APR01-91JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1666
MAX SPEED (mph) 50.2
QUARTILE SPEEDS
8.3
13.8
19.7
WIND SPEED mph

Figure 10a

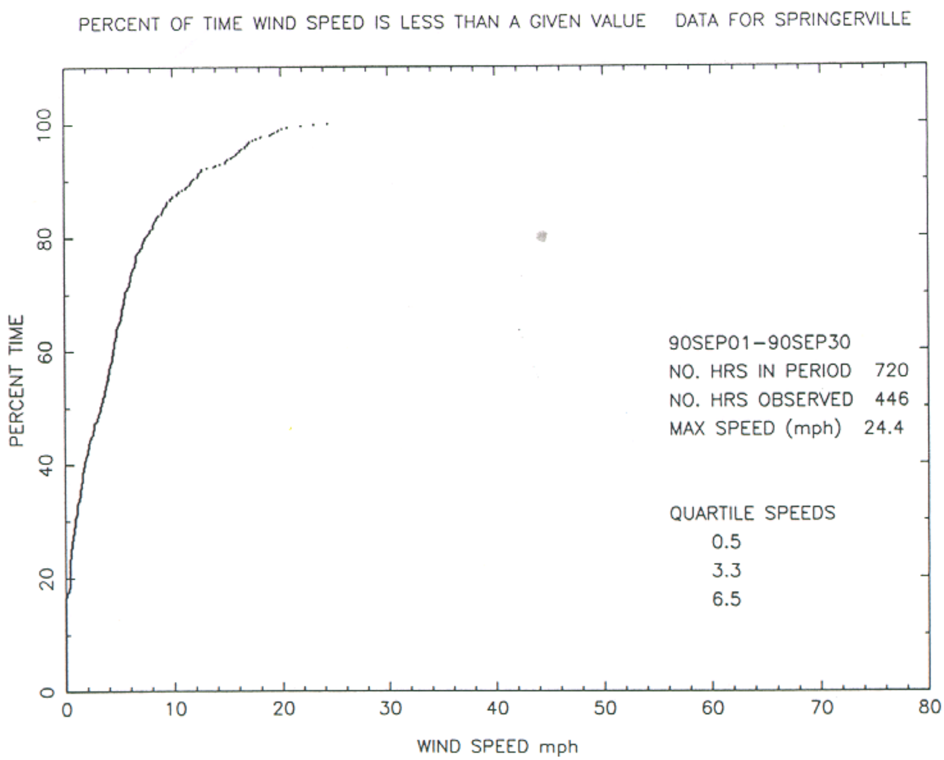

PERCENT OF TIME WIND SPEED IS LESS THAN A GIVEN VALUE
DATA FOR SPRINGERVILLE
PERCENT TIME
WIND SPEED mph
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80
90SEP01-90SEP30
NO. HRS IN PERIOD 720
NO. HRS OBSERVED 446
MAX SPEED (mph) 24.4
QUARTILE SPEEDS
0.5
3.3
6.5

Figure 10b

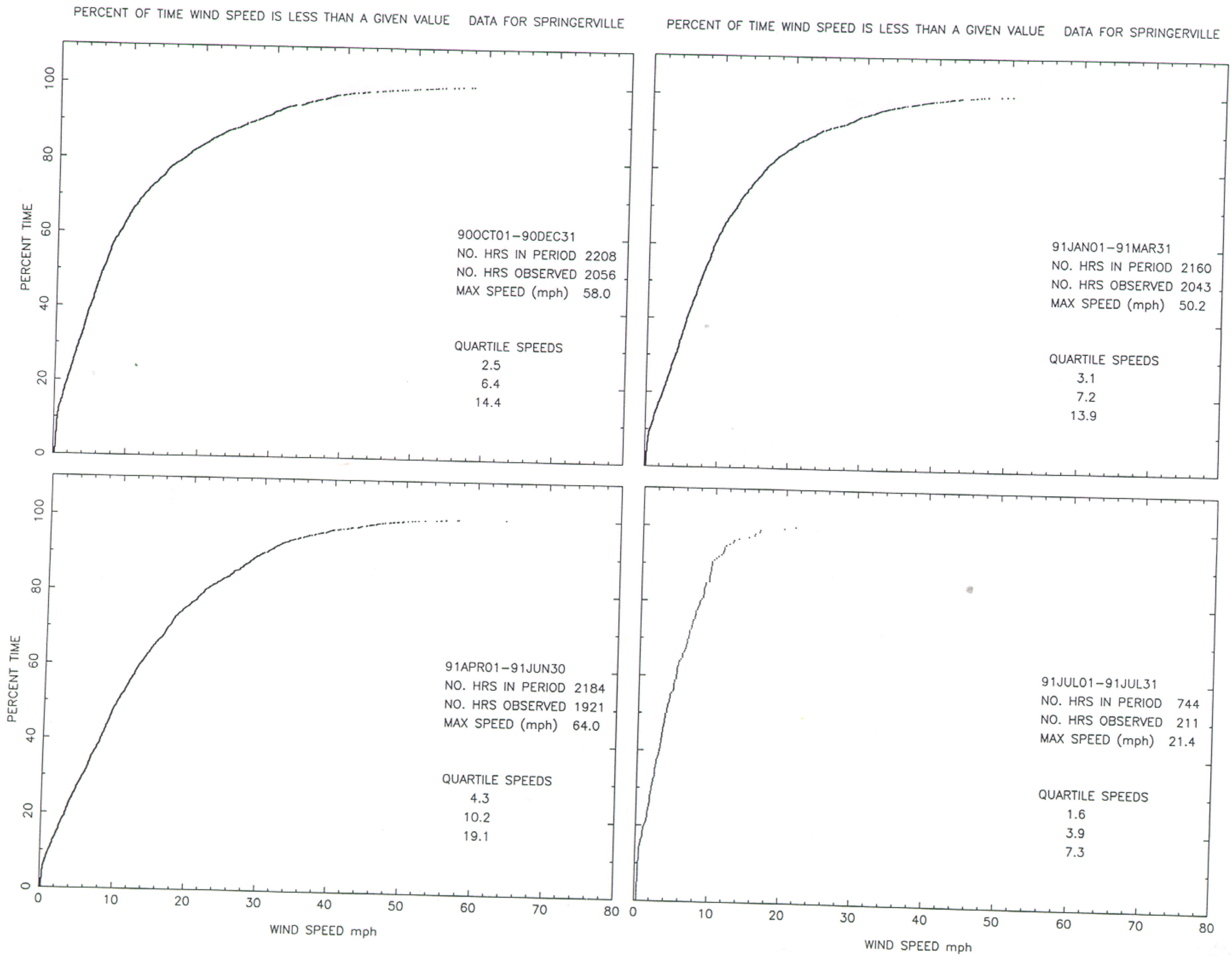

PERCENT OF TIME WIND SPEED IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
90OCT01–90DEC31
NO. HRS IN PERIOD 2208
NO. HRS OBSERVED 2056
MAX SPEED (mph) 58.0
QUARTILE SPEEDS
2.5
6.4
14.4
PERCENT OF TIME WIND SPEED IS LESS THAN A GIVEN VALUE DATA FOR SPRINGERVILLE
91JAN01–91MAR31
NO. HRS IN PERIOD 2160
NO. HRS OBSERVED 2043
MAX SPEED (mph) 50.2
QUARTILE SPEEDS
3.1
7.2
13.9
91APR01–91JUN30
NO. HRS IN PERIOD 2184
NO. HRS OBSERVED 1921
MAX SPEED (mph) 64.0
QUARTILE SPEEDS
4.3
10.2
19.1
91JUL01–91JUL31
NO. HRS IN PERIOD 744
NO. HRS OBSERVED 211
MAX SPEED (mph) 21.4
QUARTILE SPEEDS
1.6
3.9
7.3
PERCENT TIME
WIND SPEED mph

Figure 10b