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SURFACE-REFRACTIVITY MEASUREMENTS AT NASA SPACECRAFT TRACKING SITES

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16. Abstract

High-accuracy spacecraft tracking requires tropospheric modeling which is generally scaled by either estimated or measured values of surface refractivity. This report summarizes the results of a worldwide surface-refractivity test conducted in 1968 in support of the Apollo program. The results are directly applicable to all NASA radio-tracking systems.

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INTRODUCTION

Tracking data bias caused by the refractivity of the troposphere (and the remainder of the un-ionized atmosphere) is elevation-angle dependent: At 5° elevation, the bias may be up to 20 m in range, 50 cm/s in range rate, and several milliradians in angle (Reference 1); at the zenith, the tropospheric range bias decreases to 2 or 3 m, and the range rate and angle tropospheric biases tend to zero. The ionized portion of the upper atmosphere, the ionosphere, can also be a significant bias source, especially at spacecraft tracking frequencies below 2000 MHz. However, ionospheric effects are not discussed in this paper.

The frequency-independent tropospheric refraction effect on angle of arrival data is highly correlated with surface refractivity at the reception point of the radio wave. Range and range rate data tropospheric biases are due to integrated propagation delay effects; the greatest source of variability is the "wet term" contribution in the near-Earth refractivity. Refractivity N is simply a convenient means for specifying index of refraction n; the relation between the two is given by

$$n = 1 + N(10^{-6}) .$$

In this report, the measured time-dependent variation in surface refractivity is presented for 12 Apollo sites during 2 months in 1967 and for 15 sites during 8 consecutive months in 1968. This information is useful in estimating the absolute tracking accuracy attainable if, as generally is the case, average values of surface refractivity are used in the reduction of tracking data from any given site. The original purpose of this test was to ensure that the estimated monthly surface-refractivity values used by NASA's Manned Spacecraft Center (MSC) were adequate for the Apollo program. It was seen that Apollo tropospheric corrections were consistent with the spacecraft tracking accuracy required for the mission. All Apollo stations were assigned monthly average values of refractivity which in no case differed by more than 13 percent from the measured monthly averages.

However, for tracking experiments such as very-long-baseline interferometry (References 2 and 3), the tropospheric variations throughout the day or month cannot be neglected. This is also true for the stringent tracking accuracy associated with geodesy and Earth-physics studies (Reference 4), such as those now being undertaken at Goddard Space Flight Center (GSFC).

The best correction for tropospheric bias would of course be obtained from a measured profile along the ray path between tracking site and spacecraft. However, such information is not usually available; instead, some type of mathematical model is normally assumed. For purposes of radio refraction and time-delay correction, an exponential troposphere such as that presented by the National Bureau of Standards offers good agreement with measured profiles for most tracking applications (References 1 and 5). The scale height for such a model at any given site can be determined empirically as a function of surface refractivity (Reference 5) or derived from knowledge of the surface refractivity and the vertical integrated profile, the dry component of which is only a function of surface pressure.

It should be noted that for short-baseline interferometers, such as in the NASA Minitrack system, there is an inherent first-order correction for tropospheric biasing effects. This inherent correction results whenever one uses the free-space value of the wavelength of the arriving radio signal to calculate the short-baseline interferometer angle (Reference 6).

There are, of course, other tropospheric errors which may predominate, especially at elevation angles below about 10°. Horizontal gradients are not included in the usual model, in which a spherically stratified (i.e., horizontally homogeneous) troposphere is assumed. Also, at low elevation angles, tropospheric turbulence can introduce noise into the tracking measurements. However, these noise-like errors tend to be averaged out by the data-smoothing and orbit-computation processes and are therefore less serious than steady-state or biasing errors. It should be noted that the noise considered in the foregoing sense is not a radio noise, such as that attributed to thermal emission by the atmosphere, but rather a phase modulation of radio signals traversing regions of time-varying permittivity and hence time-varying radio index of refraction.

CALCULATION OF SURFACE REFRACTIVITY

The relationship between surface refractivity and total tropospheric biasing effects on tracking data is well established (Reference 7). This report is concerned only with presenting the means for calculating surface refractivity based on surface meteorological data and showing how this value of refractivity varies from site to site throughout the year. The relationship between meteorological data and refractivity is also well known. The relationship reported by Smith and Weintraub in 1953 (Reference 8) is still in widespread use by radio scientists throughout the world (Reference 9). Reference 9 presents an excellent review of the physics relating the radio dielectric constant (and, therefore, index of refraction) to the parameters of temperature, total air pressure, and relative humidity; the derivations will not be repeated here.

Scope of Test

Meteorological data were collected from the 15 Manned Space Flight Network (MSFN) stations listed in Table 1. Station personnel measured the air temperature, wet-bulb temperature (using various

Table 1–MSFN sites that participated in the surface-refractivity test.

Station	Station Name	Latitude (deg)	Longitude (deg)	Elevation Above Mean Sea Level (m)
MIL	Merritt Island, Florida	28.508 272	–80.693 417	9.2
BDA	Bermuda	32.351 286	–64.658 181	22.6
GBM	Grand Bahama	26.632 858	–78.237 664	11.4
ANG	Antigua Island	17.016 692	–61.752 689	34.4
CRO	Carnarvon, Australia	–24.907 592	113.724 247	44.5
HAW	Hawaii	22.124 897	–159.664 989	1150.9
GYM	Guaymas, Mexico	27.963 206	–110.720 850	23.9
TEX	Corpus Christi, Texas	27.653 750	–97.378 469	12.3
GWM	Guam	13.309 244	144.734 414	92.1
GDS	Goldstone, California	35.341 694	–116.873 289	973
ACN	Ascension Island	–7.955 056	–14.327 578	544.2
HSK (CNB)*	Canberra, Australia	–35.597 222	148.979 167	1130.8
MAD	Madrid, Spain	40.455 358	–4.167 394	785.1
CYI	Grand Canary Island	27.764 536	–15.634 536	160.4
TAN	Tananarive, Madagascar	–19.018 055	47.304 444	1385.2

*Call letters changed during test to HSK (Honeysuckle Creek).

types of psychrometers), and air pressure at an average time interval of 6 hours. The test[1] was conducted throughout August and September 1967 and then again on a continuous basis from February 1968 to September 1968. The raw data were mailed to GSFC from each station and entered onto computer cards which were then used as input to a computer program. This program performed the appropriate conversion of units, refractivity calculations, and plotting. The results were excellent: Based on the reasonable assumption that readings were made to within ±0.25 K in temperature, the absolute error in the surface refractivity N_s is less than 3 N-units (Reference 9). The corresponding relative changes (i.e., resolution) are of the order of ±0.3 N-units. Thus, the accuracy of the individual refractivity values calculated in this report is of the order of 1 percent (since N_s is of the order of 300). The corresponding resolution is 0.1 percent.

[1]P. E. Schmid, "MSFN Site Meteorological Data," memorandum to R. V. Capo, Manned Flight Operations Branch, GSFC, June 19, 1967.

Mathematical Formulation of Refractivity

All data mailed from the tracking sites included the time associated with each measurement. Since several different types of psychrometers, thermometers, and barometers were used by the various stations, some data conversion was required. Where necessary, the following relationships were used:

$$P_{(\mathrm{mb})} = P_{(\text{inches mercury})} \times 33.863\,95\,,$$

$$T_{(^\circ\mathrm{C})} = (T_{(^\circ\mathrm{F})} - 32) \times \frac{5}{9}\,,$$

$$T_{(\mathrm{K})} = T_{(^\circ\mathrm{C})} + 273.16\,.$$

The tropospheric surface index of refraction n_s, which is greater than unity, can be written as

$$n_s = 1 + N_s(10^{-6})\,. \tag{1}$$

The value of N_s ranges from a minimum of 200 to a maximum of 450, depending on geographical location, time of year, weather conditions, and so on (Reference 10) since N_s is a function of atmospheric temperature, pressure, and water-vapor content (Reference 9). That is,

$$N_s = \frac{77.6}{T}\left(P + \frac{4810e}{T}\right), \tag{2}$$

where T is the air, or dry-bulb, temperature (Kelvin); P is the total air pressure (in millibars); and e is the partial water-vapor pressure (in millibars). In turn, e is related to psychrometric measurements by (Reference 9)

$$e = e_s' - 0.000\,67(T - T')P\,, \tag{3}$$

where e_s' is the saturation vapor pressure (in millibars) at T' and T' is the wet-bulb temperature (Kelvin). The value of e_s' can be obtained directly from appropriate psychrometric charts (Reference 11). However, in order to facilitate computer computation, an empirical formulation was used, which resulted in negligible error relative to the uncertainty in the meteorological field measurements. The expression used to calculate the saturated vapor pressure in millibars is given by (Reference 12)

$$e_s' = 6.11 \times 10^{at/(b+t)}\,, \tag{4}$$

where $a = 7.5$, t is the wet-bulb temperature (Celsius), and $b = 237.3$. Note that

$$T' = t + 273.16 \text{ (Kelvin)}\,.$$

Thus, the value of N_s, which can be directly related to radio-wave tropospheric refraction and time delay, is determined by three basic measurements: (1) dry-bulb temperature, (2) wet-bulb temperature, and (3) total atmospheric pressure.

Once all the data for a particular month from a given station were processed, the monthly mean and standard deviation (SD) were computed, with

$$\text{mean} = \bar{N}_s = \sum_{i=1}^{m} \frac{N_{s_i}}{m} \tag{5}$$

$$\text{SD} = \left[\frac{1}{m-1} \sum_{i=1}^{m} (N_{s_i} - \bar{N}_s)^2 \right]^{1/2} , \tag{6}$$

where m is the number of observations.

The computer processed some 50 000 measurements and provided point-to-point, 35-mm-film plotting as well as printout of over 15 000 values of refractivity. The next section of this report presents the surface-refractivity measurement results.

SURFACE-REFRACTIVITY MEASUREMENT RESULTS

Monthly Variations

Table 2 summarizes the maximum, minimum, and monthly averages of refractivity as obtained from the 15 Apollo sites. The Antigua Island (ANG) station did not furnish pressure data; therefore, a nominal atmospheric pressure of 76.2 cm of mercury was used to obtain the ANG values in Table 2. This value of pressure corresponded to the average at Carnarvon, Australia, which is approximately the same height above sea level as Antigua (see Table 1). The maximum absolute variation in pressure at Carnarvon throughout the test was 1.5 cm of mercury. It is therefore estimated that the ANG values are correct to at least ±5 N-units. Also, it was noted (after the fact) that the GDS August and September 1967 pressure data were in error. Therefore, the values for these 2 months in Table 2 were computed with $P = 910$ mb, based on 1968 GDS data; the results for these 2 months were not plotted.

Figure 1 shows the measured total atmospheric average pressure during mid-May 1968. The expected correlation between station altitude and pressure (Figure 1) is quite apparent. In this test, the pressure values were seen to be primarily a function of station altitude, with maximum variation of only a few percent of total pressure throughout the test.

The computer plots of refractivity measurements versus time from all sites (except ANG) are presented in Appendix A. These results clearly show the degree of variability in surface refractivity one can expect throughout any given month. The 1-sigma spread is seen to be typically ±10 to ±15 N-units over a given month, depending on geographical location. The value of SD is a measure of the variability throughout a given month for a particular station. It is not an indication of measurement accuracy. The maximum and minimum values of refractivity reflect temperature extremes (low temperatures resulting in high refractivity and vice versa). The plots indicate the diurnal variations, which again are primarily temperature dependent, with lower temperatures generally being associated with local night.

Table 2–Monthly values of refractivity in *N*-units.

Year	Month	Value	ACN	ANG	BDA	CRO	CYI	GBM	GDS	GWM	GYM	HAW	HSK*	MAD	MIL	TAN	TEX
1967	Aug.	Max	368.1	–	388.3	366.4	367.9	393.5	340.7	398.2	430.0	334.7	–	335.8	394.9	311.6	395.6
		Min	313.7		343.9	306.2	299.4	365.8	237.4	372.2	351.2	295.8		251.9	319.2	262.2	314.3
		Avg	336.4		367.3	331.4	334.4	378.9	283.1	386.3	380.6	314.8		282.9	378.8	286.8	375.7
		SD	7.4		9.0	11.4	10.4	5.9	17.2	5.3	13.7	7.8		14.3	13.2	8.9	16.9
	Sept.	Max	351.6	–	393.4	364.7	358.1	413.0	335.5	396.3	450.1	335.5	–	321.3	391.6	334.7	399.9
		Min	296.3		322.3	288.9	264.1	364.5	243.2	347.8	317.0	290.4		258.3	303.6	260.9	318.6
		Avg	338.2		360.7	333.9	338.7	381.1	286.2	384.6	373.2	313.8		285.9	372.0	291.3	371.9
		SD	8.9		13.6	15.1	11.4	8.2	18.6	7.0	19.7	7.8		10.5	11.5	10.8	18.0
1968	Feb.	Max	361.2	–	358.1	391.3	353.1	370.6	327.5	388.8	356.1	319.6	315.4	310.0	350.7	338.1	370.7
		Min	329.3		300.8	323.9	295.2	288.1	273.1	325.3	299.4	283.3	252.1	256.5	280.0	275.9	313.4
		Avg	349.2		322.9	367.3	327.5	334.2	293.6	367.9	328.8	306.2	287.5	292.9	315.2	308.5	337.6
		SD	5.6		12.0	13.6	12.3	15.6	12.4	11.1	11.9	7.7	14.2	7.3	17.7	8.8	12.2
	Mar.	Max	364.9	369.6	358.3	385.7	352.5	369.4	315.9	423.7	355.8	329.5	323.6	307.9	370.5	328.3	392.8
		Min	323.9	328.9	301.5	326.9	295.5	307.0	247.2	325.8	288.2	286.7	263.5	274.5	275.3	287.9	323.1
		Avg	351.3	351.2	328.9	357.1	322.5	338.4	287.7	377.6	322.2	306.2	294.8	291.5	326.0	310.3	354.7
		SD	6.7	8.2	13.0	13.6	9.5	12.9	12.8	12.2	15.9	7.9	14.5	8.1	20.6	7.7	17.4
	Apr.	Max	361.6	386.8	358.9	402.1	350.4	381.6	312.9	406.5	378.4	331.1	312.6	315.7	380.4	320.5	418.9
		Min	333.5	319.3	309.4	319.0	309.0	321.6	246.7	348.3	289.0	283.6	274.2	278.7	267.4	272.1	338.4
		Avg	348.9	361.6	333.4	353.2	327.3	354.6	284.2	378.3	326.5	309.3	290.9	294.9	341.9	302.2	374.9
		SD	5.6	12.6	11.6	14.4	8.4	13.5	12.5	13.2	16.2	8.1	7.9	8.4	25.8	8.3	15.1
	May	Max	362.7	386.2	385.2	364.8	354.6	394.6	316.6	423.1	384.7	334.1	309.1	318.5	384.6	313.8	414.9
		Min	329.1	357.3	293.7	308.8	306.3	318.8	249.5	351.9	300.7	291.9	271.3	249.4	263.9	274.8	322.9
		Avg	346.9	372.3	345.5	337.8	330.7	369.3	287.4	382.8	339.9	309.8	287.5	288.8	352.1	294.7	381.4
		SD	6.5	5.3	21.0	11.4	10.3	13.1	15.6	13.2	19.9	7.3	8.1	10.6	21.0	8.5	11.1
	June	Max	359.6	390.4	395.9	369.9	359.0	409.6	328.0	395.1	404.0	335.5	293.4	325.1	390.7	308.4	400.8
		Min	323.0	357.6	325.4	322.1	317.6	359.3	230.7	364.4	316.9	294.6	254.5	255.7	312.5	264.8	365.7
		Avg	343.0	374.7	364.9	342.8	337.3	383.6	285.2	381.2	367.6	311.0	279.7	286.5	370.0	289.4	385.4
		SD	7.3	6.5	14.9	9.6	8.4	7.2	21.5	5.7	17.0	7.5	6.5	12.7	11.5	7.3	6.6

	July	Max	348.6	390.4	394.9	357.5	359.9	420.2	328.6	396.6	430.0	334.6	289.5	321.3	386.6	311.4	433.6
		Min	317.4	344.4	349.1	307.4	312.2	356.1	258.4	370.9	344.0	292.3	256.4	261.0	336.2	284.3	370.2
		Avg	336.8	375.2	372.8	337.5	337.8	383.5	281.9	384.6	381.6	315.5	278.8	285.0	372.5	294.2	385.3
		SD	6.0	7.0	10.1	9.2	12.0	8.4	16.5	6.1	12.7	7.9	5.4	13.8	10.1	7.3	7.4
	Aug.	Max	346.2	395.4	399.7	367.1	370.3	399.8	319.9	406.7	418.2	336.7	288.9	288.2	402.5	305.4	398.4
		Min	325.0	367.5	336.3	319.9	315.2	373.8	253.2	358.2	326.8	272.2	262.4	246.8	336.2	261.0	362.3
		Avg	334.3	379.7	372.9	337.5	342.9	385.3	280.3	384.7	384.3	312.6	278.0	266.2	372.2	291.3	382.7
		SD	5.9	6.0	12.2	9.3	11.6	5.9	15.9	7.0	13.8	9.4	4.7	8.0	9.0	8.2	7.4
	Sept.	Max	353.1	418.5	395.9	403.8	365.2	398.8	298.4	401.9	421.7	331.9	293.9	362.3	387.8	306.8	399.2
		Min	316.6	365.3	321.1	318.6	289.5	362.6	249.8	317.7	316.0	299.0	262.8	244.7	325.2	250.7	336.2
		Avg	336.8	377.6	362.3	345.6	341.6	382.1	270.3	383.9	378.3	314.7	278.0	293.1	365.3	289.6	375.9
		SD	5.9	6.6	17.7	15.6	15.1	8.1	12.6	9.3	20.8	7.1	5.4	13.1	11.6	11.7	16.0

*No data available for 1967.

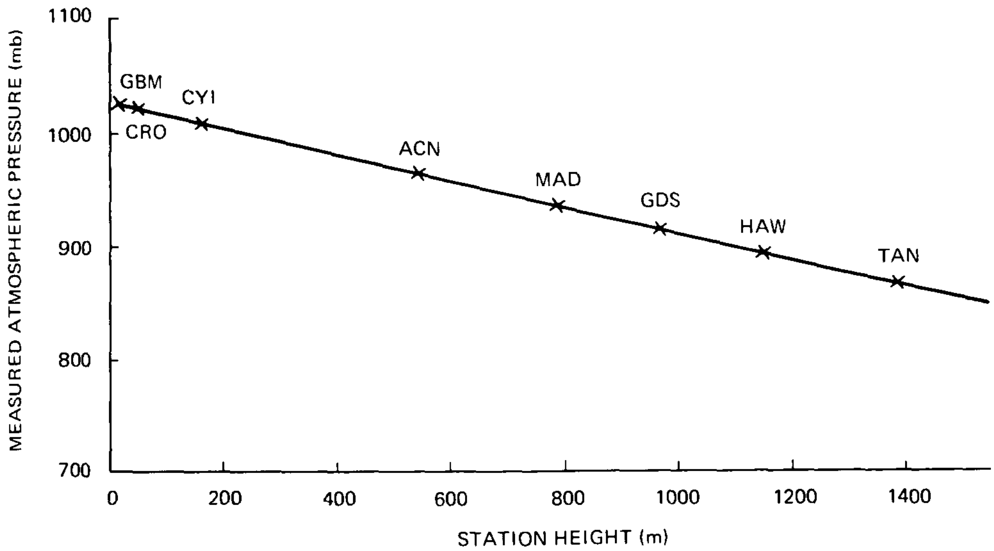

Figure 1—Example of measured atmospheric pressure distribution. The pressures are averages for May 25 to 26, 1968.

Monthly Averages Compared With Apollo Values

Table 3 lists the monthly average refractivity estimates used in the Apollo program. Table 4 presents the differences between the measured monthly averages and the corresponding Apollo estimates. In general, the agreement is good (within 13 percent or better for all cases), considering the fact that the measured monthly averages ranged from 266 to 385 in 1968, with individual values ranging from 231 to 434. Where the Apollo refractivity averages are consistently above or below the observed monthly averages (for example, BDA or CRO), some adjustment of the Apollo values may be warranted.

Table 5 compares the August 1967 to August 1968 and September 1967 to September 1968 monthly average refractivity. The year-to-year variation in the monthly average refractivity in all cases is less than 6 percent and in several instances is less than 0.5 percent.

CONCLUDING REMARKS

The monthly average refractivity values used in the Apollo program are in all cases within 13 percent of the measured values.

At any given site, humidity and temperature variations were seen to be the primary cause of changes in refractivity. Changes in air pressure at a given site (in the absence of temperature and humidity variations) were noted to result in a maximum change in refractivity of approximately ±5 N-units per year.

This test has shown given site time variations in surface refractivity, a scaling quantity in most mathematical models for the troposphere. A necessary continuing study is the comparison of mathematical models of the troposphere with measured profiles (e.g., Reference 13). An efficient and accurate algorithm for computing satellite tracking data tropospheric corrections is given in Reference 14.

Table 3—Monthly average refractivity estimates used in the Apollo program.

Station	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
ACN	361	364	366	363	361	356	353	353	354	356	355	357
ANG	360	359	359	361	372	375	378	379	376	377	372	366
BDA	335	333	335	343	353	372	377	378	371	359	345	338
CRO	338	339	341	348	362	378	385	386	381	361	349	339
CYI	333	336	336	335	338	346	343	352	354	350	343	336
GBM	343	354	352	361	370	375	386	383	384	373	364	356
GDS	279	281	278	279	297	277	279	279	278	277	276	279
GWM	372	377	378	383	381	377	373	379	381	380	375	379
GYM	318	322	320	321	331	351	368	370	372	346	328	321
HAW	299	298	297	299	301	305	308	310	309	309	304	302
HSK	306	312	309	293	300	297	296	295	298	301	300	301
MAD	295	293	295	294	298	302	299	300	306	304	299	296
MIL	338	339	341	348	362	378	385	386	381	361	349	339
TAN	310	310	313	305	298	292	291	290	291	293	303	310
TEX	328	333	340	350	362	377	395	375	372	353	336	334

Table 4—Observed minus Apollo values of N_s.*

Station	1967		1968							
	Aug.	Sept.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
ACN	-17	-16	-15	-15	-14	-14	-13	-16	-19	-17
ANG	—	—	—	-8	+1	0	0	-3	+1	+2
BDA	-11	-10	-10	-6	-10	-7	-7	-4	-5	-9
CRO	+9	+9	+19	+13	+19	+11	+14	+13	+15	+21
CYI	-18	-15	-8	-13	-8	-7	-9	-5	-9	-12
GBM	-4	-3	-20	-14	-6	-1	+9	-2	+2	-2
GDS	+4	+8	+13	+10	+5	-10	+8	+3	+1	-8
GWM	+7	+4	-9	0	-5	+2	+4	+12	+6	+3
GYM	+11	+1	+7	+2	+6	+9	+17	+14	+14	+6
HAW	+5	+5	+8	+9	+10	+9	+6	+8	+3	+6
HSK	—	—	-24	-14	-2	-12	-17	-17	-17	-20
MAD	-17	-20	0	-3	+1	-9	-15	-14	-34	-13
MIL	-7	-9	-24	-15	-6	-10	-8	-12	-14	-16
TAN	-3	0	-2	-3	-3	-3	-3	+3	+1	-1
TEX	+1	0	+5	+15	+25	+19	+8	-10	+8	+4

*The Apollo values are NASA-MSC best estimates of monthly averages at each site. The same values are used each year. The range of the measured 1968 monthly average ΔN_s is 119, the maximum being 385 (TEX, June 1968) and the minimum being 266 (MAD, August 1968). These values are best estimates based on past meteorological surveys such as compiled in Reference 10.

Table 5—Year-to-year variation in the August and September averages of N_s for 1967 and 1968.

Station	August 1967	August 1968	$\|\Delta N\|$	September 1967	September 1968	$\|\Delta N\|$
ACN	336	334	2	338	337	1
ANG	no data	380	–	no data	378	–
BDA	367	373	6	361	362	1
CRO	331	338	7	334	346	12
CYI	334	343	9	339	342	3
GBM	379	385	6	381	382	1
GDS	283	280	3	286	270	16
GWM	386	385	1	385	384	1
GYM	381	384	3	373	378	5
HAW	315	313	2	314	315	1
HSK	no data	278	–	no data	278	–
MAD	283	266	17	286	293	7
MIL	379	372	7	372	365	7
TAN	287	291	4	291	290	1
TEX	376	383	7	372	376	4

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The cooperation of all participating tracking-site personnel is especially acknowledged since this refractivity survey was possible only as a consequence of their dedicated support. The efficiency of the data handling and computer programming is due primarily to J. F. Cook, R. V. Capo, and B. Rosenbaum (NASA-GSFC); C. K. Lambert and J. Harlow (formerly with Bendix); and H. G. De Vezin (NASA-MSC).

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, September 28, 1971
311-80-43-01-51

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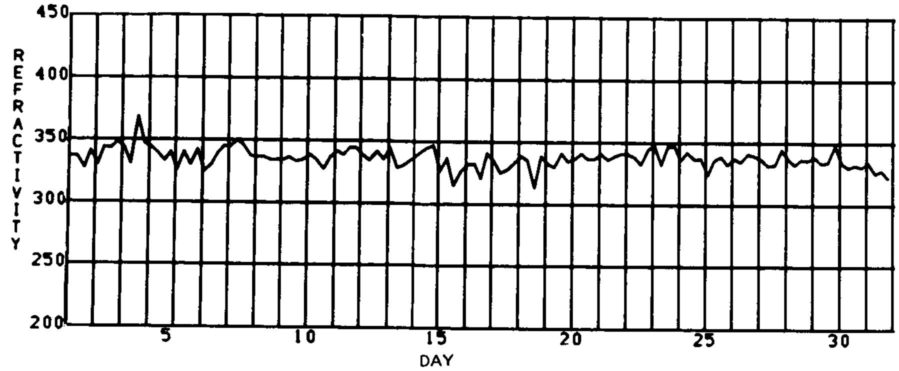
Appendix A

Computer Plots of Refractivity Versus Time

ACN

MAX	368.1
MIN	313.7
AVG	336.4
SD	7.4

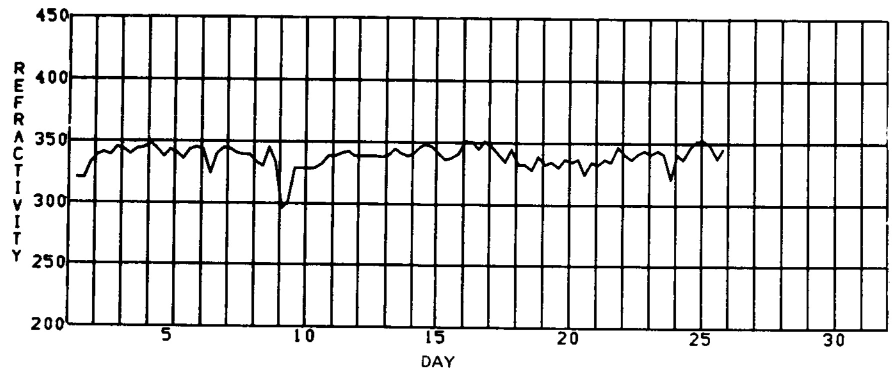
AUGUST 1967



ACN

MAX	351.6
MIN	296.3
AVG	338.2
SD	8.9

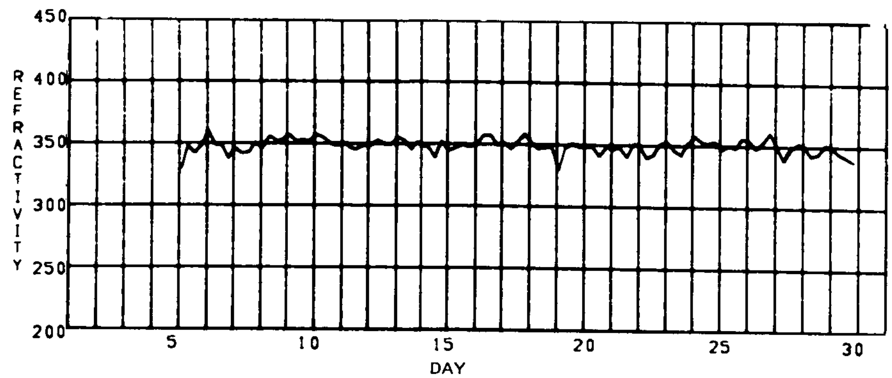
SEPTEMBER 1967



ACN

MAX	361.2
MIN	329.3
AVG	349.2
SD	5.6

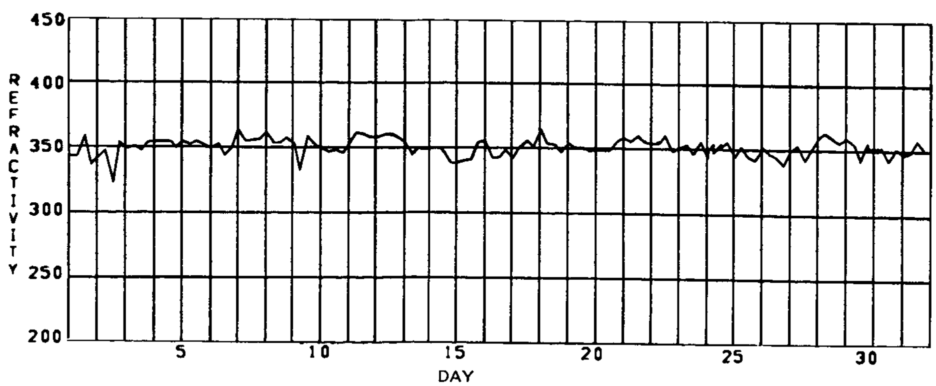
FEBRUARY 1968



ACN

MAX	364.9
MIN	323.9
AVG	351.3
SD	6.7

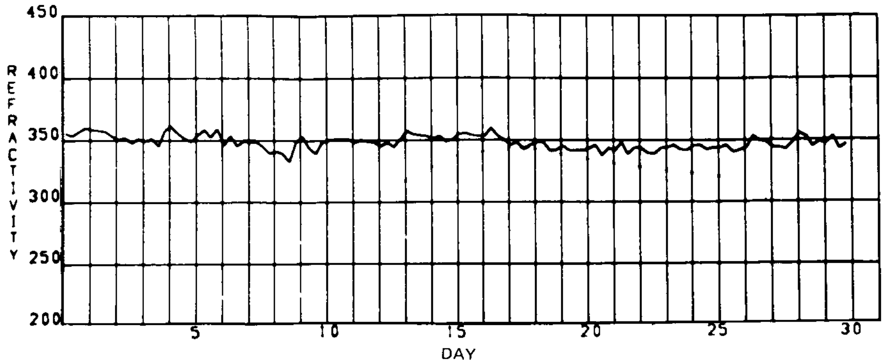
MARCH 1968



ACN

MAX	361.6
MIN	333.5
AVG	348.9
SD	5.6

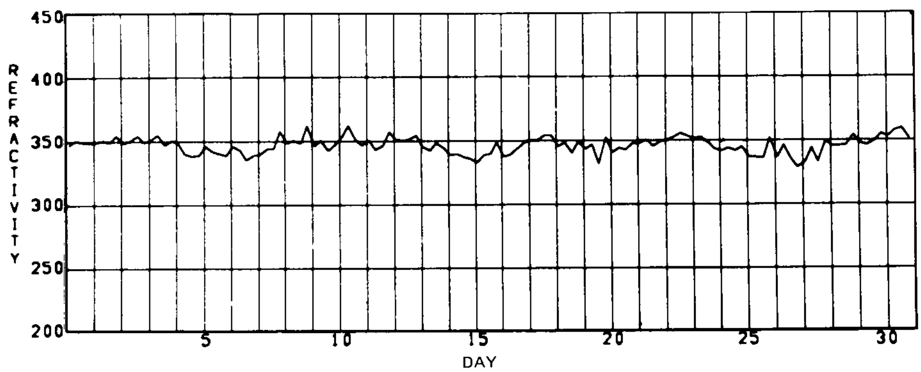
APRIL 1968



ACN

MAX	362.7
MIN	329.1
AVG	346.9
SD	6.5

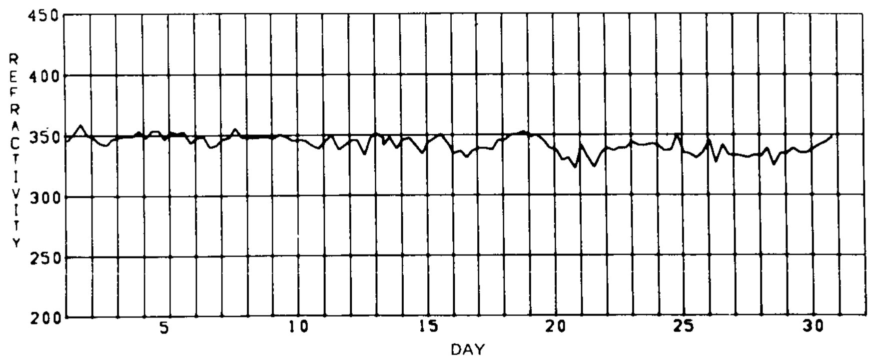
MAY 1968



ACN

MAX	359.6
MIN	323.0
AVG	343.0
SD	7.3

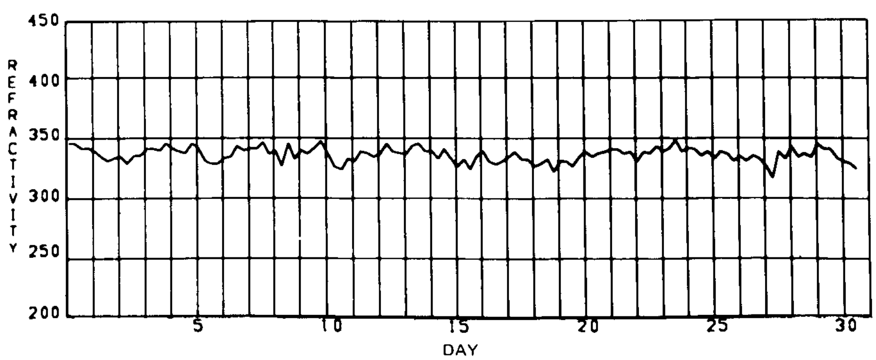
JUNE 1968



ACN

MAX	348.6
MIN	317.4
AVG	336.8
SD	6.0

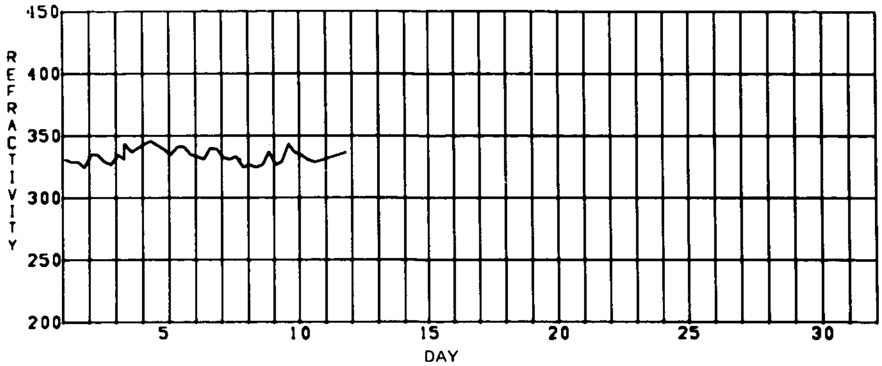
JULY 1968



ACN

MAX	346.2
MIN	325.0
AVG	334.3
SD	5.9

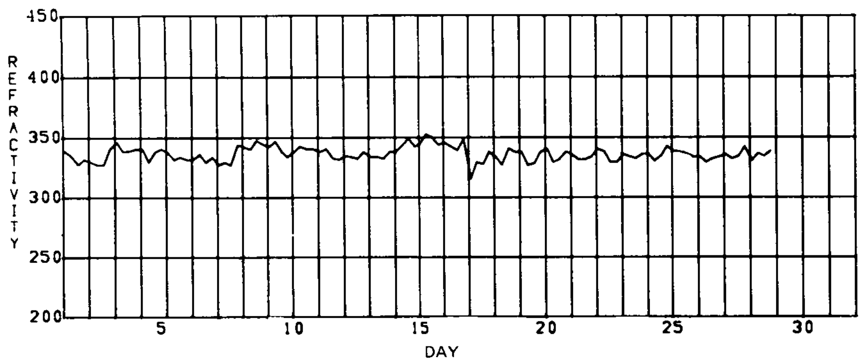
AUGUST 1968



ACN

MAX	353.1
MIN	316.6
AVG	336.8
SD	5.9

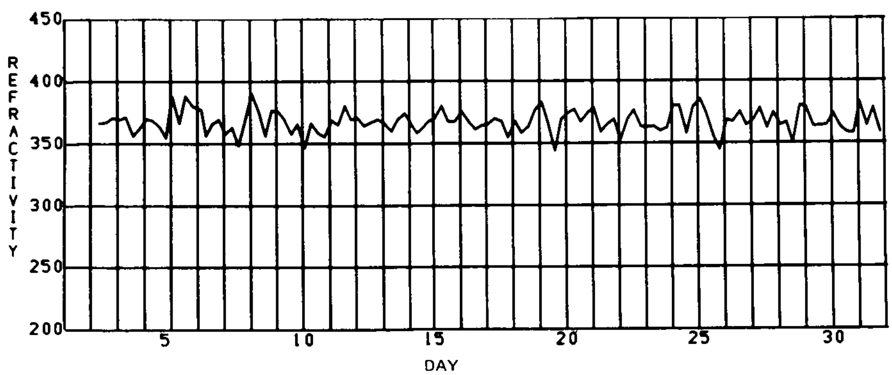
SEPTEMBER 1968



BDA

MAX	388.3
MIN	343.9
AVG	367.3
SD	9.0

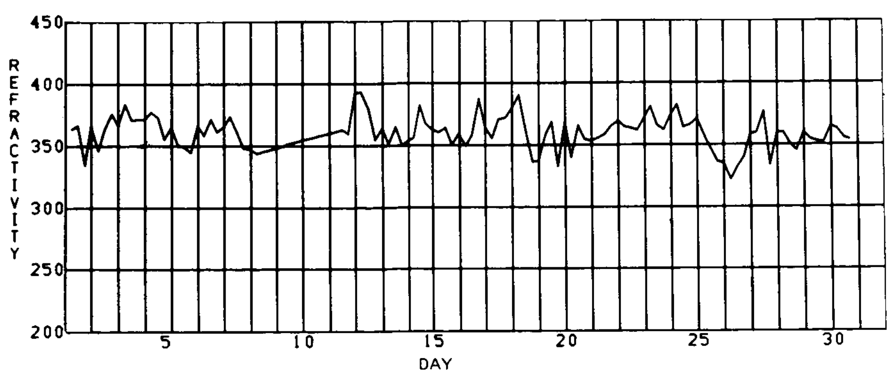
AUGUST 1967



BDA

MAX	393.4
MIN	322.3
AVG	360.7
SD	13.6

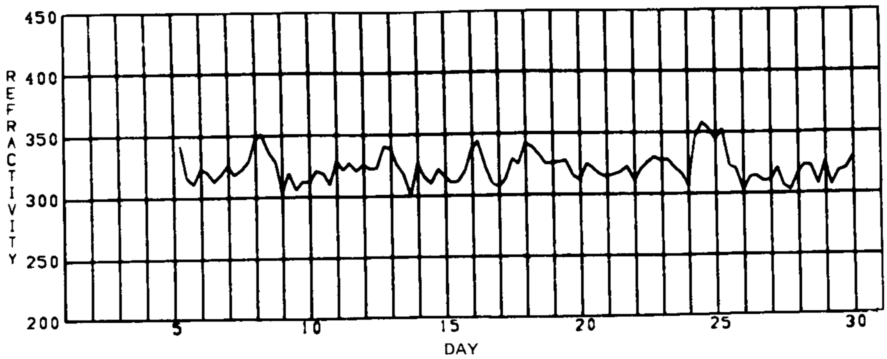
SEPTEMBER 1967



BDA

MAX	358.1
MIN	300.8
AVG	322.9
SD	12.0

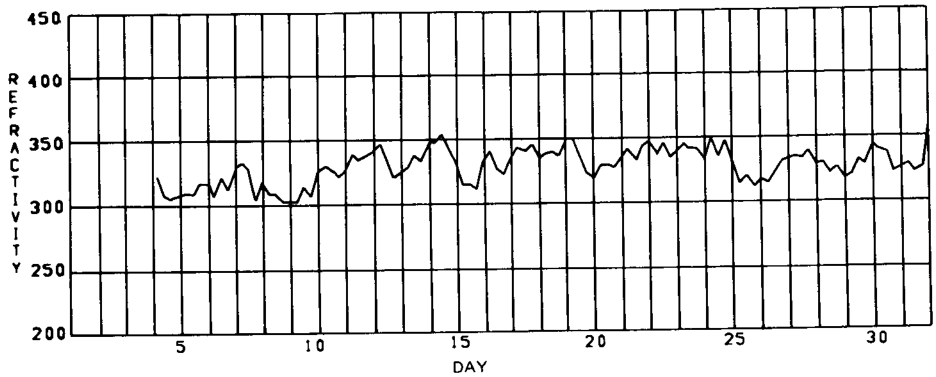
FEBRUARY 1968



BDA

MAX	358.3
MIN	301.5
AVG	328.9
SD	13.0

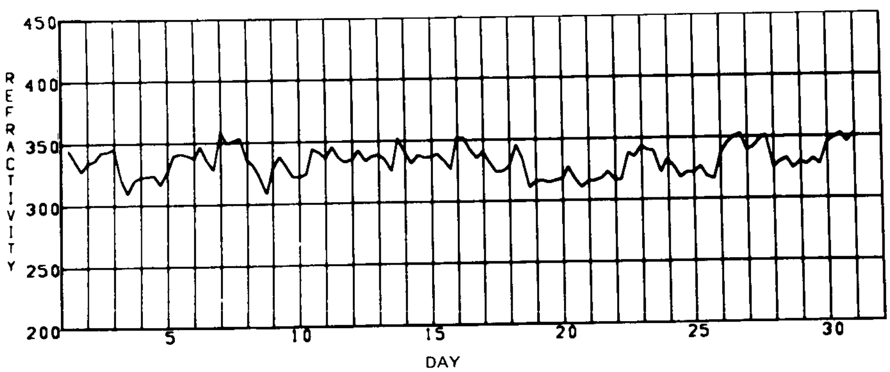
MARCH 1968



BDA

MAX	358.9
MIN	309.4
AVG	333.4
SD	11.6

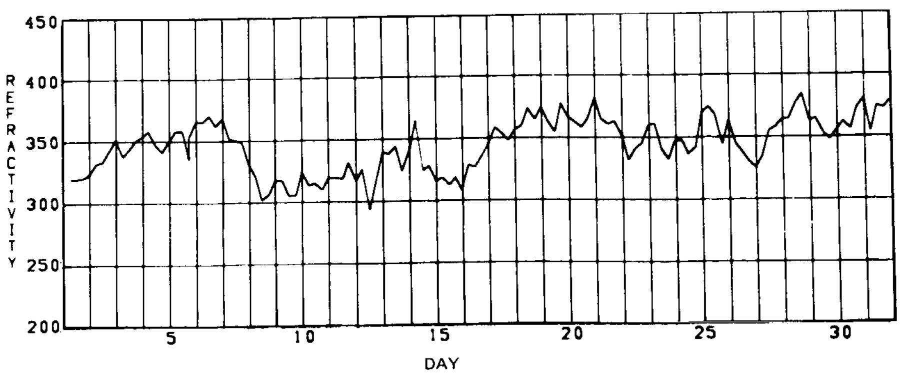
APRIL 1968



BDA

MAX	385.2
MIN	293.7
AVG	345.5
SD	21.0

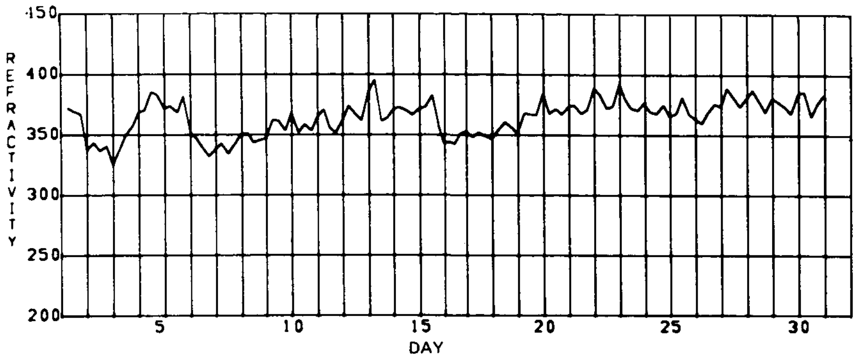
MAY 1968



BDA

MAX	395.9
MIN	325.4
AVG	364.9
SD	14.9

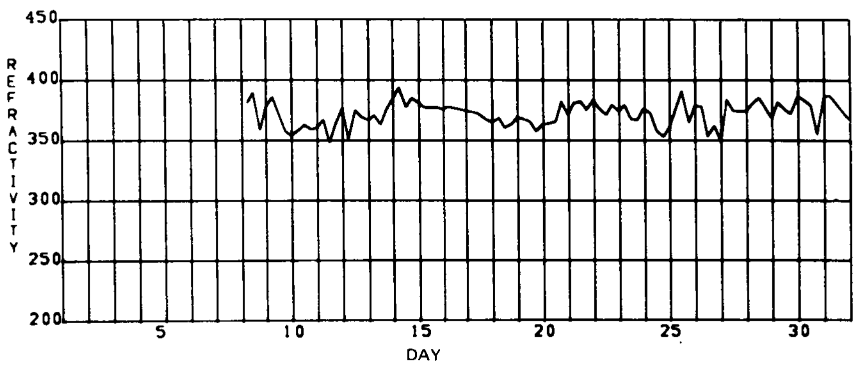
JUNE 1968



BDA

MAX	394.9
MIN	349.1
AVG	372.8
SD	10.1

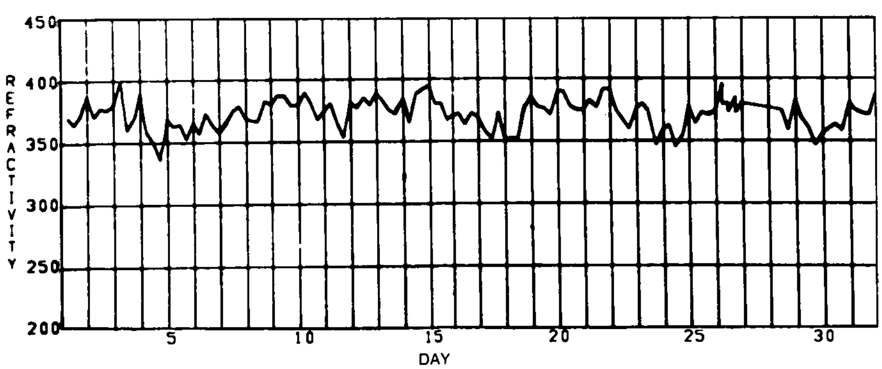
JULY 1968



BDA

MAX	399.7
MIN	336.3
AVG	372.9
SD	12.2

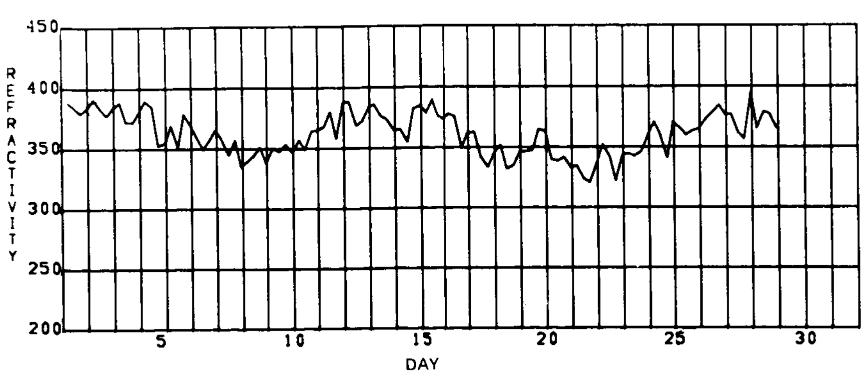
AUGUST 1968



BDA

MAX	395.9
MIN	321.1
AVG	362.3
SD	17.7

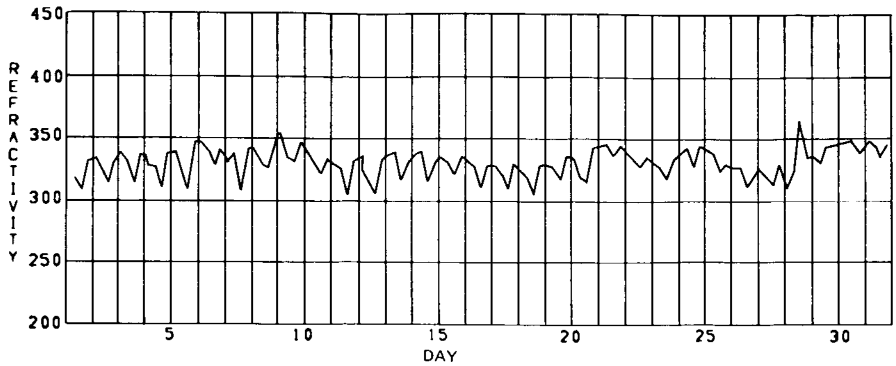
SEPTEMBER 1968



CRO

MAX	366.4
MIN	306.2
AVG	331.4
SD	11.4

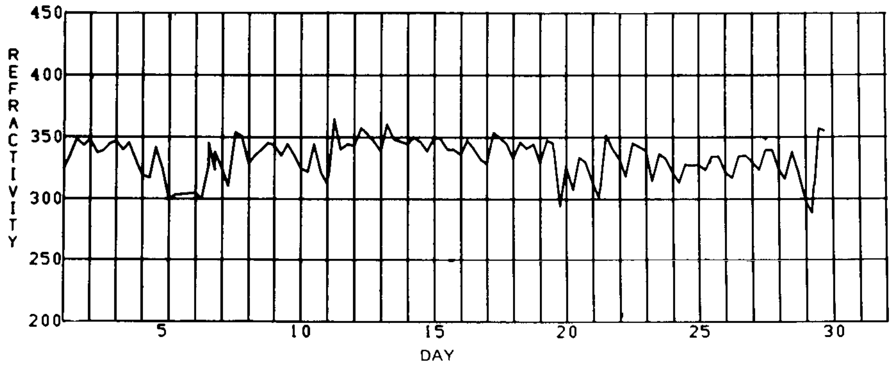
AUGUST 1967



CRO

MAX	364.7
MIN	288.9
AVG	333.9
SD	15.1

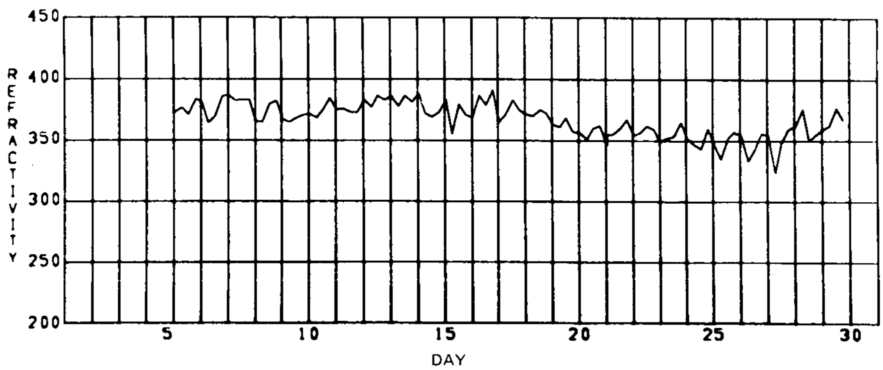
SEPTEMBER 1967



CRO

MAX	391.3
MIN	323.9
AVG	367.3
SD	13.6

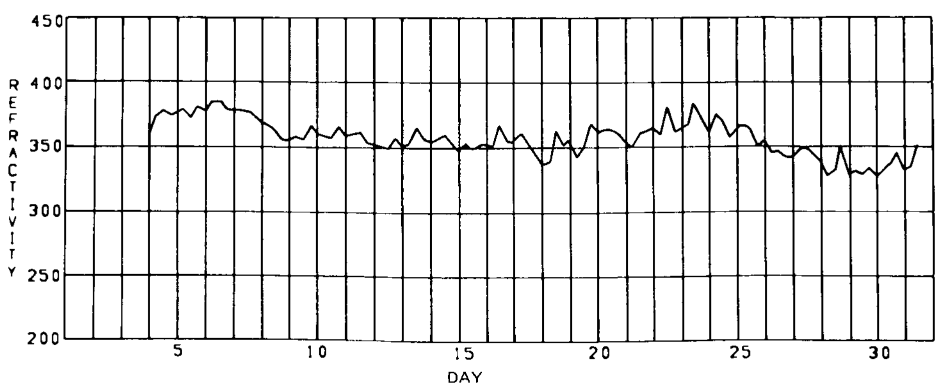
FEBRUARY 1968



CRO

MAX	385.7
MIN	326.9
AVG	357.1
SD	13.6

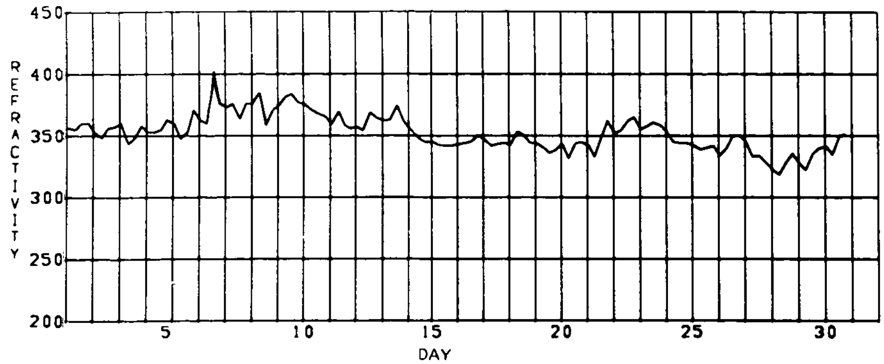
MARCH 1968



CRO

MAX	402.1
MIN	319.0
AVG	353.2
SD	14.4

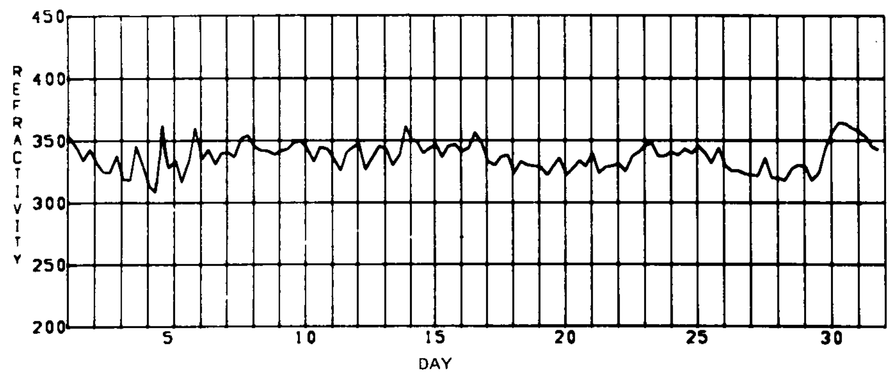
APRIL 1968



CRO

MAX	364.8
MIN	308.8
AVG	337.8
SD	11.4

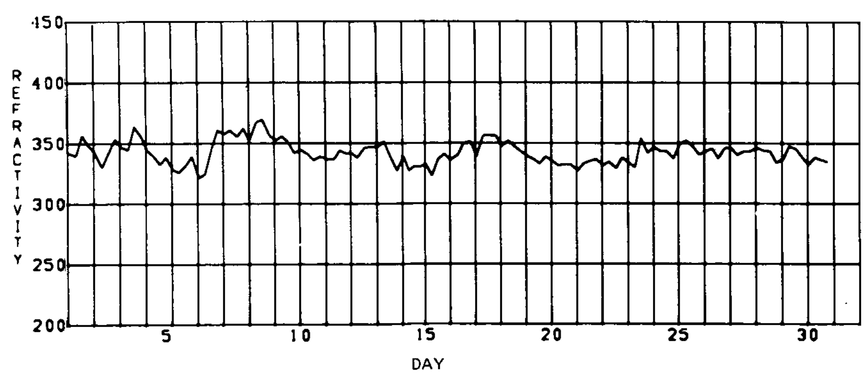
MAY 1968



CRO

MAX	369.9
MIN	322.1
AVG	342.8
SD	9.6

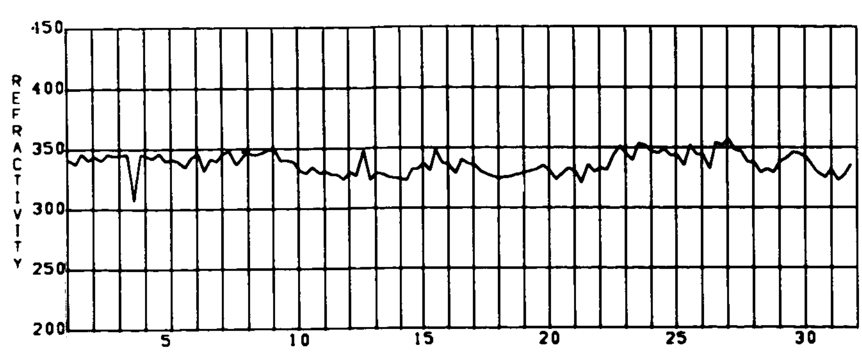
JUNE 1968



CRO

MAX	357.5
MIN	307.4
AVG	337.5
SD	9.2

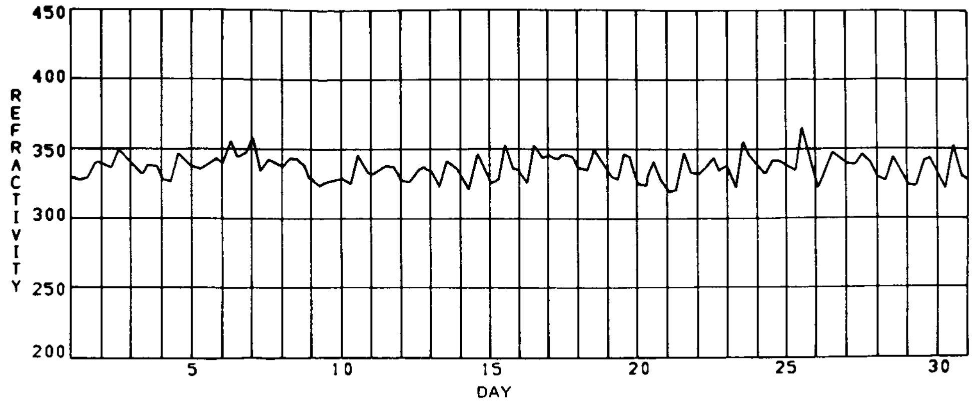
JULY 1968



CRO

MAX	367.1
MIN	319.9
AVG	337.5
SD	9.3

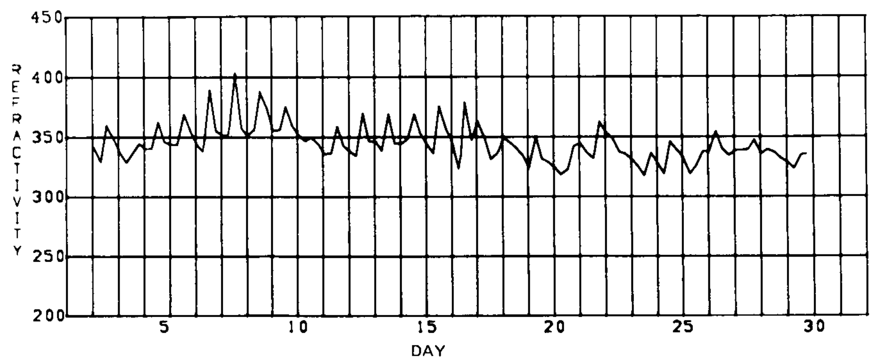
AUGUST 1968



CRO

MAX	403.8
MIN	318.6
AVG	345.6
SD	15.6

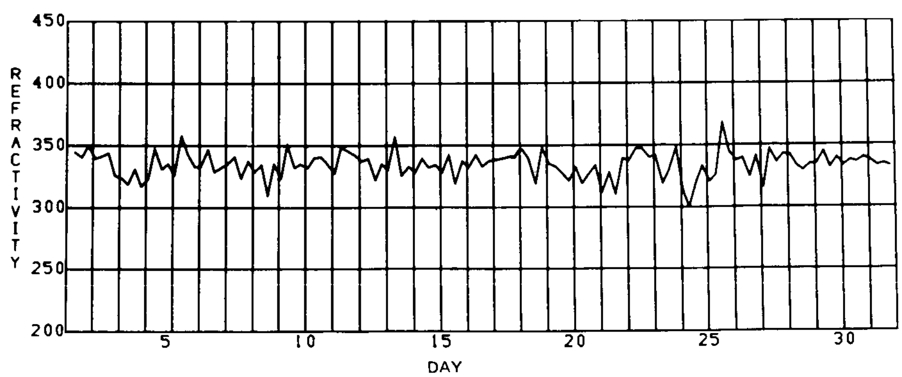
SEPTEMBER 1968



CYI

MAX	367.9
MIN	299.4
AVG	334.4
SD	10.4

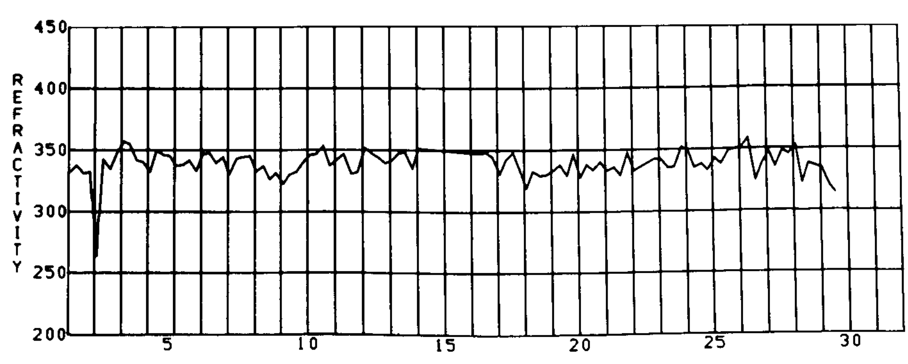
AUGUST 1967



CYI

MAX	358.1
MIN	264.1
AVG	338.7
SD	11.4

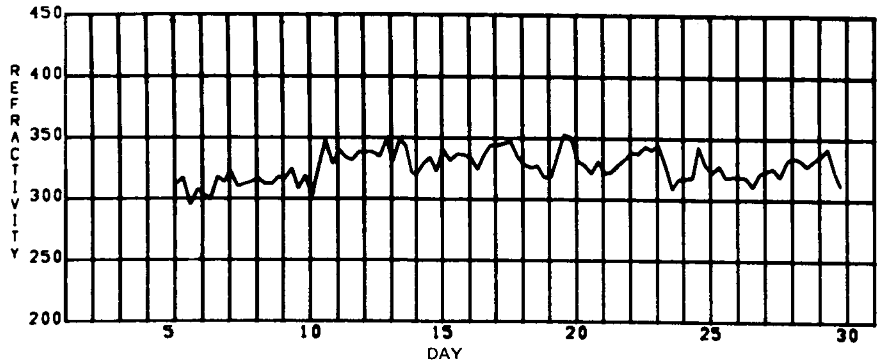
SEPTEMBER 1967



CYI

MAX	353.1
MIN	295.2
AVG	327.5
SD	12.3

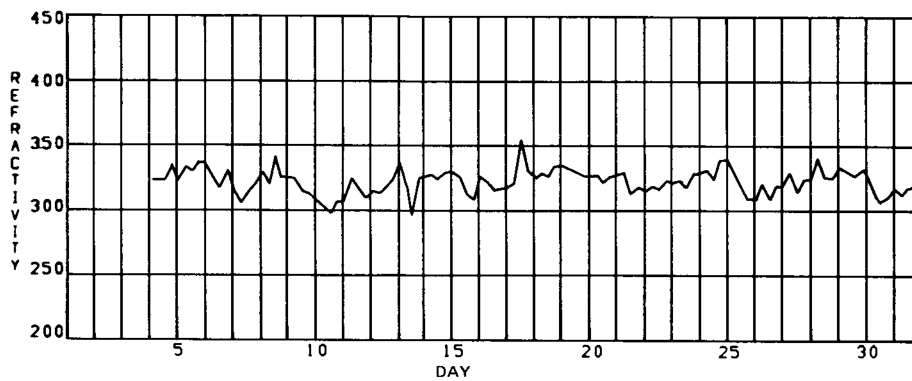
FEBRUARY 1968



CYI

MAX	352.5
MIN	295.5
AVG	322.5
SD	9.5

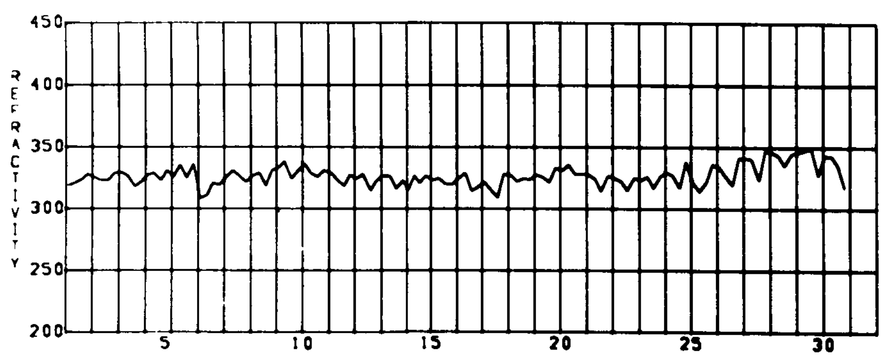
MARCH 1968



CYI

MAX	350.4
MIN	309.0
AVG	327.3
SD	8.4

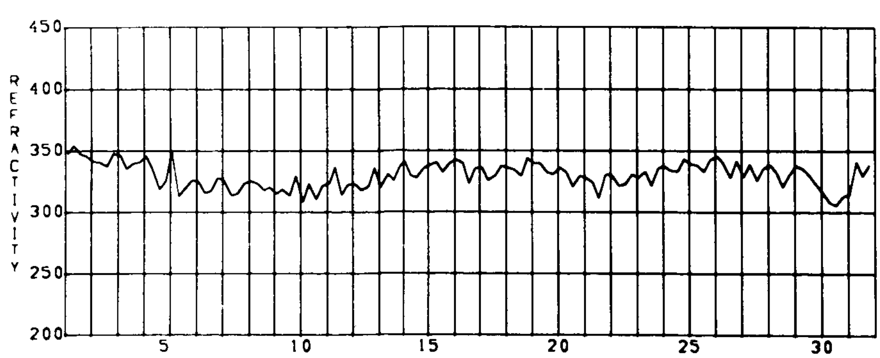
APRIL 1968



CYI

MAX	354.6
MIN	306.3
AVG	330.7
SD	10.3

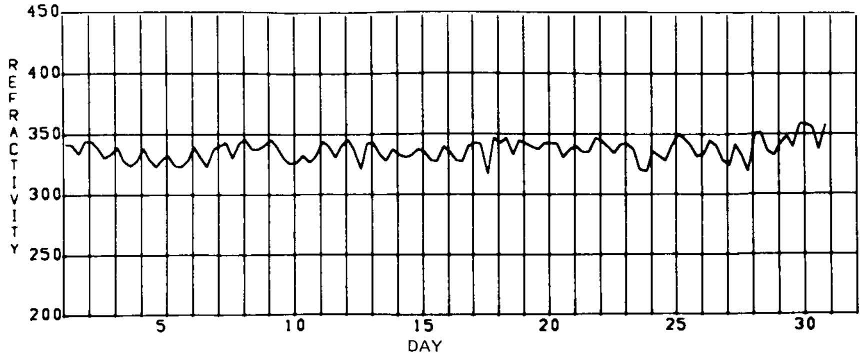
MAY 1968



CYI

MAX	359.0
MIN	317.6
AVG	337.3
SD	8.4

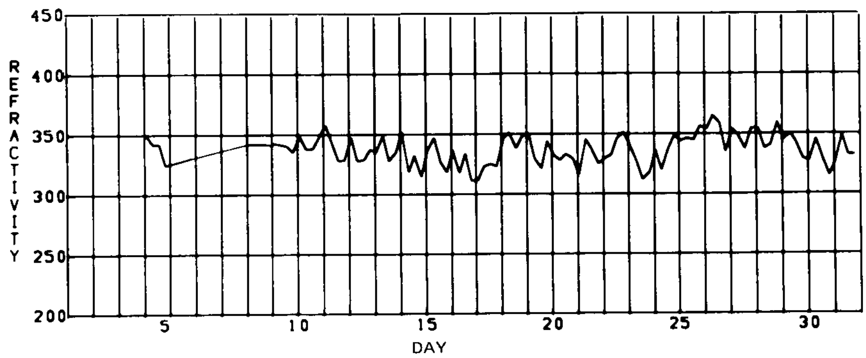
JUNE 1968



CYI

MAX	359.9
MIN	312.2
AVG	337.8
SD	12.0

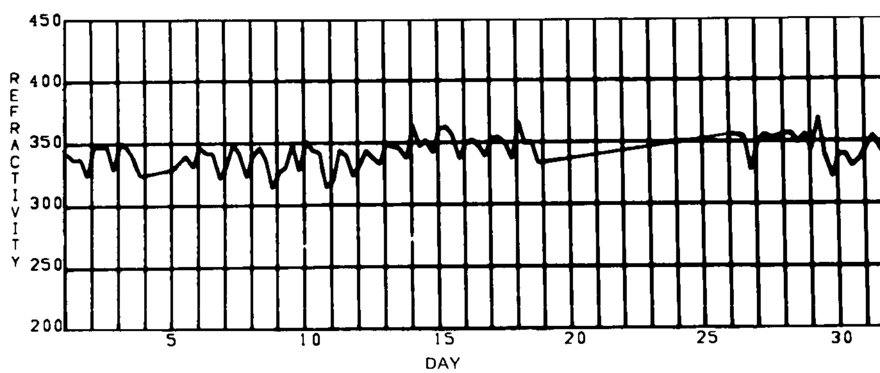
JULY 1968



CYI

MAX	370.3
MIN	315.2
AVG	342.9
SD	11.6

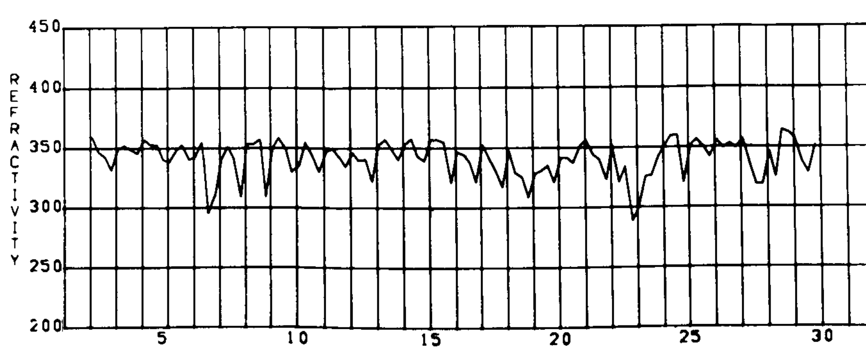
AUGUST 1968



CYI

MAX	365.2
MIN	289.5
AVG	341.6
SD	15.1

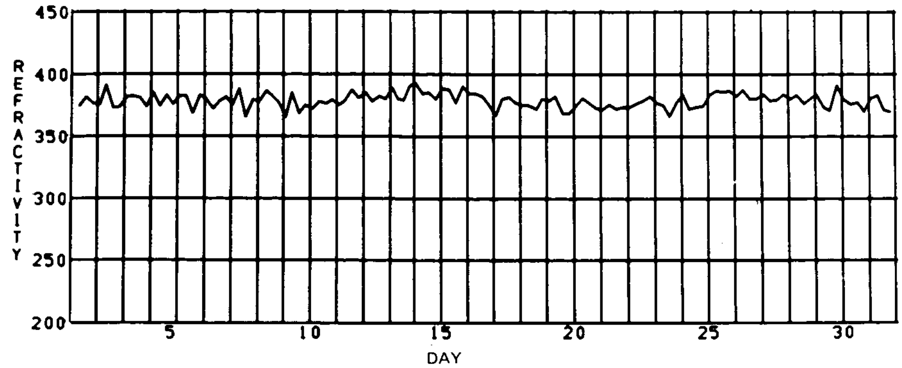
SEPTEMBER 1968



GBM

MAX	393.5
MIN	365.8
AVG	378.9
SD	5.9

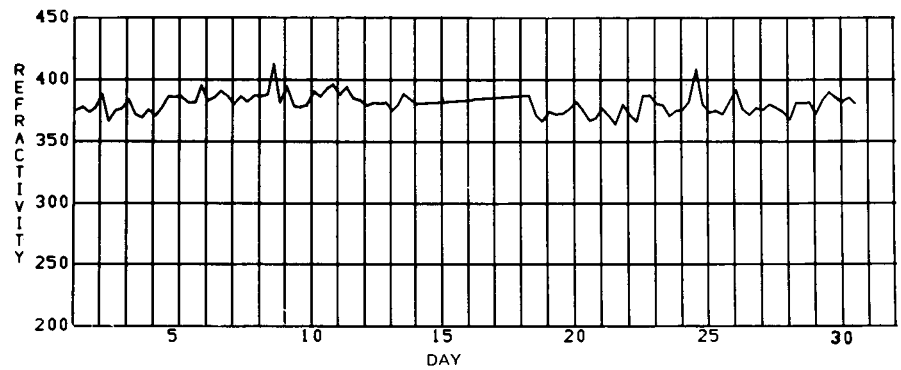
AUGUST 1967



GBM

MAX	413.0
MIN	364.5
AVG	381.1
SD	8.2

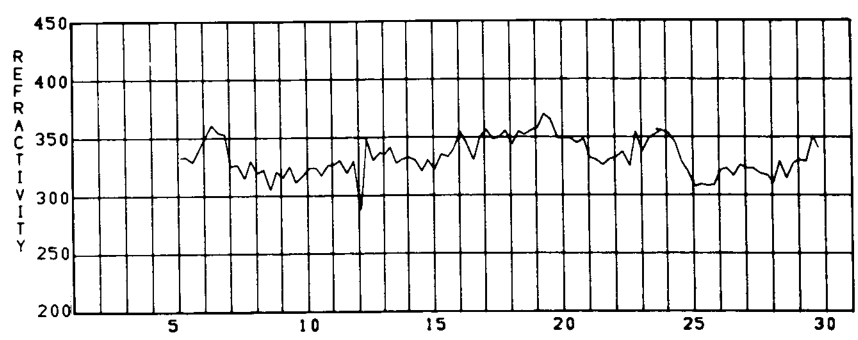
SEPTEMBER 1967



GBM

MAX	370.6
MIN	288.1
AVG	334.2
SD	15.6

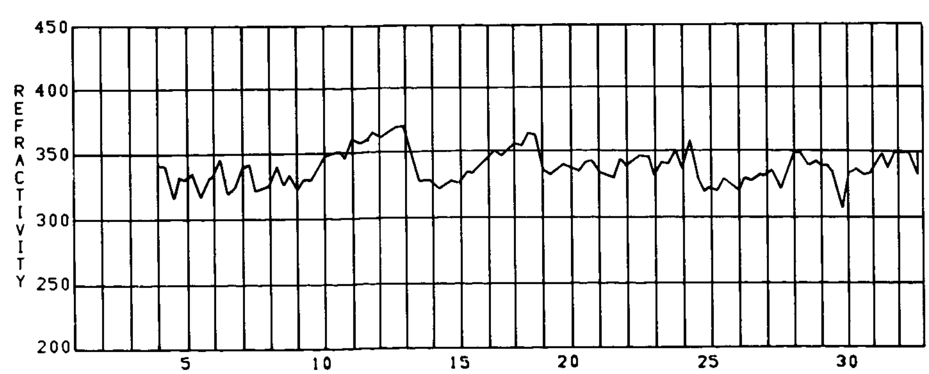
FEBRUARY 1968



GBM

MAX	369.4
MIN	307.0
AVG	338.4
SD	12.9

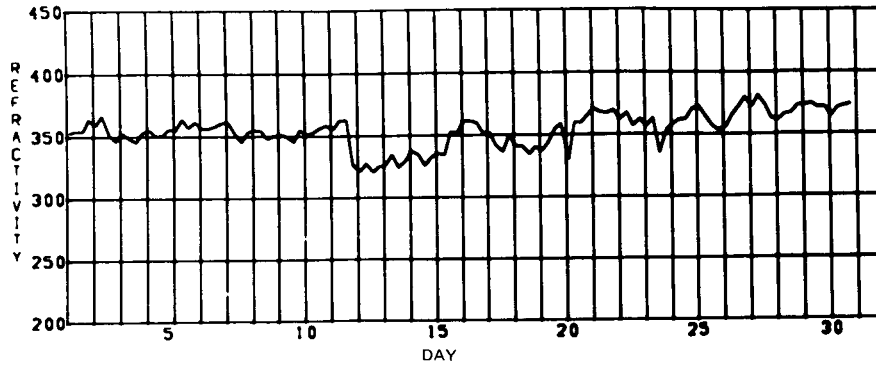
MARCH 1968



GBM

MAX	381.6
MIN	321.6
AVG	354.6
SD	13.5

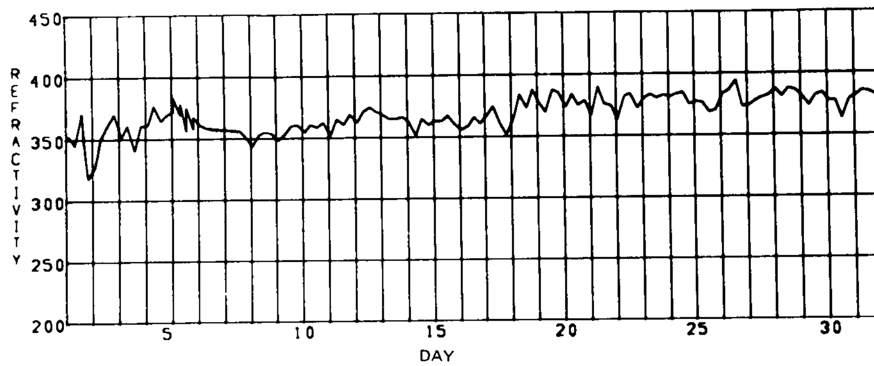
APRIL 1968



GBM

MAX	394.6
MIN	318.8
AVG	369.3
SD	13.1

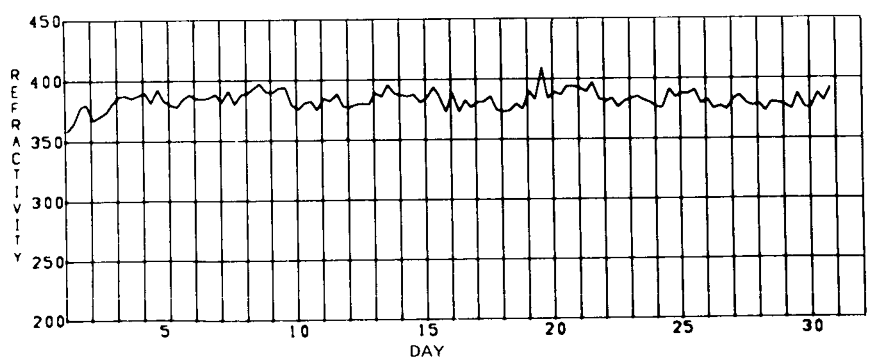
MAY 1968



GBM

MAX	409.6
MIN	359.3
AVG	383.6
SD	7.2

JUNE 1968



GBM

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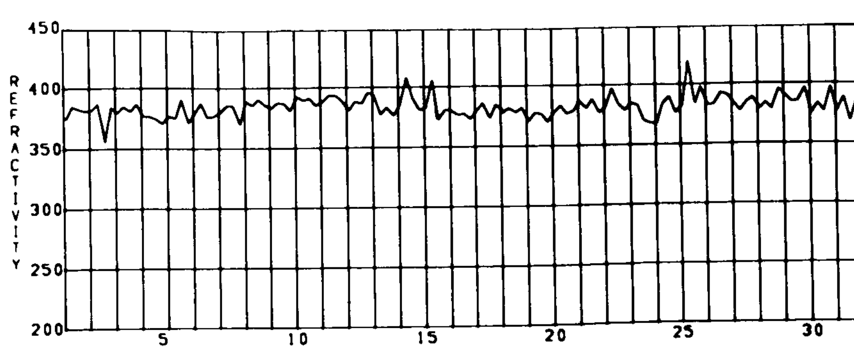
SD	8.4

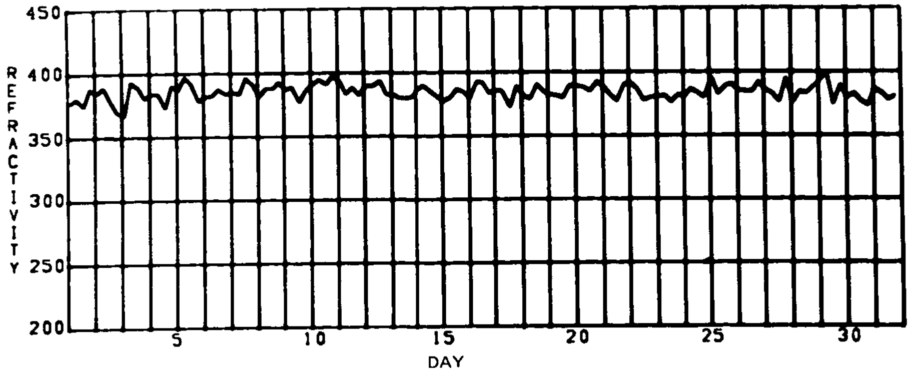
JULY 1968



GBM

MAX	399.8
MIN	373.8
AVG	385.3
SD	5.9

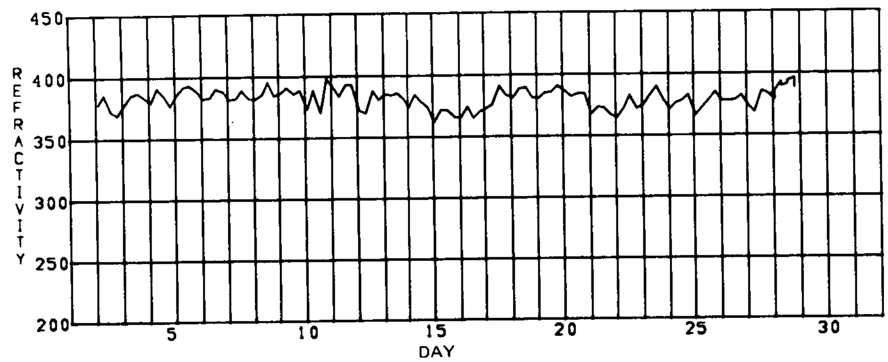
AUGUST 1968



GBM

MAX	398.8
MIN	362.6
AVG	382.1
SD	8.1

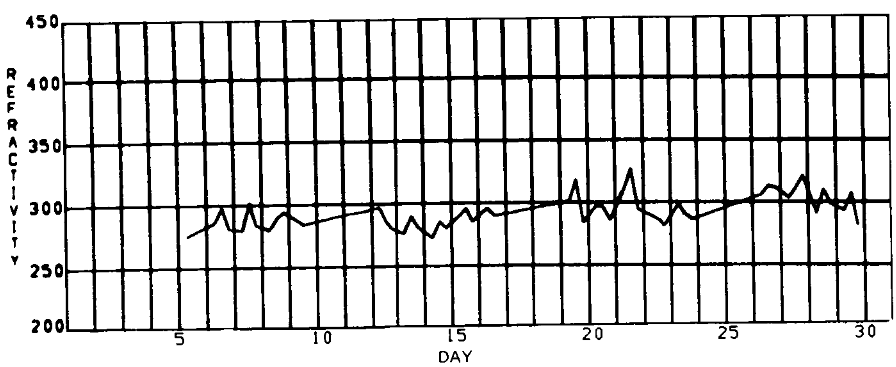
SEPTEMBER 1968



GDS

MAX	327.5
MIN	273.1
AVG	293.6
SD	12.4

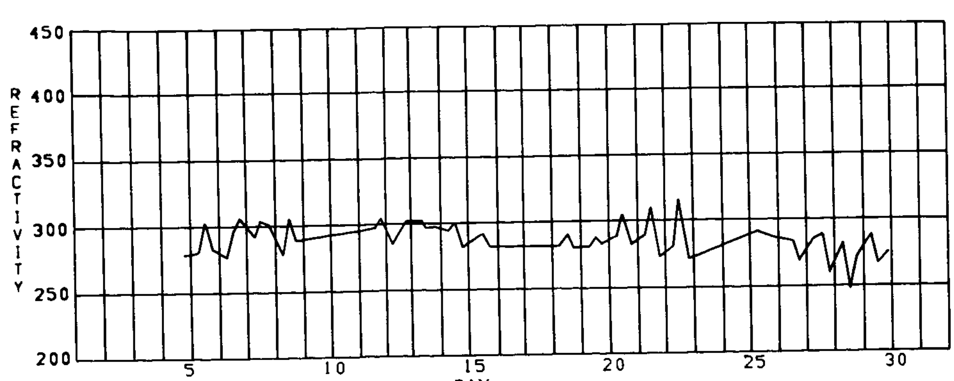
FEBRUARY 1968



GDS

MAX	315.9
MIN	247.2
AVG	287.7
SD	12.8

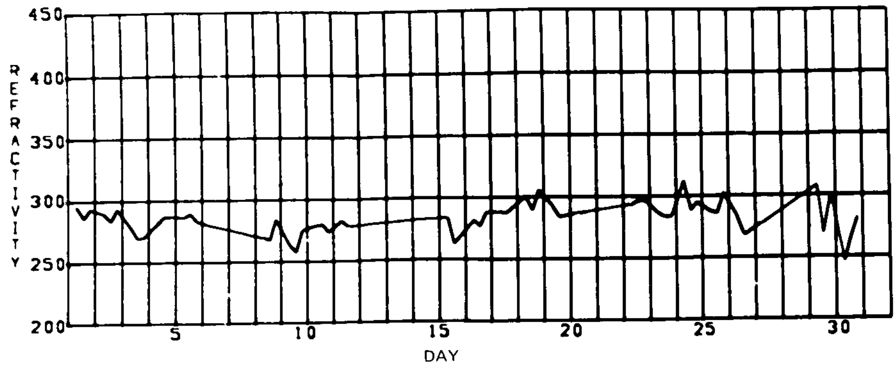
MARCH 1968



GDS

MAX	312.9
MIN	246.7
AVG	284.2
SD	12.5

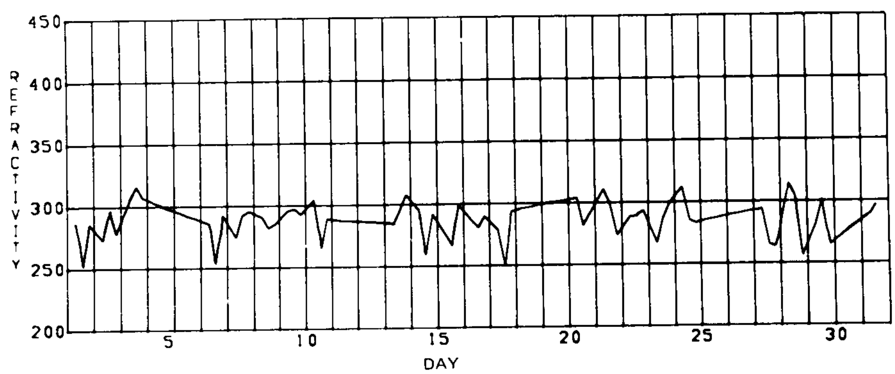
APRIL 1968



GDS

MAX	316.6
MIN	249.5
AVG	287.4
SD	15.6

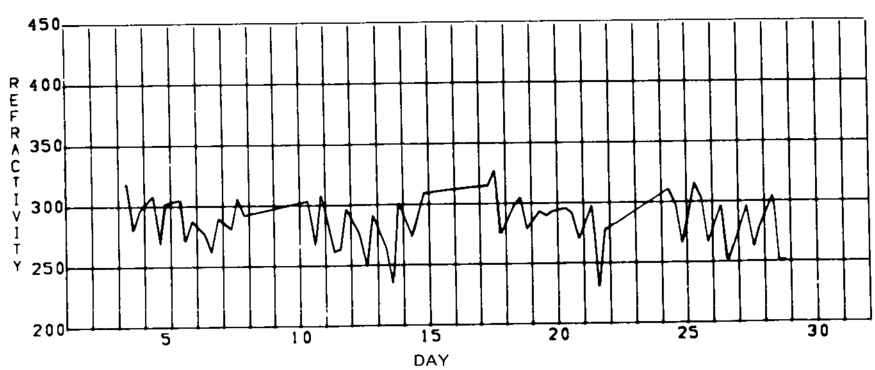
MAY 1968



GDS

MAX	328.0
MIN	230.7
AVG	285.2
SD	21.5

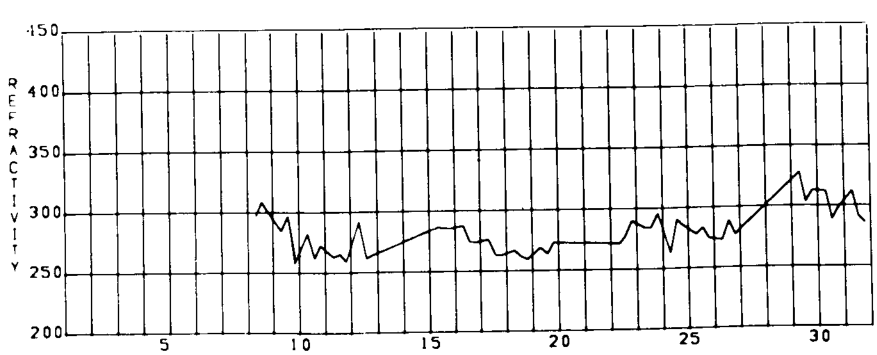
JUNE 1968



GDS

MAX	328.6
MIN	258.4
AVG	281.9
SD	16.5

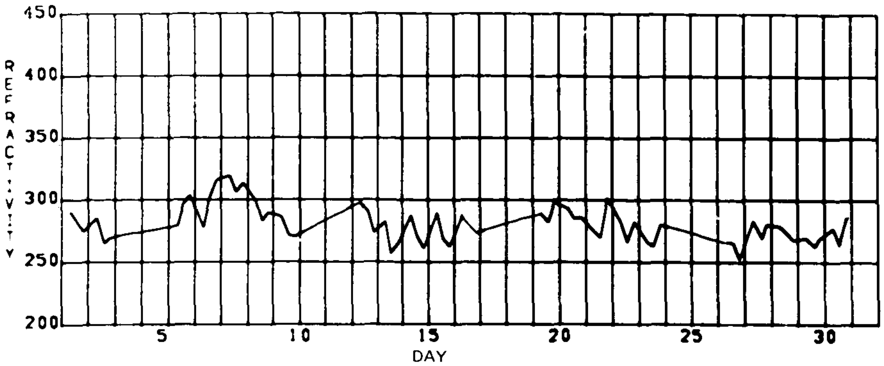
JULY 1968



GDS

MAX	319.9
MIN	253.2
AVG	280.3
SD	15.9

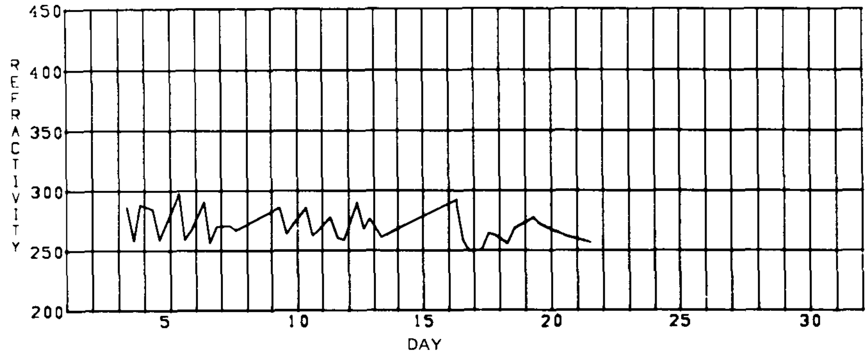
AUGUST 1968



GDS

MAX	298.4
MIN	249.8
AVG	270.3
SD	12.6

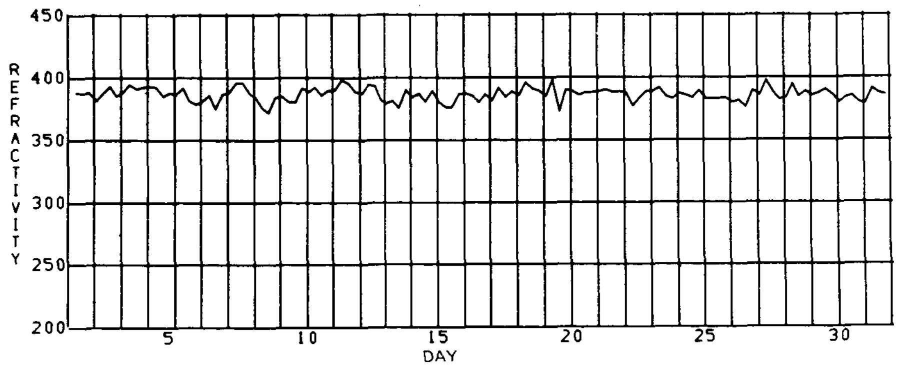
SEPTEMBER 1968



GWM

MAX	398.2
MIN	372.2
AVG	386.3
SD	5.3

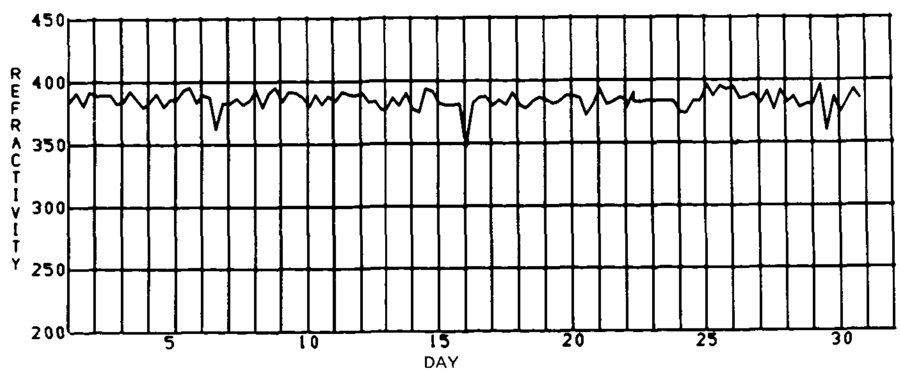
AUGUST 1967



GWM

MAX	396.3
MIN	347.8
AVG	384.6
SD	7.0

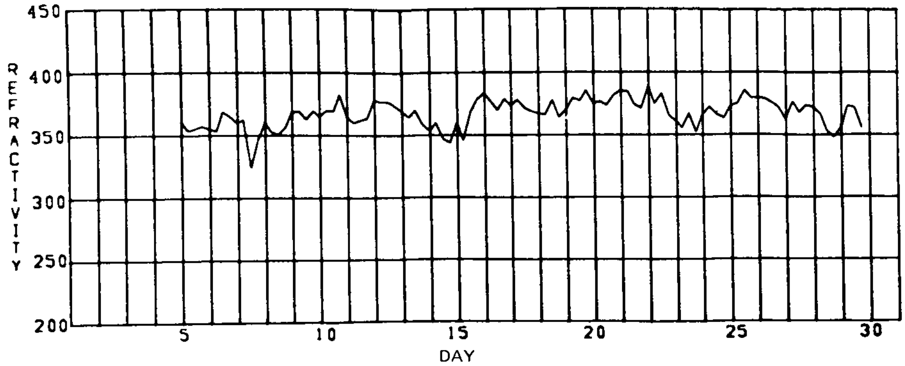
SEPTEMBER 1967



GWM

MAX	388.8
MIN	325.3
AVG	367.9
SD	11.1

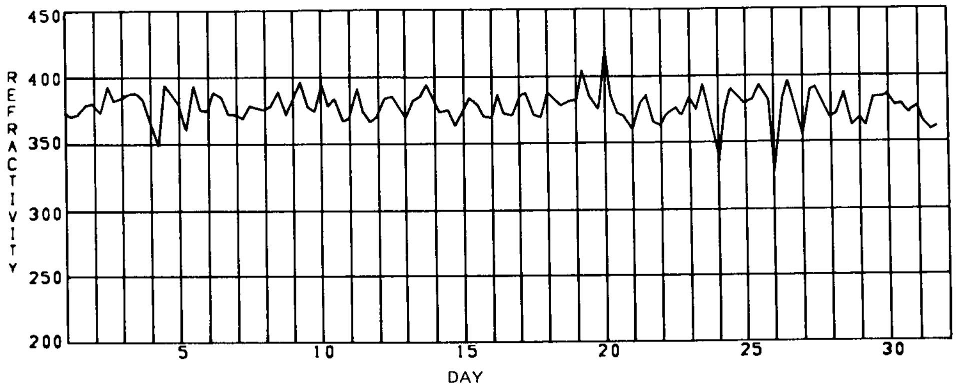
FEBRUARY 1968



GWM

MAX	423.7
MIN	325.8
AVG	377.6
SD	12.2

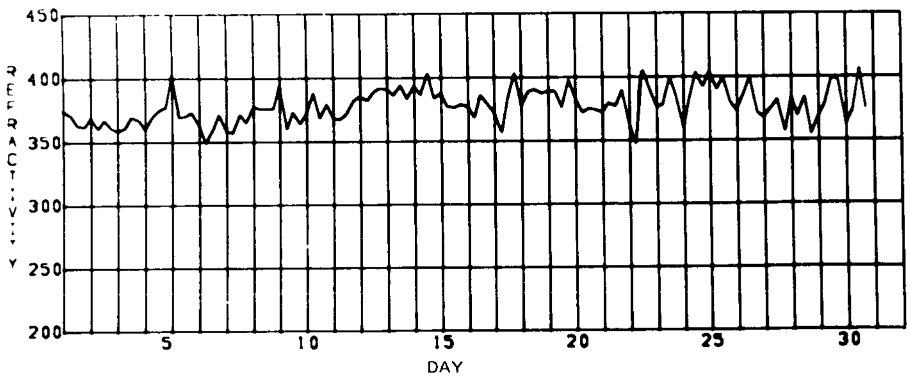
MARCH 1968



GWM

MAX	406.5
MIN	348.3
AVG	378.3
SD	13.2

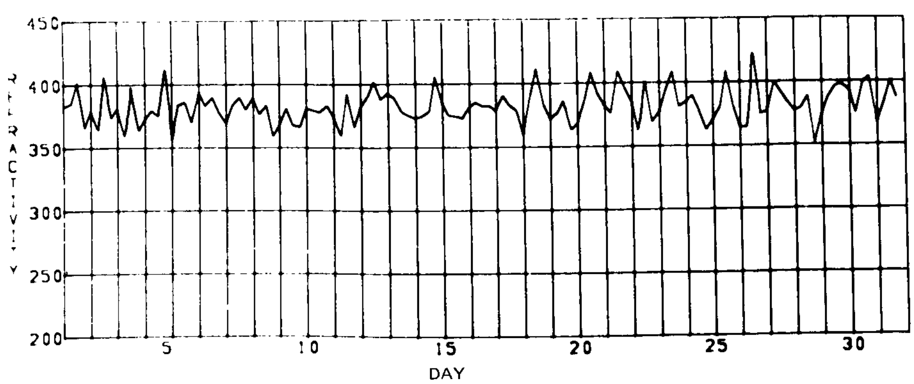
APRIL 1968



GWM

MAX	423.1
MIN	351.9
AVG	382.8
SD	13.2

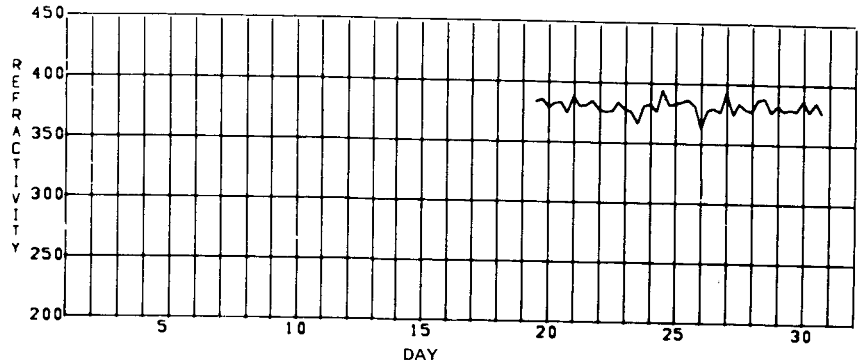
MAY 1968



GWM

MAX	395.1
MIN	364.4
AVG	381.2
SD	5.7

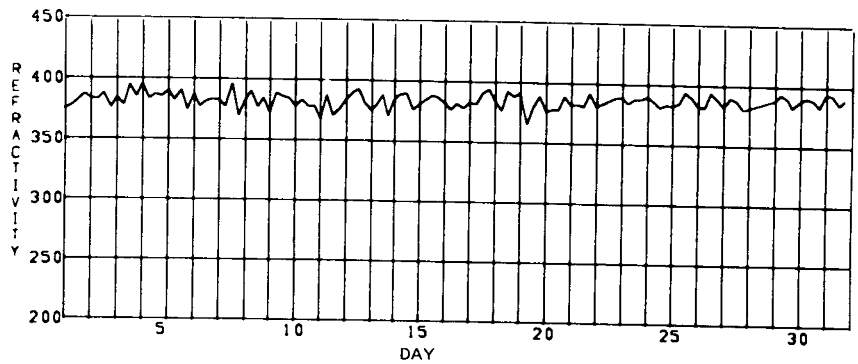
JUNE 1968



GWM

MAX	396.6
MIN	370.9
AVG	384.6
SD	6.1

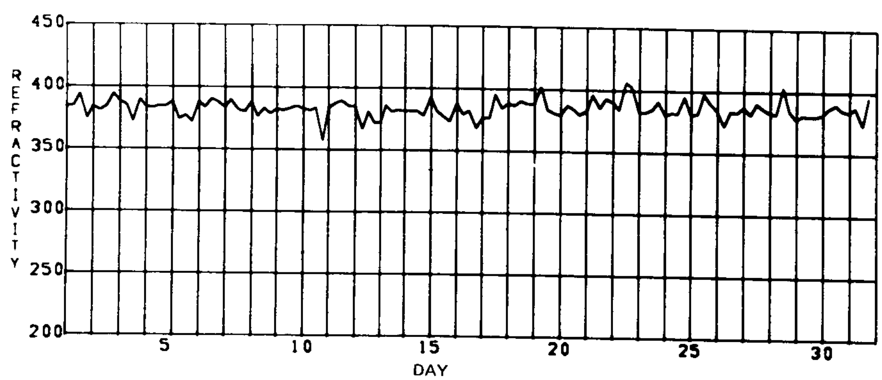
JULY 1968



GWM

MAX	406.7
MIN	358.2
AVG	384.7
SD	7.0

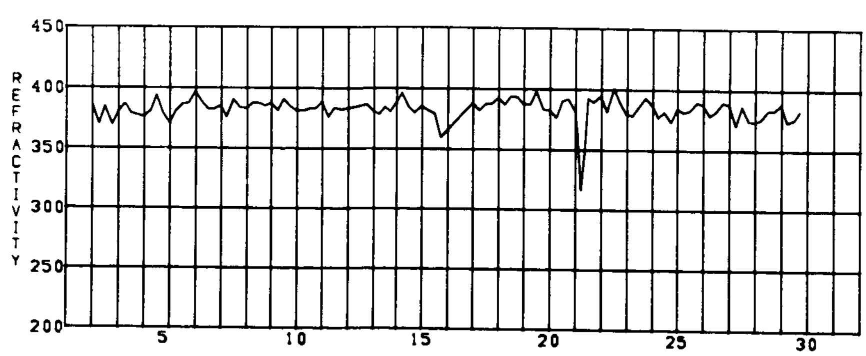
AUGUST 1968



GWM

MAX	401.9
MIN	317.7
AVG	383.9
SD	9.3

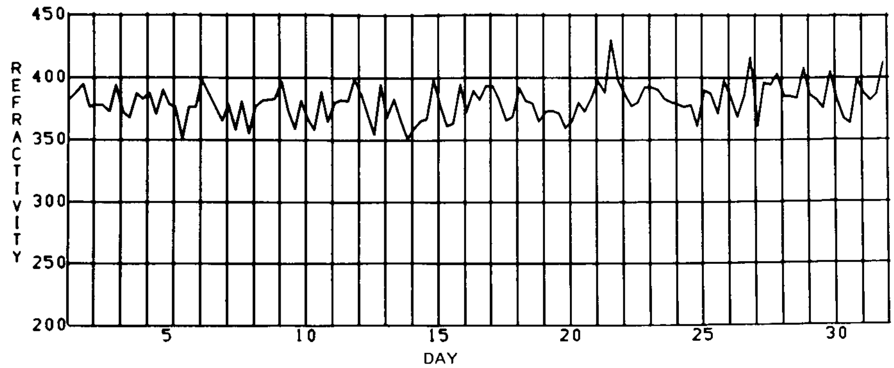
SEPTEMBER 1968



GYM

MAX	430.0
MIN	351.2
AVG	380.6
SD	13.7

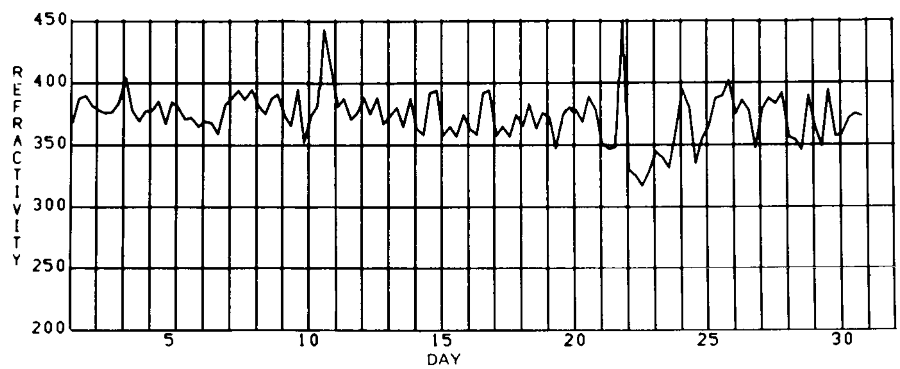
AUGUST 1967



GYM

MAX	450.1
MIN	317.0
AVG	373.2
SD	19.7

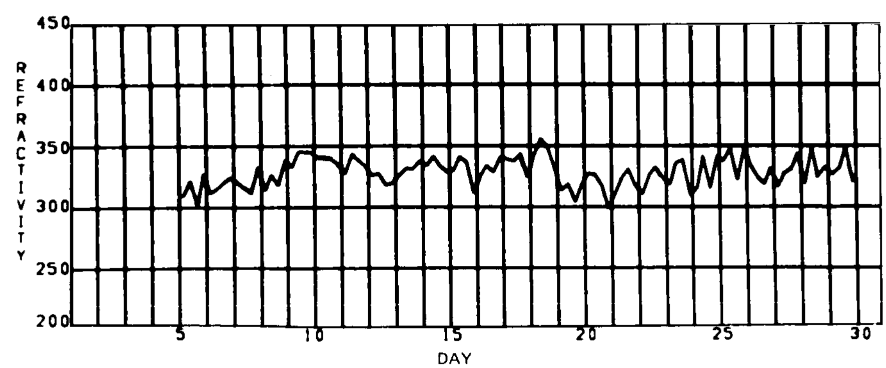
SEPTEMBER 1967



GYM

MAX	356.1
MIN	299.4
AVG	328.8
SD	11.9

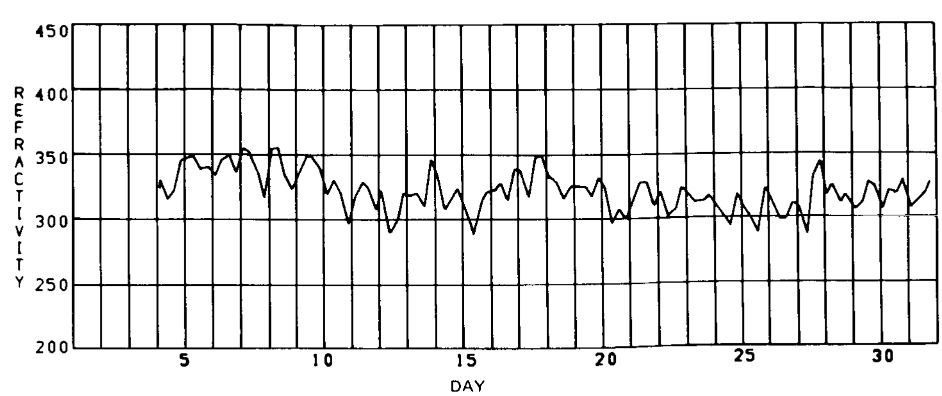
FEBRUARY 1968



GYM

MAX	355.8
MIN	288.2
AVG	322.2
SD	15.9

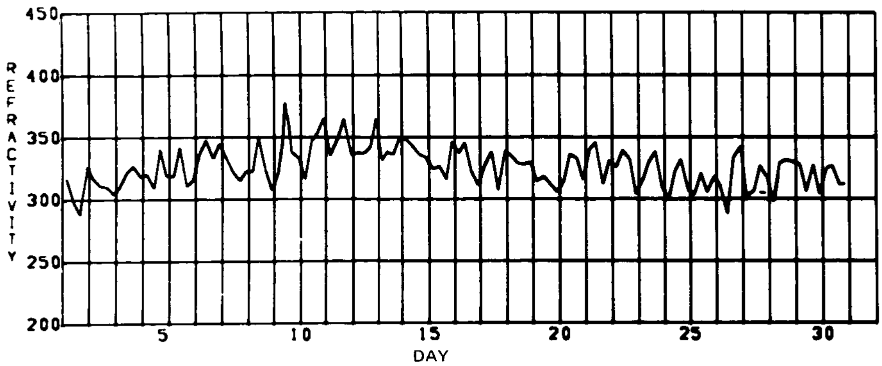
MARCH 1968



GYM

MAX	378.4
MIN	289.0
AVG	326.5
SD	16.2

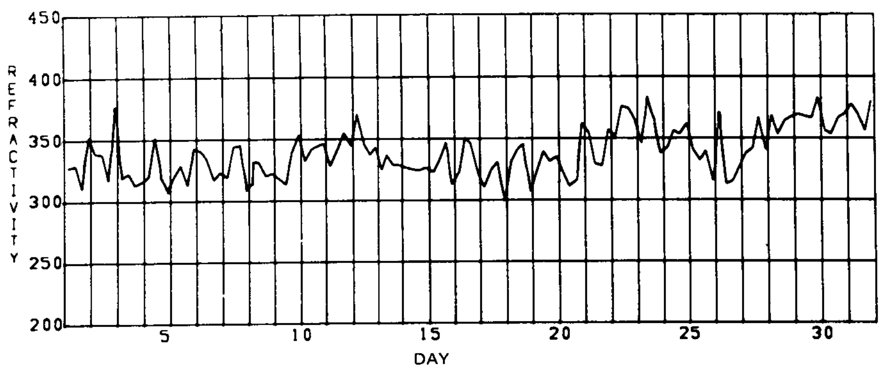
APRIL 1968



GYM

MAX	384.7
MIN	300.7
AVG	339.9
SD	19.9

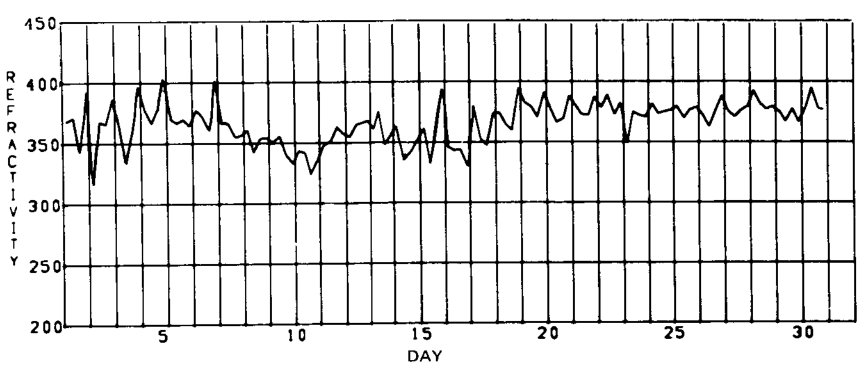
MAY 1968



GYM

MAX	404.0
MIN	316.9
AVG	367.6
SD	17.0

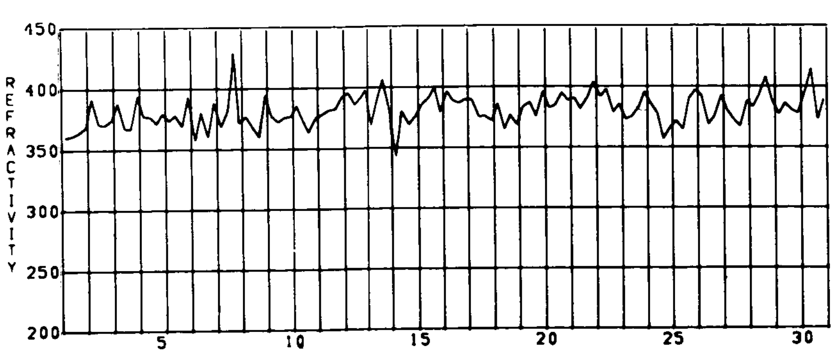
JUNE 1968



GYM

MAX	430.0
MIN	344.0
AVG	381.6
SD	12.7

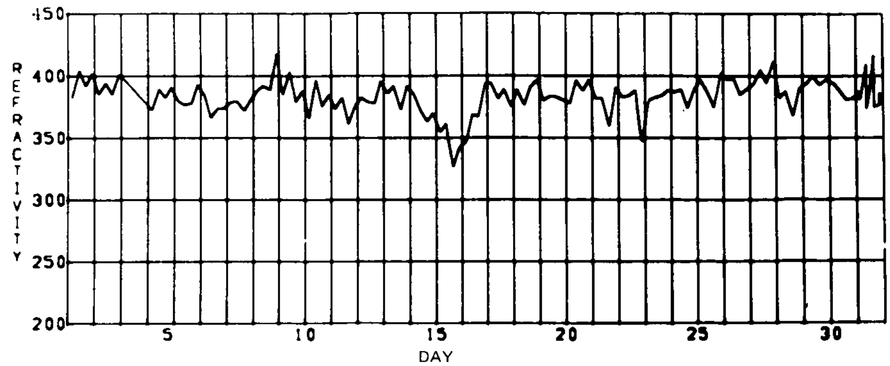
JULY 1968



GYM

MAX	418.2
MIN	326.8
AVG	384.3
SD	13.8

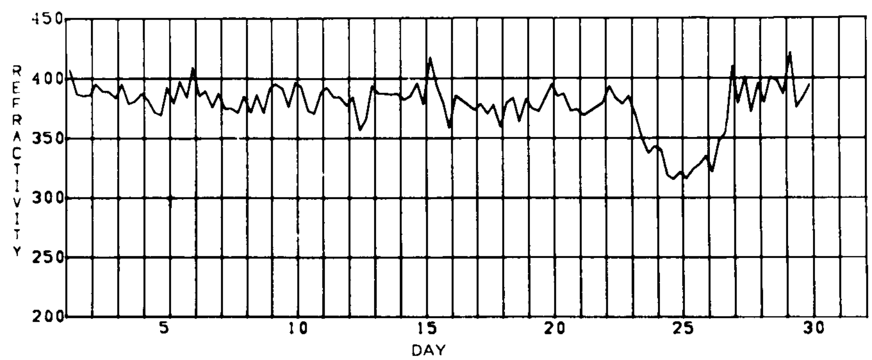
AUGUST 1968



GYM

MAX	421.7
MIN	316.0
AVG	378.3
SD	20.8

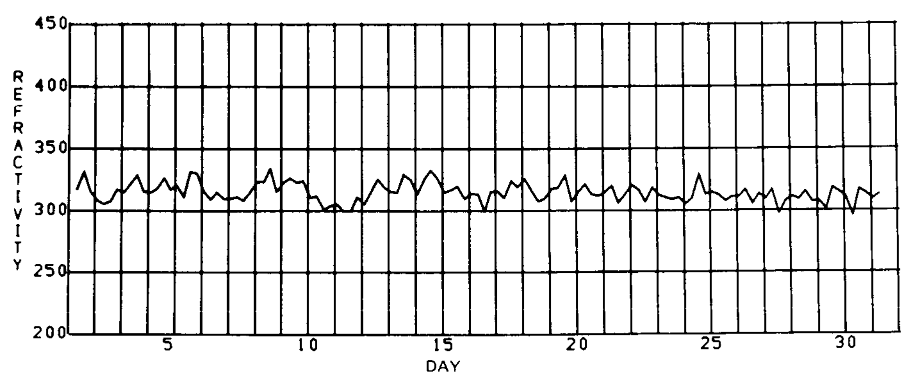
SEPTEMBER 1968



HAW

MAX	334.7
MIN	295.8
AVG	314.8
SD	7.8

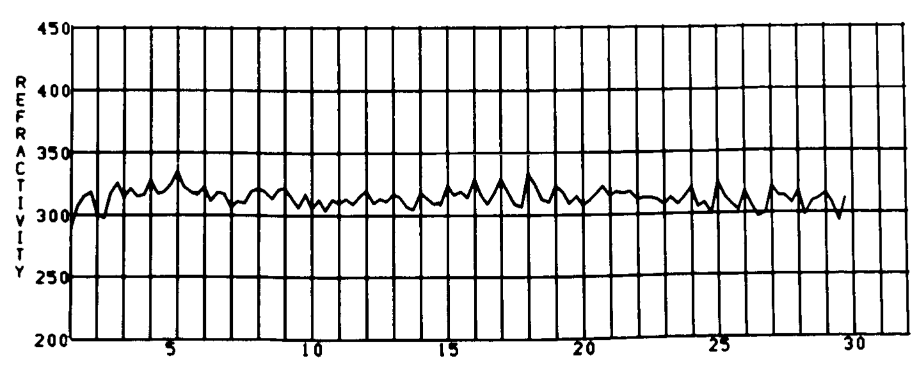
AUGUST 1967



HAW

MAX	335.5
MIN	290.4
AVG	313.8
SD	7.8

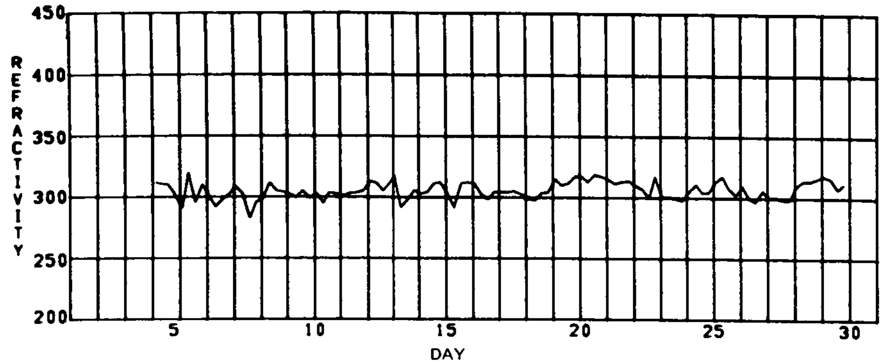
SEPTEMBER 1967



HAW

MAX	319.6
MIN	283.3
AVG	306.2
SD	7.7

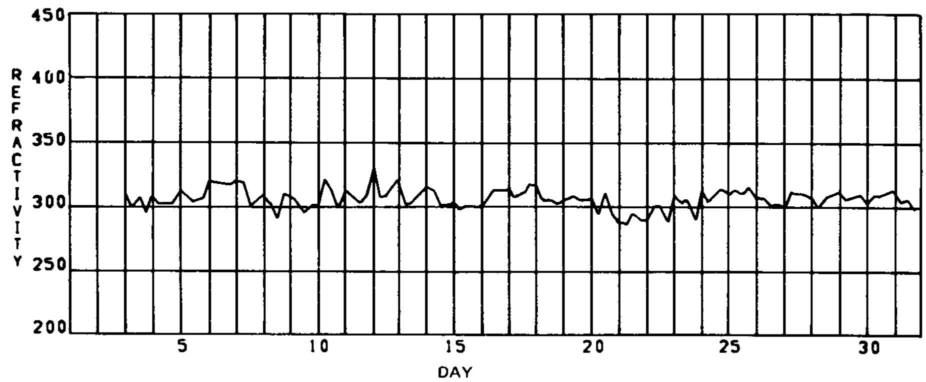
FEBRUARY 1968



HAW

MAX	329.5
MIN	286.7
AVG	306.2
SD	7.9

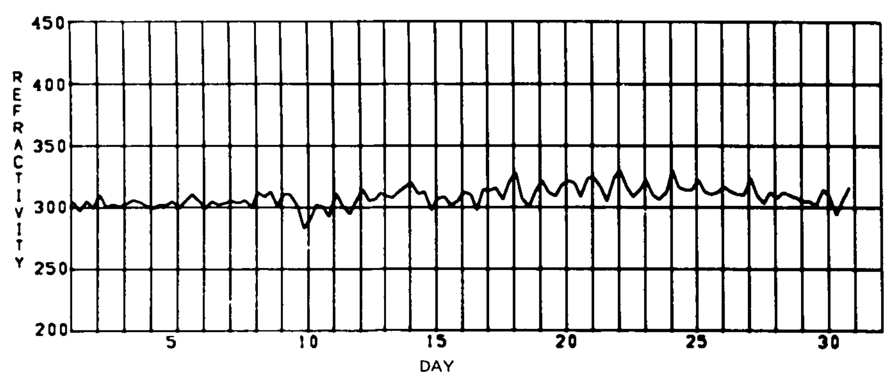
MARCH 1968



HAW

MAX	331.1
MIN	283.6
AVG	309.3
SD	8.1

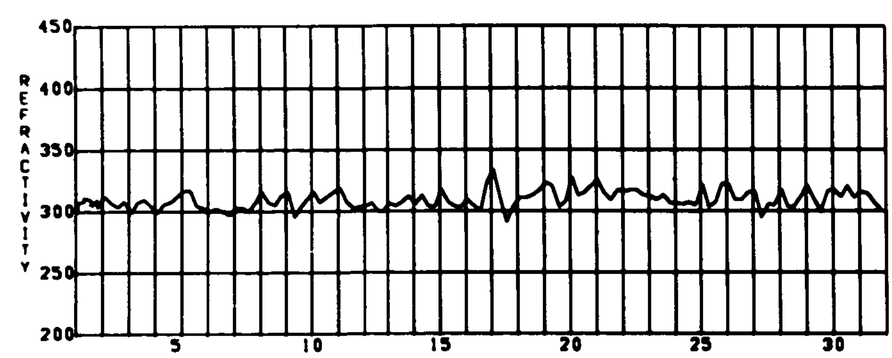
APRIL 1968



HAW

MAX	334.1
MIN	291.9
AVG	309.8
SD	7.3

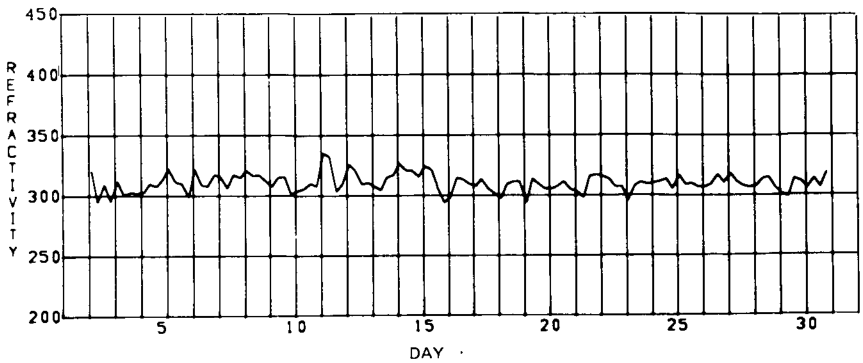
MAY 1968



HAW

MAX	335.5
MIN	294.6
AVG	311.0
SD	7.5

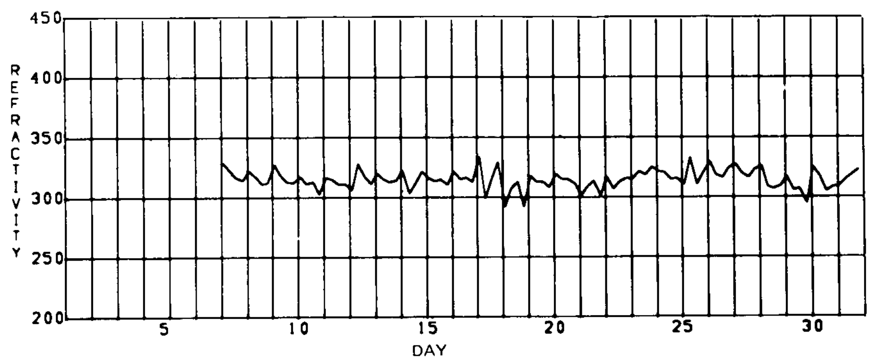
JUNE 1968



HAW

MAX	334.6
MIN	292.3
AVG	315.5
SD	7.9

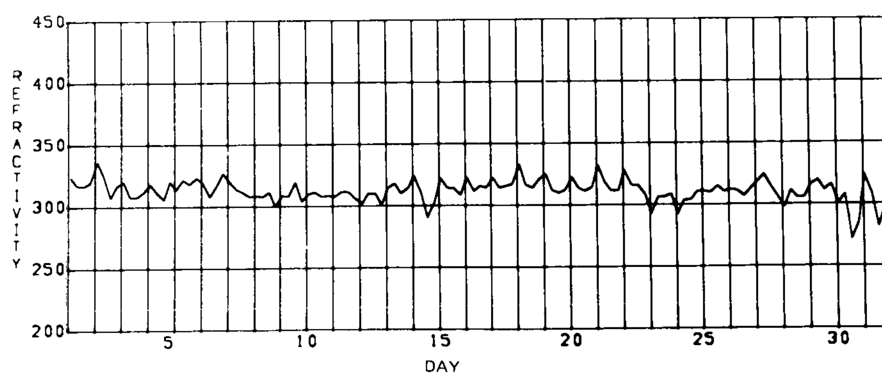
JULY 1968



HAW

MAX	336.7
MIN	272.2
AVG	312.6
SD	9.4

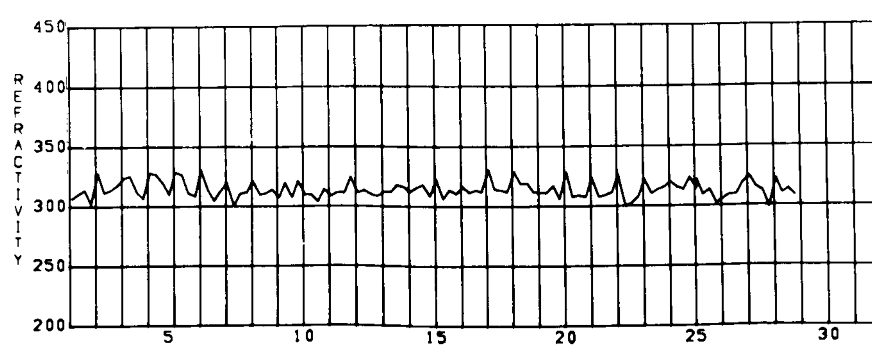
AUGUST 1968



HAW

MAX	331.9
MIN	299.0
AVG	314.7
SD	7.1

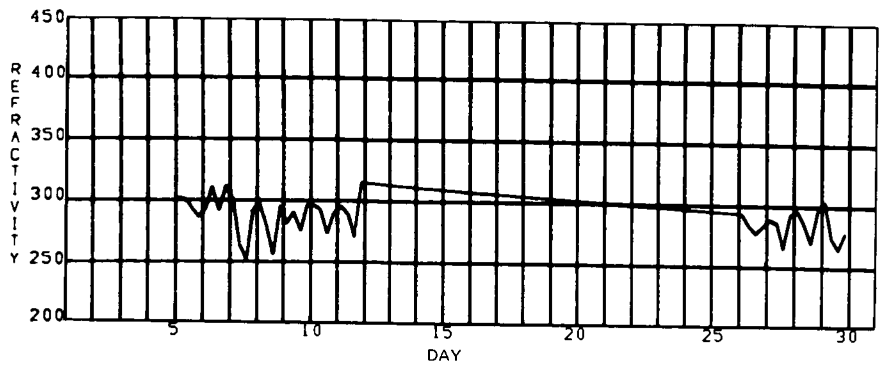
SEPTEMBER 1968



HSK

MAX	315.4
MIN	252.1
AVG	287.5
SD	14.2

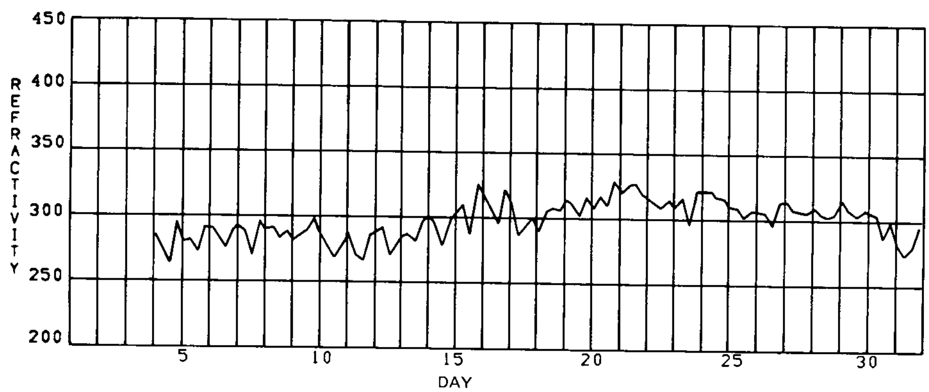
FEBRUARY 1968



HSK

MAX	323.6
MIN	263.5
AVG	294.8
SD	14.5

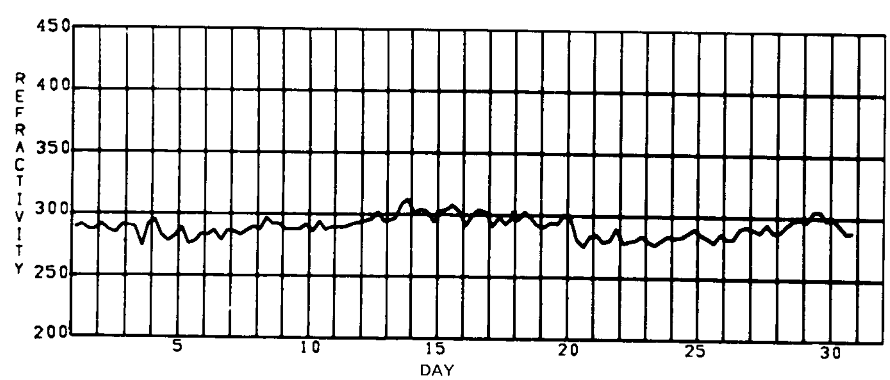
MARCH 1968



HSK

MAX	312.6
MIN	274.2
AVG	290.9
SD	7.9

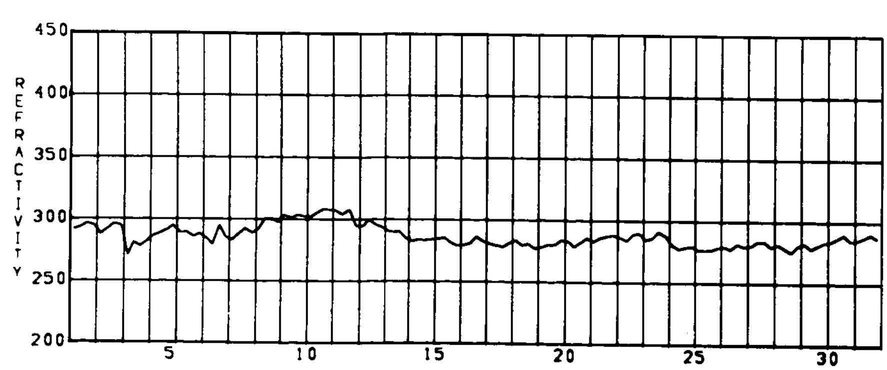
APRIL 1968



HSK

MAX	309.1
MIN	271.3
AVG	287.5
SD	8.1

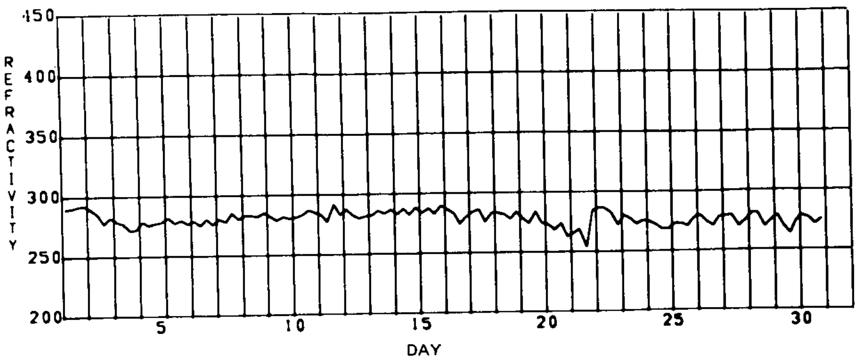
MAY 1968



HSK

MAX	293.4
MIN	254.5
AVG	279.7
SD	6.5

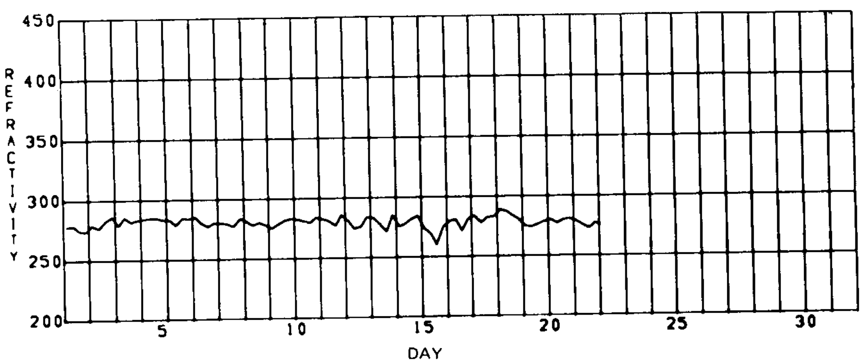
JUNE 1968



HSK

MAX	289.5
MIN	256.4
AVG	278.8
SD	5.4

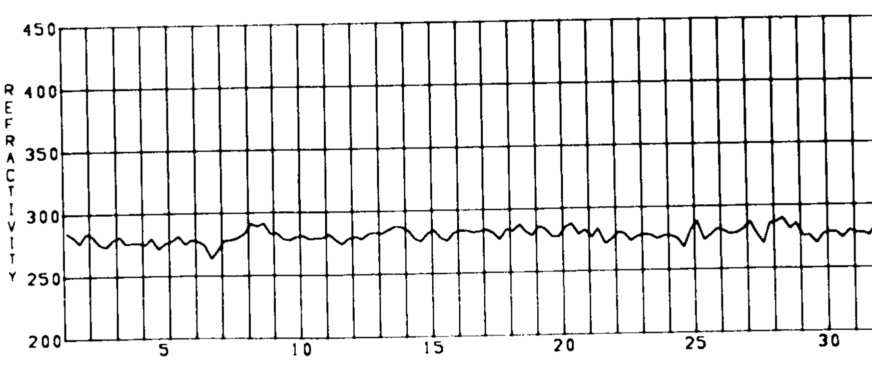
JULY 1968



HSK

MAX	288.9
MIN	262.4
AVG	278.0
SD	4.7

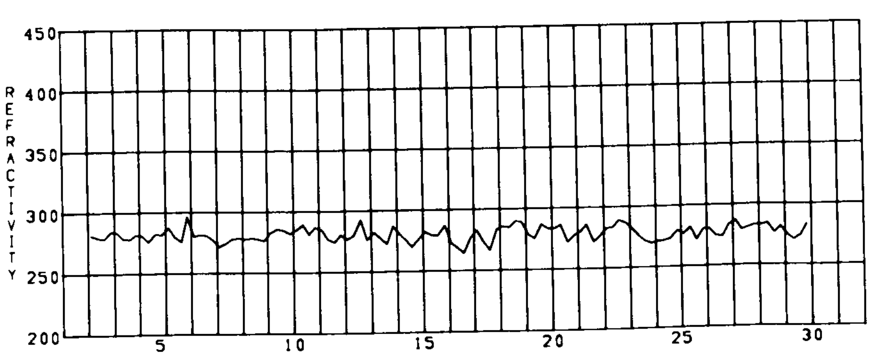
AUGUST 1968



HSK

MAX	293.9
MIN	262.8
AVG	278.0
SD	5.4

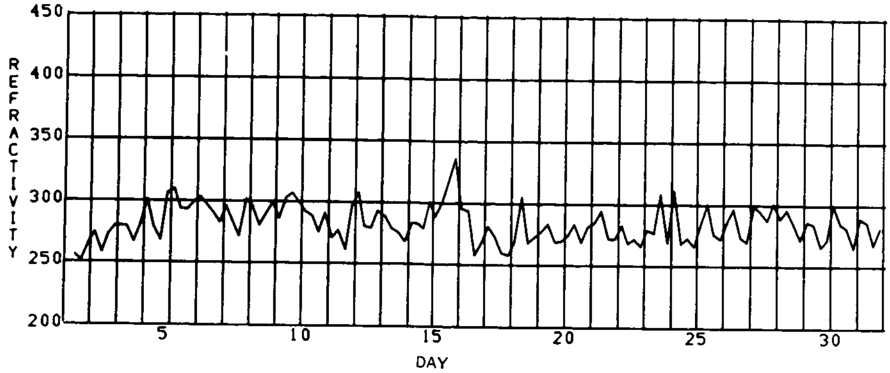
SEPTEMBER 1968



MAD

MAX	335.8
MIN	251.9
AVG	282.9
SD	14.3

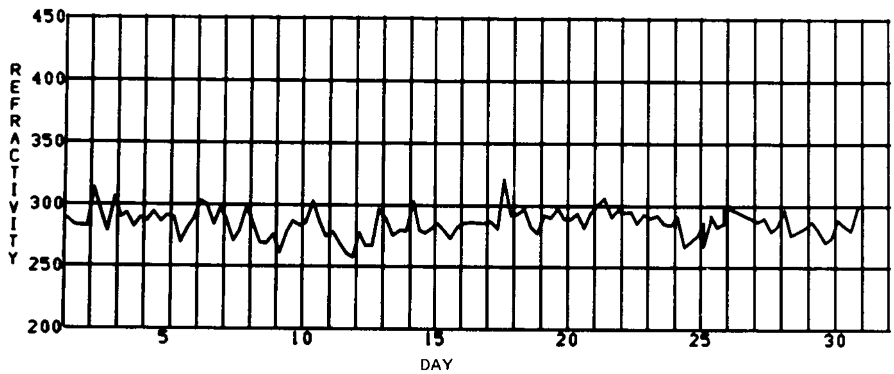
AUGUST 1967



MAD

MAX	321.3
MIN	258.3
AVG	285.9
SD	10.5

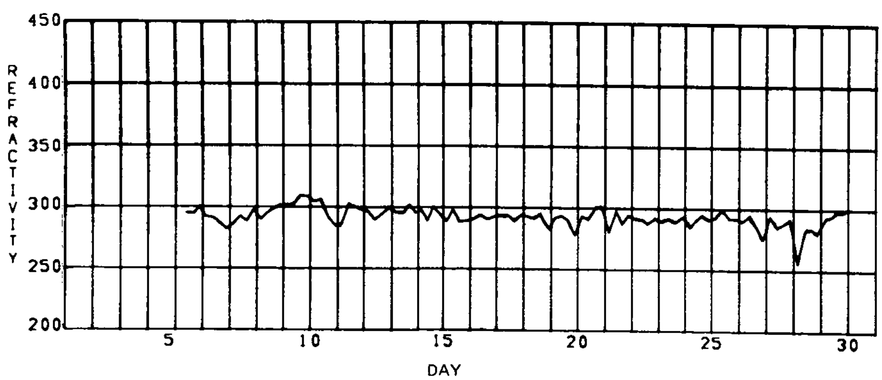
SEPTEMBER 1967



MAD

MAX	310.0
MIN	256.5
AVG	292.9
SD	7.3

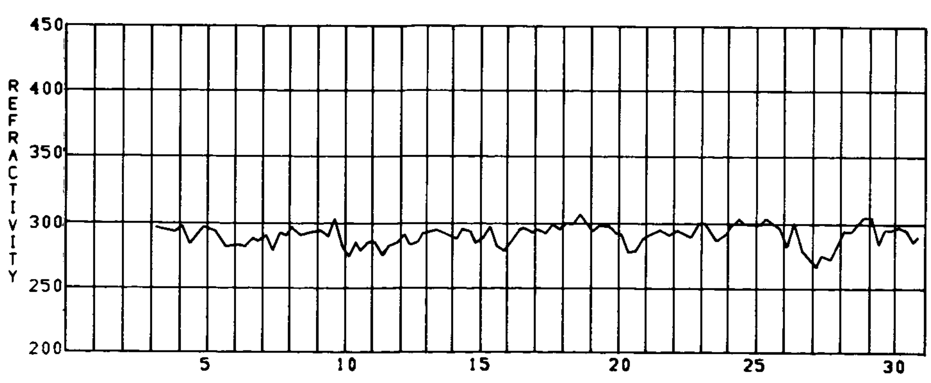
FEBRUARY 1968



MAD

MAX	307.9
MIN	274.5
AVG	291.5
SD	8.1

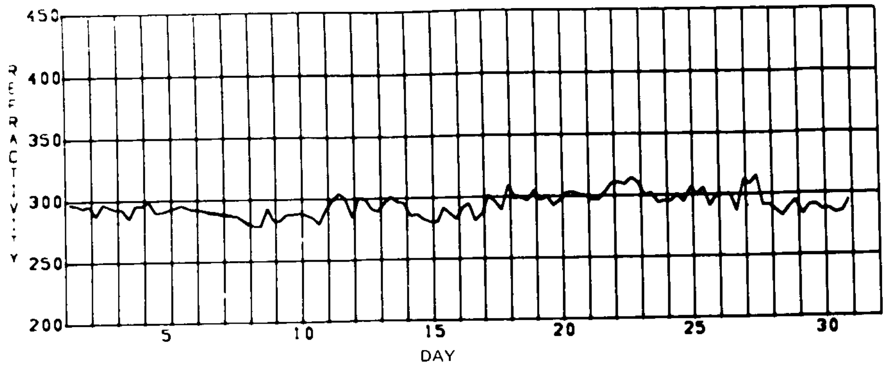
MARCH 1968



MAD

MAX	315.7
MIN	278.7
AVG	294.9
SD	8.4

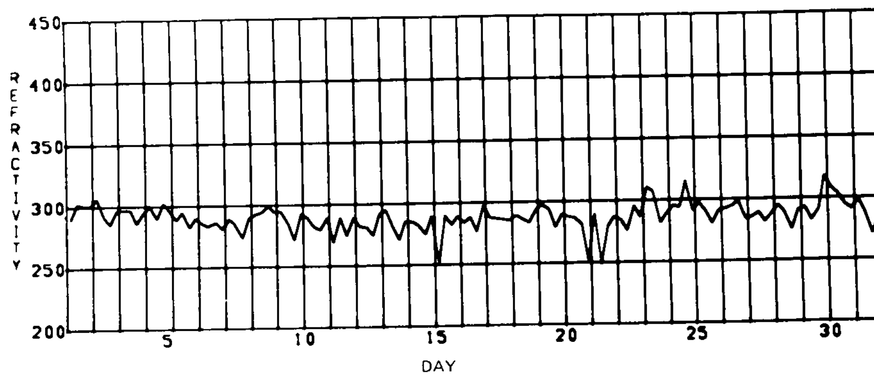
APRIL 1968



MAD

MAX	318.5
MIN	249.4
AVG	288.8
SD	10.6

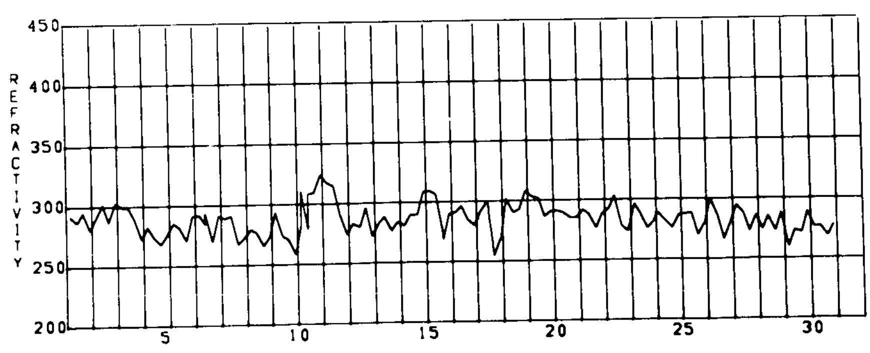
MAY 1968



MAD

MAX	325.1
MIN	255.7
AVG	286.5
SD	12.7

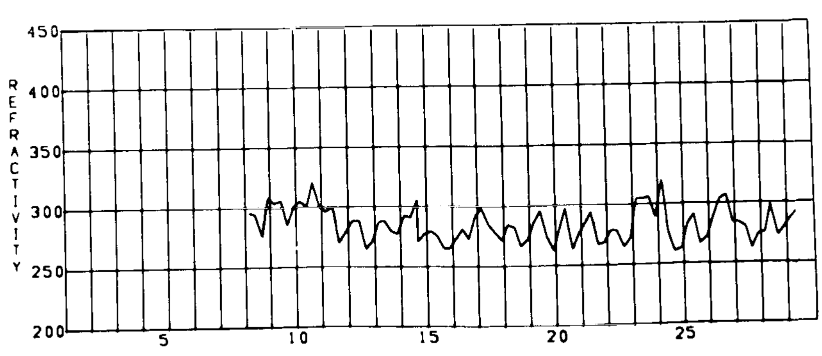
JUNE 1968



MAD

MAX	321.3
MIN	261.0
AVG	285.0
SD	13.8

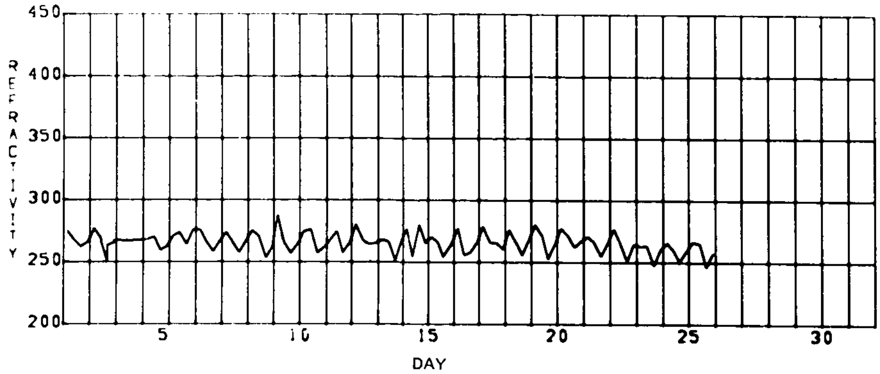
JULY 1968



MAD

MAX	288.2
MIN	246.8
AVG	266.2
SD	8.0

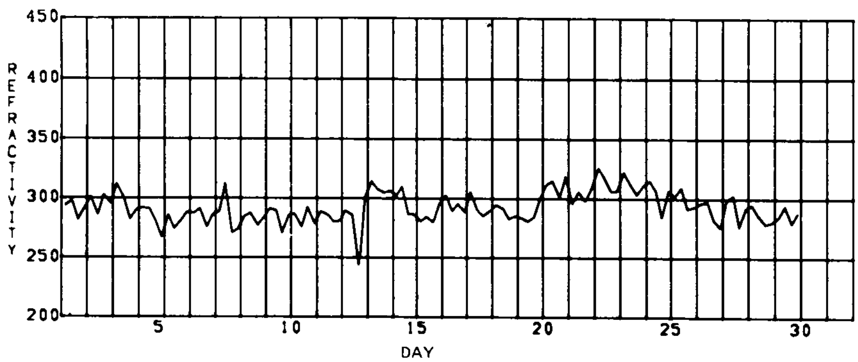
AUGUST 1968



MAD

MAX	362.3
MIN	244.7
AVG	293.1
SD	13.1

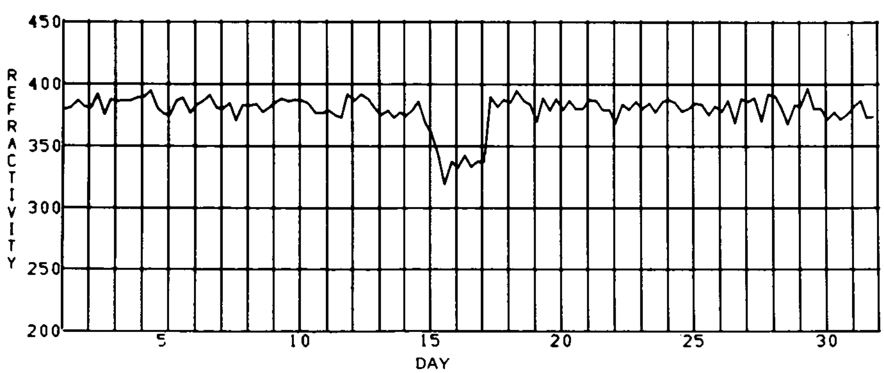
SEPTEMBER 1968



MIL

MAX	394.9
MIN	319.2
AVG	378.8
SD	13.2

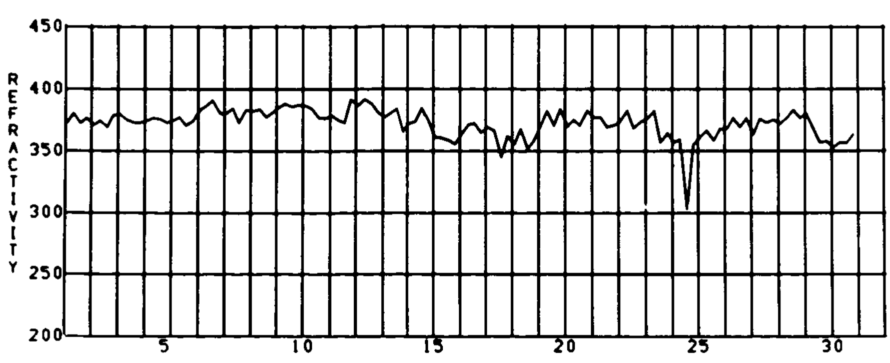
AUGUST 1967



MIL

MAX	391.6
MIN	303.6
AVG	372.0
SD	11.5

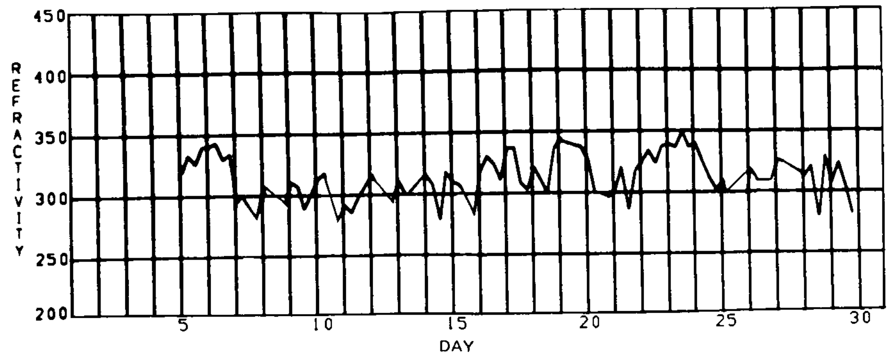
SEPTEMBER 1967



MIL

MAX	350.7
MIN	280.0
AVG	315.2
SD	17.7

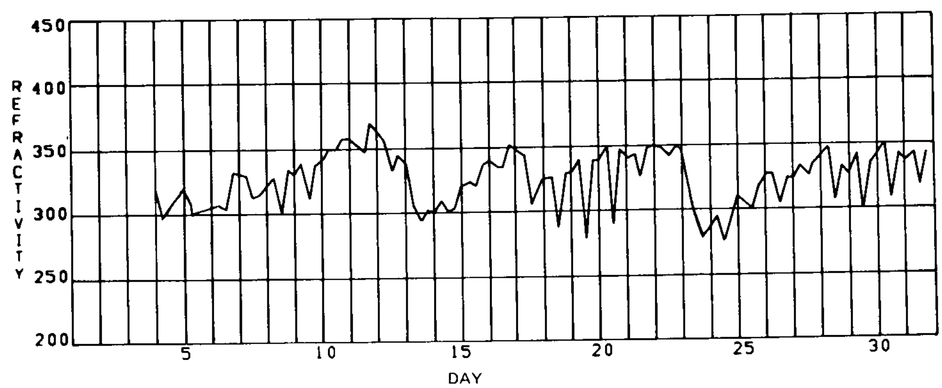
FEBRUARY 1968



MIL

MAX	370.5
MIN	275.3
AVG	326.0
SD	20.6

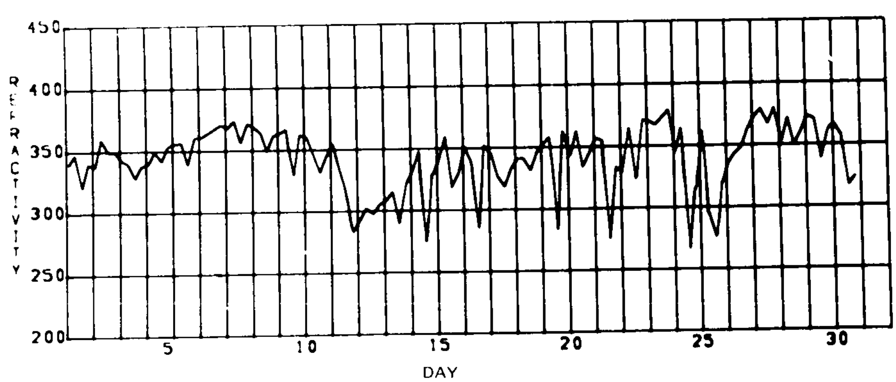
MARCH 1968



MIL

MAX	380.4
MIN	267.4
AVG	341.9
SD	25.8

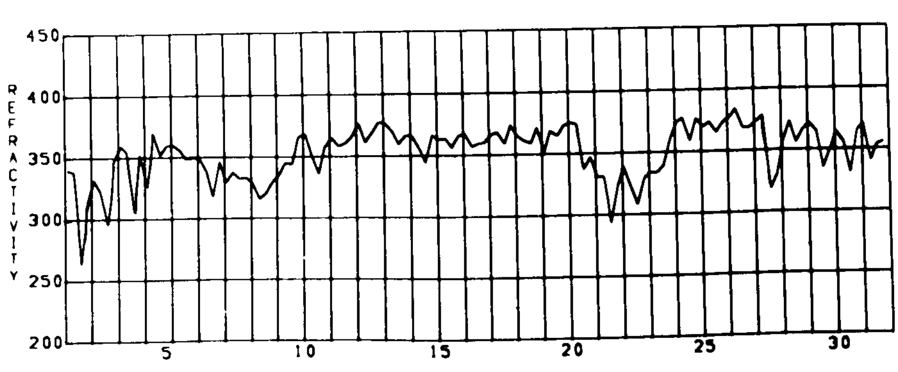
APRIL 1968



MIL

MAX	384.6
MIN	263.9
AVG	352.1
SD	21.0

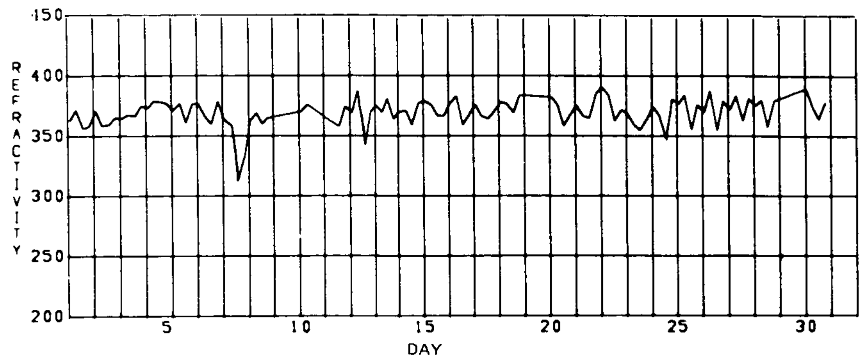
MAY 1968



MIL

MAX	390.7
MIN	312.5
AVG	370.0
SD	11.5

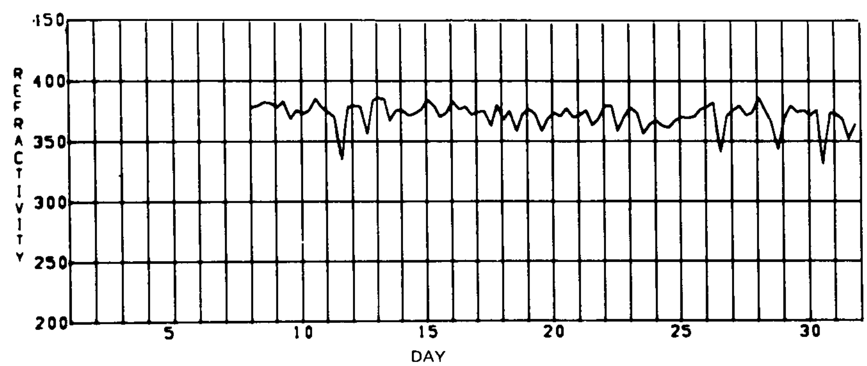
JUNE 1968



MIL

MAX	386.6
MIN	336.2
AVG	372.5
SD	10.1

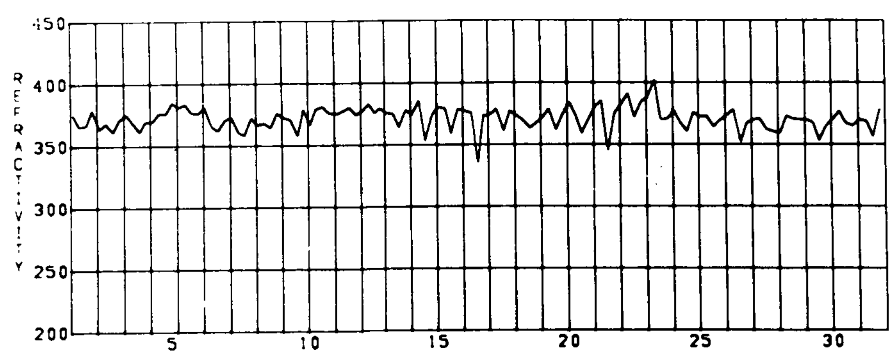
JULY 1968



MIL

MAX	402.5
MIN	336.2
AVG	372.2
SD	9.0

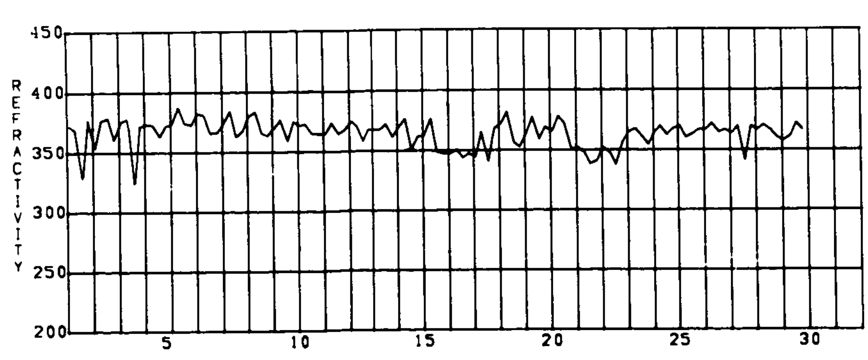
AUGUST 1968



MIL

MAX	387.8
MIN	325.2
AVG	365.3
SD	11.6

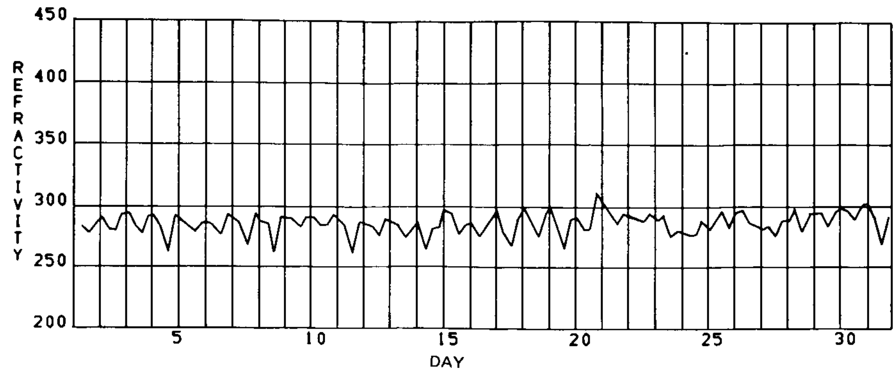
SEPTEMBER 1968



TAN

MAX	311.6
MIN	262.2
AVG	286.8
SD	8.9

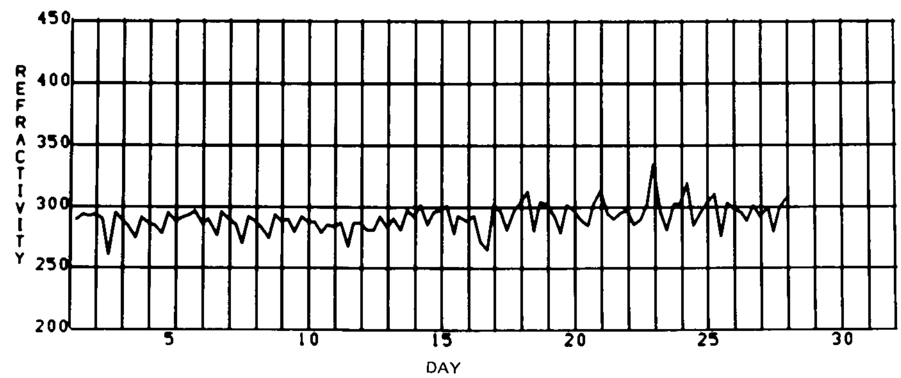
AUGUST 1967



TAN

MAX	334.7
MIN	260.9
AVG	291.3
SD	10.8

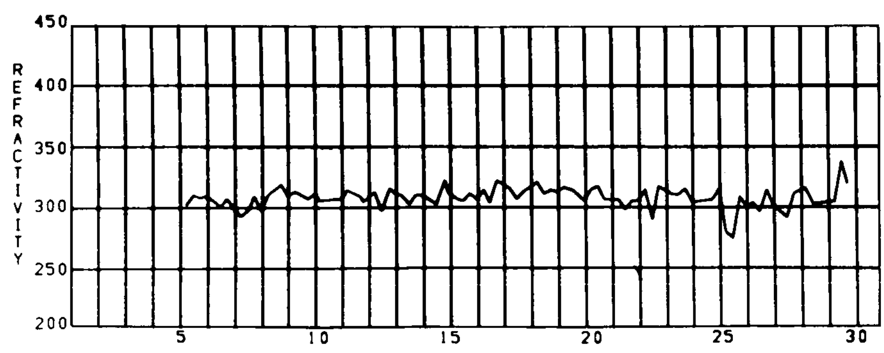
SEPTEMBER 1967



TAN

MAX	338.1
MIN	275.9
AVG	308.5
SD	8.8

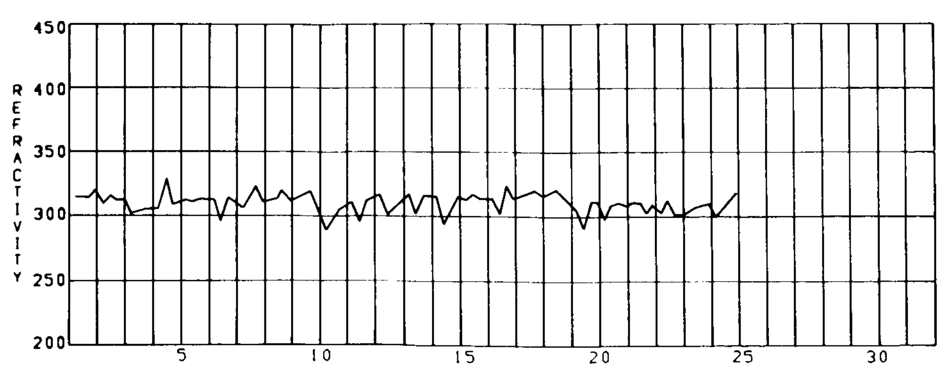
FEBRUARY 1968



TAN

MAX	328.3
MIN	287.9
AVG	310.3
SD	7.7

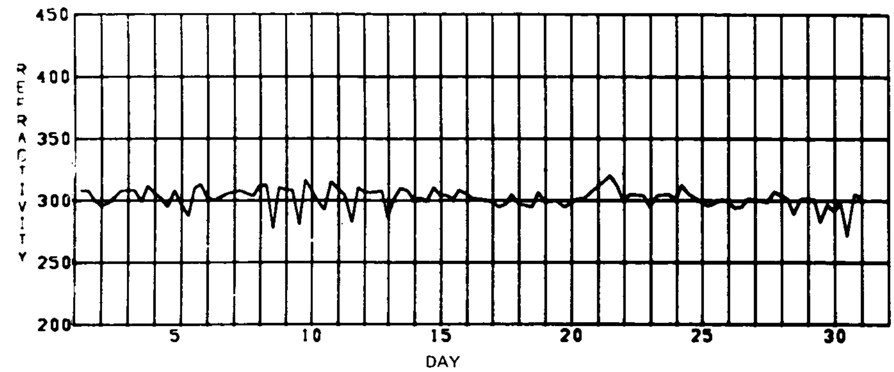
MARCH 1968



TAN

MAX	320.5
MIN	272.1
AVG	302.2
SD	8.3

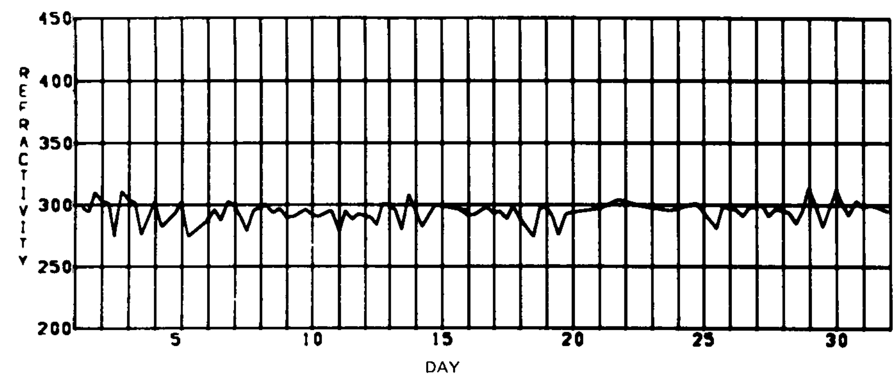
APRIL 1968



TAN

MAX	313.8
MIN	274.8
AVG	294.7
SD	8.5

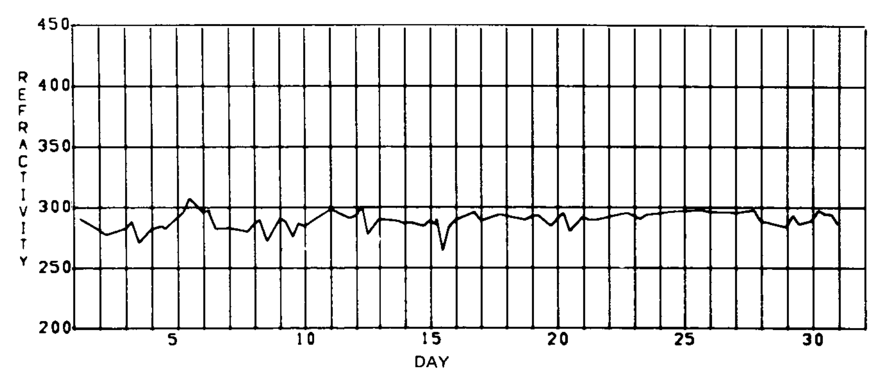
MAY 1968



TAN

MAX	308.4
MIN	264.8
AVG	289.4
SD	7.3

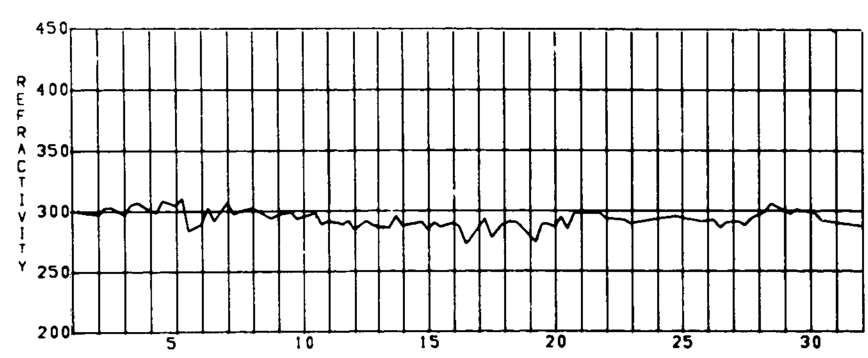
JUNE 1968



TAN

MAX	311.4
MIN	284.3
AVG	294.2
SD	7.3

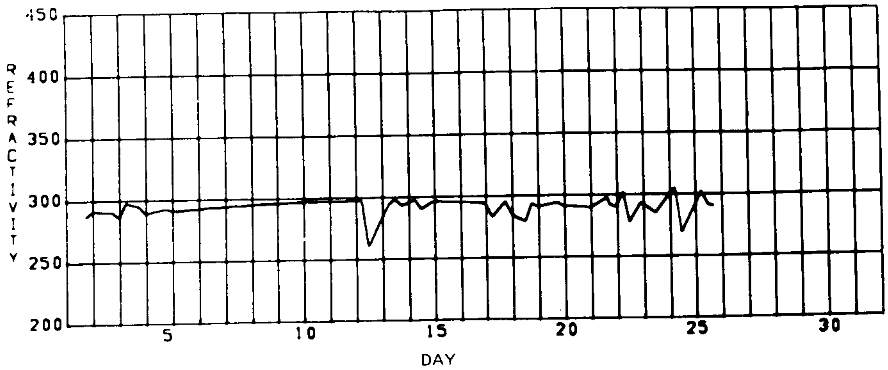
JULY 1968



TAN

MAX	305.4
MIN	261.0
AVG	291.3
SD	8.2

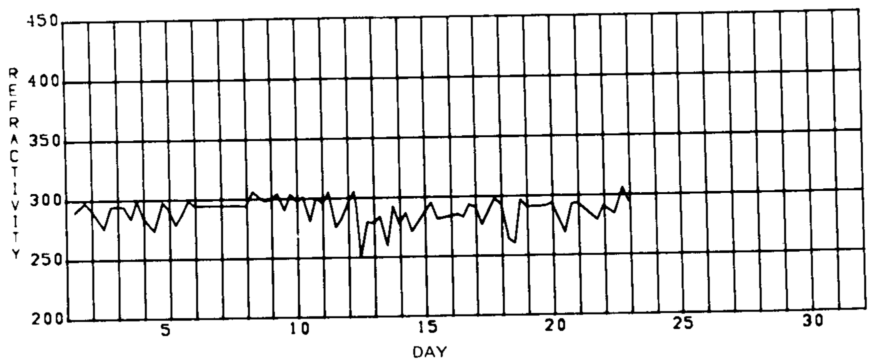
AUGUST 1968



TAN

MAX	306.8
MIN	250.7
AVG	289.6
SD	11.7

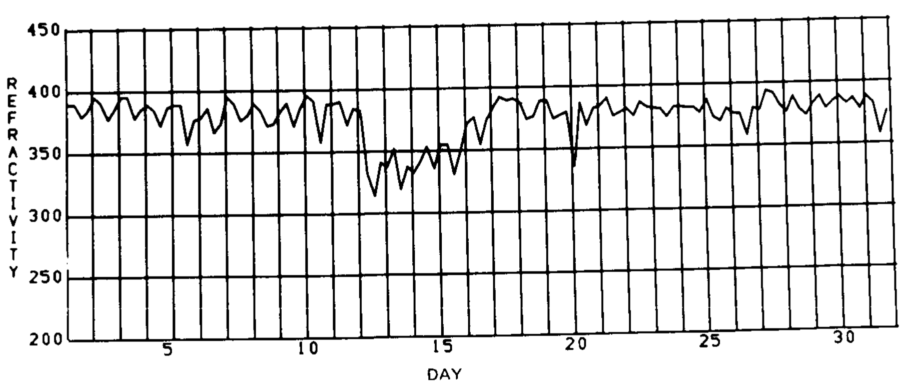
SEPTEMBER 1968



TEX

MAX	395.6
MIN	314.3
AVG	375.7
SD	16.9

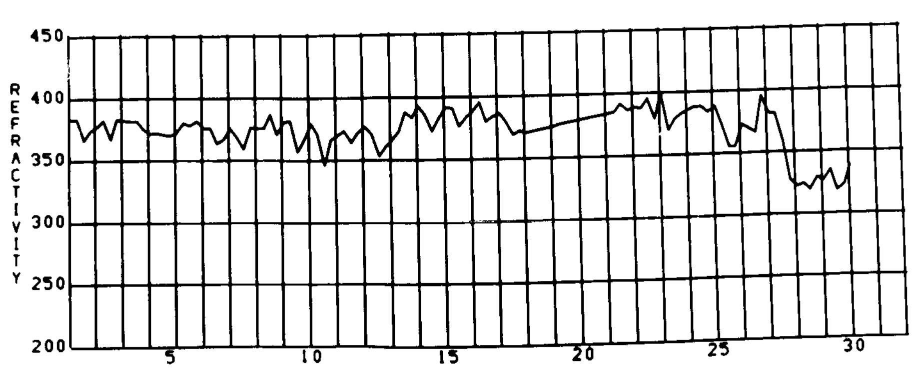
AUGUST 1967



TEX

MAX	399.9
MIN	318.6
AVG	371.9
SD	18.0

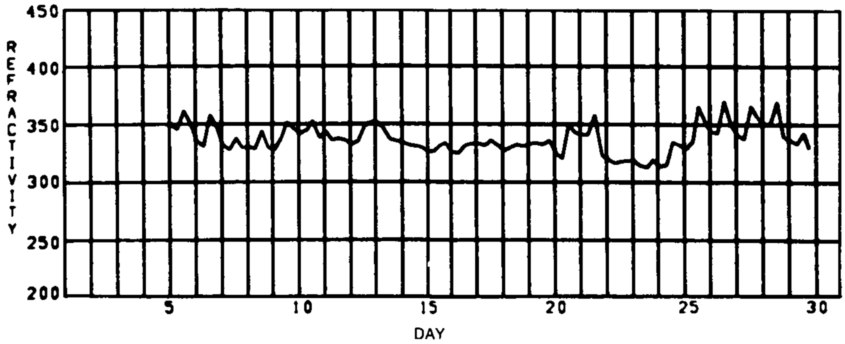
SEPTEMBER 1967



TEX

MAX	370.7
MIN	313.4
AVG	337.6
SD	12.2

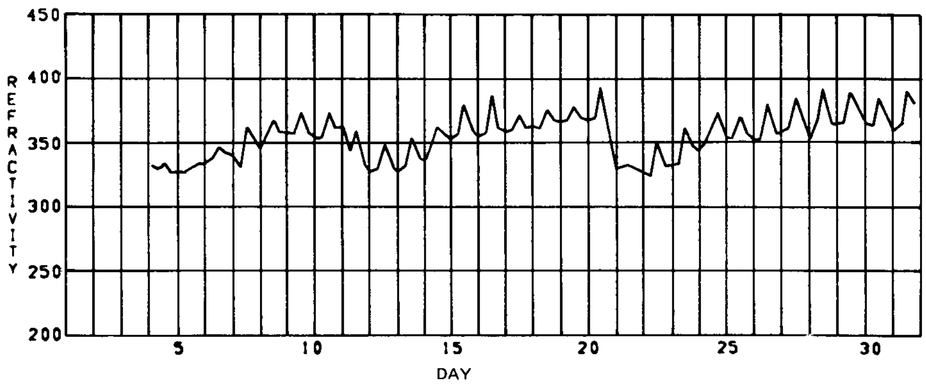
FEBRUARY 1968



TEX

MAX	392.8
MIN	323.1
AVG	354.7
SD	17.4

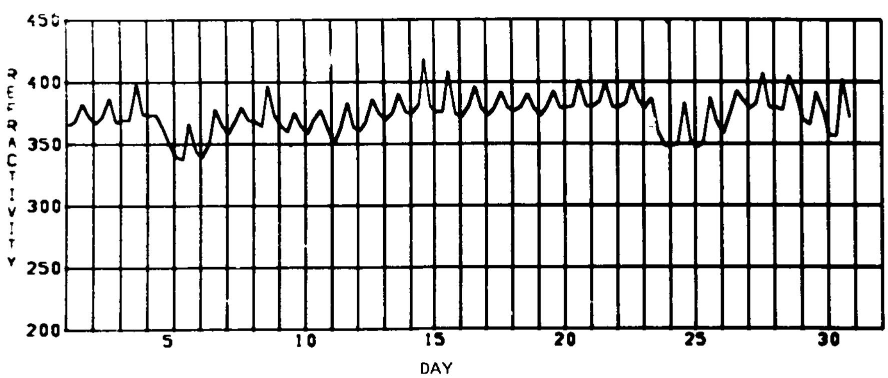
MARCH 1968



TEX

MAX	418.9
MIN	338.4
AVG	374.9
SD	15.1

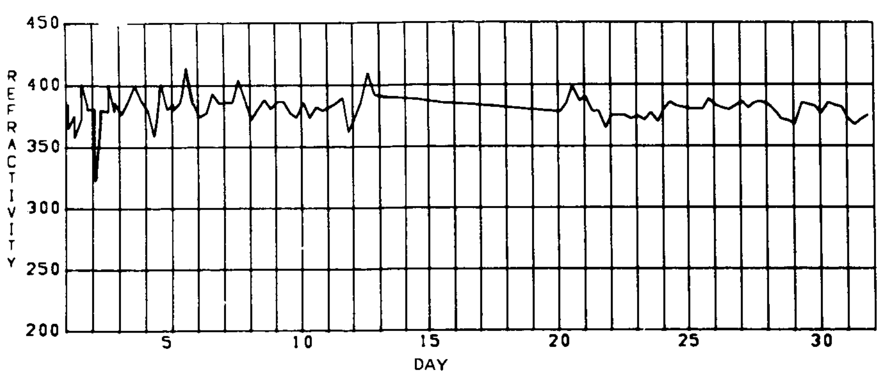
APRIL 1968



TEX

MAX	414.9
MIN	322.9
AVG	381.4
SD	11.1

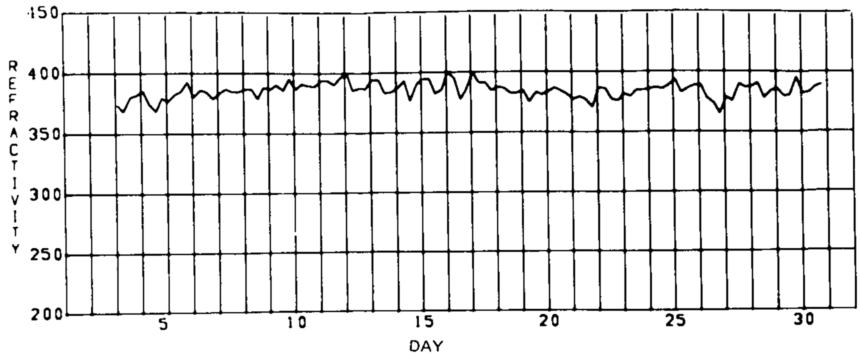
MAY 1968



TEX

MAX	400.8
MIN	365.7
AVG	385.4
SD	6.6

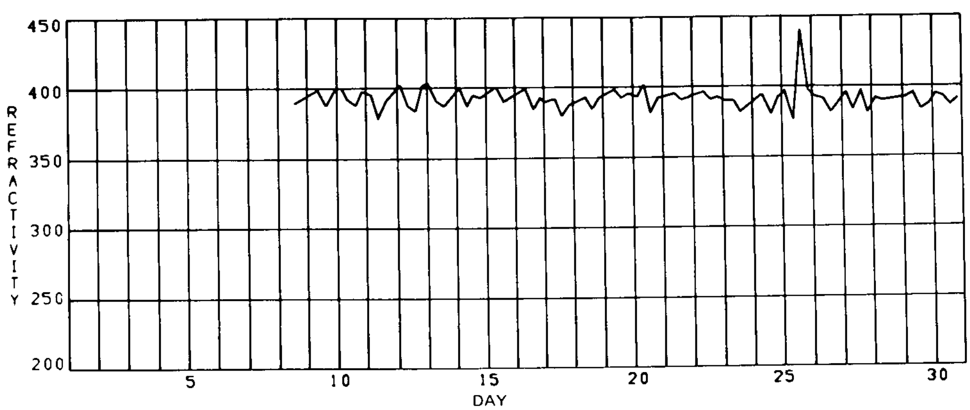
JUNE 1968



TEX

MAX	433.6
MIN	370.2
AVG	385.3
SD	7.4

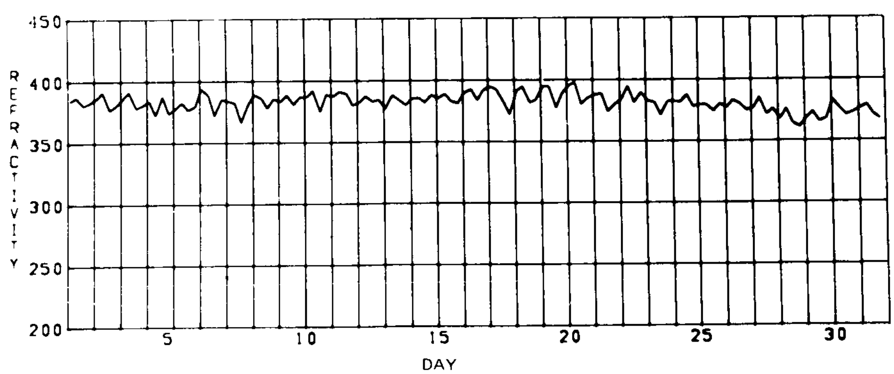
JULY 1968



TEX

MAX	398.4
MIN	362.3
AVG	382.7
SD	7.4

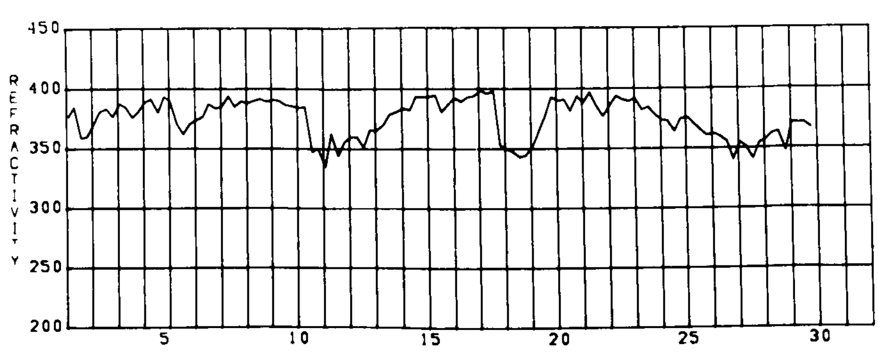
AUGUST 1968



TEX

MAX	399.2
MIN	336.2
AVG	375.9
SD	16.0

SEPTEMBER 1968



NASA-Langley, 1972 —— 20