STUDY OF INTERFEROMETER PHASE INSTABILITIES AND POSSIBLE CORRELATION WITH METEOROLOGICAL INFLUENCES

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I. INTRODUCTION

A relation was sought between the phase instabilities of the NRAO interferometer output and meteorological variables. The interferometer works at a frequency of 2695 MHz and with baselines between 1200 and 2700 meter.

The study was initiated in the hope that a possible clear correlation between phase variations and weather changes could be used to predict from simple meteorological measurements the expected quality of interferometer observations or the suitability of a specific site for the establishment of a very long baseline array.

From the available observations we chose a few sources from the position determination program, which were observed for many days over the whole range of hour angle, sometimes in one single run of about 10 to 12 hours, other times in short pieces of about one half hour intermittent with other sources. The sources are 3C48 and 3C147 which are observed at baseline 2 (1500m) during November and December 1964 and 3C48, 3C147 and 3C286 on baseline 5 (2400m) from March till May 1965. There are 25 or more days of observation on each source at each baseline; each days observation gives between 60 and 600 points on the visibility curve and the phase plot.

During November and December the only data on the weather (made at the site) are some remarks on the general conditions made by the telescope operator once every eight hours. During the baseline 5 observations (Spring 1965) continuous recordings at the site of the 85-2 telescope were made of:

Temperature, relative humidity and barometric pressure.

The fringe reduction program gives the following information pertaining to the phase:

a. The mean phase value of the principal solution. The sources are unresolved and hence the phase should be constant over the entire region of hour angle.

b. The rms scatter of the data points about the principal solution φ_{rms}

c. A plot of the phase over the hour angle range. If there were no phase fluctuations this would be a straight line.

Taking these data I have plotted different variables against each other in order to find possible correlations.

II. PHASE SCATTER

1. The rms phase scatter φ_{rms} as function of time (fig. 1)

    a. At baseline 2 φ seems to increase from 4 to 6 degrees between 1 November and 1 January (for 3C48 and 3C147).

    b. At baseline 5 the scatter is bigger than on baseline 2. 3C286, which is a night-time object, has the lowest scatter, rising from approximately 5° at 15 March to 15° at 20 May. The day-time object 3C147 has a slightly faster increasing scatter while 3C48 shows a high scatter between 20 and 30 degrees in May.

2. The average temperature during each day's observing period (for 3C48 and 147) increased from 1°C on 15 March to 22°C on 20 May.

3. In fig. 2 we have plotted the scatter against types of weather.

    a. φ_{rms} is plotted against the trend in barometric pressure; there is no indication of any dependence.

    b. Here the scatter for baseline 5 is plotted against general type of weather (sky coverage, temperature, pressure). Some correlation is present with low scatter during clear, cold weather with stationary barometer and high fluctuations during rain.

Remarkably all the points in the group "clear sky, non stationary barometer and high temperature" fall above the line. This group falls between the categories "cloudy, rain later" and "rainy." This may be an indication that the high temperature and the non stable pressure cause severe clear air turbulences, which can be responsible for the large phase scatter in the interferometer output.

c. Here the baseline 2 data show the same dependence on weather type but less clearly.

4. Figure 3 shows the φ_{rms} as function of the average temperature during a day's observing period. For baseline 5 we notice a correlation, although the spread is rather large at some points. The straight line has an equal amount of points on either side; the dashed curve is drawn to lie close to the majority of the points. The baseline 2 results cluster close together with a few high scatter values at the lower temperatures.

It should be noticed that, if we exclude the points in fig. 3a with $T > 15°C$ (the maximum in fig. 3b), we obtain a group of points, which lies in the average at somewhat higher φ values than in fig. 3b and shows much less correlation with temperature.

It is difficult to separate here the atmospheric influences from the instrumental effects. The absolute phase is strongly varying with temperature. This might also be reflected in the value of the rms scatter. Thus, I have plotted φ_{rms} against the difference in maximum and minimum temperature occurring in each observing period. The result is shown in fig. 4. Certainly no strong correlation is present.

One can conclude from this that the temperature changes do not exhibit a strong influence on that part of the rms phase scatter which originates in the instrument.

But then it might be inferred that the effect in fig. 3 is mainly caused by the atmosphere at different temperatures.

5. It is well known that the refractive index of the atmosphere is strongly dependent on the water vapor pressure e. It is on the other hand not unreasonable to expect that fluctuations in the water vapor content will be larger if much water vapor is present in the atmosphere. As the phase fluctuations will supposedly be correlated with the water vapor fluctuations, I have made a plot of φ_{rms} as a function of the specific humidity q of the atmosphere averaged over the daily observing period. The specific humidity was chosen, because it is a direct indication of the amount of water vapor per cubic meter air. To a good degree of accuracy $q = 0.622\ e/P$, where P is the total atmospheric pressure. Only the baseline 5 data could be used because during that time continuous recordings of temperature, relative humidity and pressure were made. The values of q calculated from these data vary from less than 1 gram per kilogram to more than 10 g/kg. The results are given in fig. 5; a. for 3C48 and 147, observed during the day-time, and b. for the night-time object 3C286.

There appears to be a correlation; the higher values of phase scatter fall in the region of large specific humidity. A clear difference, however, exists between the day and night-time results. The regression line for the night-time observations is about half as steep as that for the day-time results. Therefore, another quantity, changing significantly between day and night, must have a strong influence on the amount of phase scatter. This could, of course, be the temperature; inspection of fig. 3, however, reveals no difference for the phase scatter between the night-time and day-time object. From other investigations there is evidence that the atmosphere is more stable during the night. Wind speed frequently drops in the night and turbulences in the air are less. This may be reflected in the result that the scatter for 3C286 is generally lower and that it increases slowly with increasing specific humidity.

A few other things should be noted. On both baselines the scatter increases with time. For baseline 2 the increase is small but noticeable, while on baseline 5 the increase is more pronounced.

The average temperature during baseline 2 was fairly constant, a few degrees Celcius negative; on baseline 5 the average temperature increased noticeably. Apart from what was said under 4, at page 3, it is not clear which part of φ_{rms} is due to general seasonal influences (of which the temperature may be one) and which part is caused by slow degradation of equipment performance. Between 6 and 13 May some trouble with parametric amplifiers and L.O.-systems was encountered. This may be th [illegible]

occurring in that time.

The difference between the slope of the lines in fig. 5 may also be caused by instrumental effects. One possible explanation is that the average phase stability during the night is better than during the day.

From the recorded temperature, pressure and relative humidity during the baseline 5 run I have calculated the average refractivity N ($N=(n-1)\ 10^6$, n being the refractive index) during each daily observing period, separated again in day and night time observation. A graph of the rms phase scatter versus refractivity is shown in fig.6. It shows no correlation if all the points are taken together. The full line (under an angle of about 30 degrees with the horizontal) has an equal amount of points on either side. But it is clear that the spread of the points is much too big to indicate a correlation. The circles (for 3C286, night-time) show a slight tendency to follow a behavior as is indicated by the dashed line.

During the period March - May 1965 the refractivity varied between 255 and 315 N-units during the day with an average of 275 and between 271 and 315 with an average of 291 during the night.

III. ABRUPT PHASE VARIATIONS

In an attempt to localize the causes for sudden large discontinuities in the phase of the visibility curve I looked at all the phase plots for the baseline 5 data and noted the moment of occurrence of the phase jump and its magnitude. Then the weather data were examined for sudden changes. Temperature, pressure and relative humidity discontinuities were read from the charts and a general idea about the stability of the weather was obtained from the remarks in the log sheets.

Also days where the phase plot showed a remarkable constancy were taken, as were the days which showed very stable weather.

Comparison between the two sets of data (phase variations and weather changes) gave the following summarized results.

For 3C286 (night-time observations) 14 nights gave very stable phase, 12 had phase jumps in excess of 20 degrees, while during 7 nights the phase jumps stayed under 20 degrees.

3C48 and 147, together, had during the day-time 18 runs without phase discontinuities, 24 days with jumps over 20 degrees and 6 days under 20 degrees.

In the case of 3C286, the correlation with weather changes at roughly the same time (the exact time reading of the recording meteorological instruments is not very well possible) is:

good correlation	:	in 9 cases
fair to marginal	:	in 8 cases
bad or none	:	in 16 cases

This shows that no decision to whether or not there is a correlation can be made.

For 3C48 and 147 we arrive at:

good correlation	:	20 cases
fair to marginal	:	13 cases
bad or none	:	15 cases

These results indicate a possible small correlation between sudden phase jumps and weather changes.

Starting with the meteorological conditions we find that:

a. Large, sudden changes in temperature, pressure and/or humidity occurred 19 times. At about the same time we had

10 times large discontinuities in the phase

9 times no sharp discontinuities in the phase

b. During calm and stable weather we had:

20 times no phase discontinuities of any reasonable size

21 times discontinuities in the phase in excess of 30°

The conclusion which one can draw from this is, that there is certainly no clear correlation between weather changes and jumps in the phase of the fringes.

It is, of course, perfectly possible that the cause of many of the phase variations lie in sudden meteorological changes, but predicting phase jumps from meteorological measurements does not seem feasible.

Then the daily weather surface maps of the United States were inspected at the Elkins Airport Weather Bureau. Special attention was given to the presence of fronts over or near to our region. The following group of weather type was made:

a. No front

1. High pressure

2. Low pressure

b. Front nearby, roughly within a 400 km radius

1. Cold front (C)

2. Warm front (W)

3. Stationary front (S)

c. Front over the local region, same subdivision as under b.

Figure 7 shows the rms phase scatter of the interferometer records for the different classes of frontal activity. The spread is large but there is an increase from "no front, H" to local front S". As the weather maps are drawn according to the situation at 01.00 EST (in the middle of the 3C286 observing period) and the data for this source show generally less anomalous (very large) scatter, the results for this source are plotted separately in fig. 6b.

The straight lines in fig. 6 have an equal amount of data points at either side. The dashed curve runs approximately close to as many points as possible. It appears that the lines in fig. 6a and 6b are very much the same.

Also I have looked for a correlation between the days that large, phase changes occur and frontal activity is noticeable. The result is summarized in the following table:

		FRONTAL ACTIVITY			
PHASE JUMPS	NO	NEAR	LOCAL	NO	NEAR OR LOCAL
YES	10	16	15	10	31
NO	23	6	3	23	10

It is clear that more jumps occur in an atmosphere influenced by fronts and that absence of frontal activity is connected to the majority of days without phase jumps. In about 70% of the cases large phase discontinuities are simultaneous with fronts and a smooth phase plot with a calm atmosphere.

We also see that taking the class "front nearby" together with "no front" a correlation is much harder to find.

Finally, we can take the local changes in temperature, humidity and pressure, together with the frontal activity from the weather maps, and compare these with the measured fluctuations in the phase.

It appears, however, that in more than 40 percent of all days, the frontal activity does not correlate well with the local weather stability. For these days it is difficult to conclude anything about a correlation between the phase discontinuities and the sudden weather changes.

For the 43 days where local weather and frontal activity were in good accordance, we had almost 70 percent of the days a good correlation between weather and phase fluctuations.

IV. SHORT TIME DISTURBANCES

Working on the reduction of the position determination program B. Clark found that the difference between optical and radio position of the sources changed with right ascension (which is also with time of the day).

Consideration has been given to the possibility that the different average refractive index during day and night-time would be the cause of the effect. The applied method of observation and reduction, however, makes the result insensitive in the first order for this kind of disturbances, which occur in both paths to the two elements of the interferometer. Only the change in phase caused by that part of the atmosphere, which is present in only one path (e.g. as a result of different elevation of the antennas), will yield a shift in the fringe position and hence in the deduced source position. This path length, in our case, is less than 30 m and the correction necessary for the difference in refractive index during day and night is (being a correction on an already small correction) negligible.

In the meantime checks have been made by W. C. Tyler of the absolute phase stability of the instrument and he finds a large diurnal variation.

This variation can, according to Clark, allow for the right ascension dependence of the source positions.

The question arose as to the extent that phase variations are caused by atmospheric irregularities occurring in front of only one of the elements of the interferometer. In our case the temperature and humidity are sensed some-where in the structure of the 85-2 telescope. It is, of course, impossible to locate atmospheric disturbances (we shall call these "turbulons") in space and time by the recording of refractivity at one place only. Let us now assume that sudden sharp changes in temperature and humidity of short duration ("spikes") recorded at the 85-2 are caused by a small atmospheric disturbance which is not present at the site of the 85-1. In that case a short time variation would occur in the pathlength of one of the beams and result in a "spike" on the phase plot of the interferometer output.

There are, of course, several reasons for a negative result, as:

a. The assumption of occurrence of the turbulon at only one station depends heavily on wind force and direction, which are unknown.

b. Each point on the phase plot is the result of one minute observation. The turbulon could have disappeared during this time or travelled to the other telescope. Connected herewith is the fact that the size of the disturbance is unknown.

c. In order to calculate the expected phase variation due to a certain measured temperature and humidity change at the 85-2 we have to assume a certain equivalent thickness for the turbulon having the refractivity as measured.

The results of a few analyzed cases are tabulated below. We assume a homogeneous slab of thickness d=1000 m to be moved in front of one of the elements giving rise to a refractivity change of ΔN units. Then the phase variation will be approximately $\Delta\Phi \sim 3.6\, \Delta N$ degrees.

Date	Time EST	Source	T(°K) ΔT	e (mb) Δe	p Δp	N ΔN	ΔΦ calc. (degrees)	ΔΦ Observed	Time	Correllation
2 Apr.	00.00	3C286	273 -3	5.4 0.2	916 -	289 -2.5	9	15	≈01.00	?
9 Apr.	21.00	3C286	281 -1	7.85 0.75	917 -	292 4.5	16	20	21.10	+
11 Apr.	17.00	3C286	285 +3	14.2 -4.0	907 +2.0	314 -21.5	77	40	17.45	?-
11 Apr.	18.00	3C286	286 -1	5.25 1.25	910 -	272 +7.0	24	20	18.00	+
8 May	13.00	3C48	296 -9	11.3 +2.8	925 -	292 23.5	85	Spikes at about >60	13.00	?+
16 May	15.30	3C147	293 2	9.9 5.0	921 -	288 19.0	69	≈ 50-60	15.25	+

In a few cases the calculated $\Delta\varphi$ is close to an observed phase jump at the same time. Some cases are not clearly correlated, while some seem to exhibit a time lag. It is good to emphasize that these are discontinuities of very short duration, both in the atmosphere and on the phase plot. They are clearly separated from a normal diurnal or other long time trend in the variables.

V. THEORETICAL PHASE FLUCTUATIONS

In this section we shall try to estimate the phase fluctuations introduced by turbulent regions (often called "blobs" or "turbulons") in the atmosphere. Due to different meteorological effects these turbulons originate and disappear after some time; generally, they are moving with the wind. According to the theory of turbulent mixing (Tatarski, Obukhov) these regions of differing refractive index have "scales", that is the distance over which a correlation between the fluctuations in refractivity is apparent, between a few decimeter and several hundred meter. Measurements of the turbulon size with refractometers on ballons and aircraft give generally values roughly between 5 and 250 meter with a median value around 60 meter. It should be born in mind, however, that these figures are very dependent on the time over which the measurement is taken (sampling time) and that a continuous scale distribution exists between about one centimeter and several kilometers. The largest fluctuations of refractivity occur in the largest turbulons. This is fortunate because it means that large fluctuations are correlated over large distances and will have less influence on the performance of an interferometer.

Assume a locally homogeneous field of refractivity fluctuations with a structure function

$$D_n(r) = C_n^2 \cdot r^{2/3} \qquad \text{for } \ell_0 \ll r \ll L_0$$

with: r the distance over which the structure function is wanted

ℓ_0 the inner scale of turbulence

L_0 the outer scale of turbulence

This is the so-called two-thirds law (Tatarski, Kolmogorov) which is a result of the theory of turbulent mixing. It is the best theory available and fits in most cases well to experimental results.

It is possible to omit the requirement $r \ll L_0$ and give $D_n(r)$ the same form for all $r \gg \ell_0$.

The structure function of the phase fluctuations $D_s(\rho)$ is hardly affected by inhomogeneities of size much larger than ρ. Following Tatarski we find for the structure function of the phase fluctuations over a distance ρ.

$$D_s(\rho) = 2.91\, k^2\, L\, C_n^2\, \rho^{5/3}$$

valid for all $\rho \gtrsim \sqrt{\lambda L}$, where L is the distance over which the incoming radiation encounters the refractivity fluctuations; as usual $k = 2\pi/\lambda$, λ being the wave-length. The factor C_n depends directly on the amount of refractivity fluctuations in the atmosphere.

The mean square phase fluctuations $\overline{S^2}$ between two points a distance ρ apart is given by the structure function

$$D_s(\rho) = \overline{[S(a + \rho) - S(a)]^2} = \overline{S^2}$$

and so we find for the phase fluctuations at point $a+\rho$ compared to the fluctuations at point a

$$\overline{\Delta S} = \sqrt{\overline{[S(a + \rho) - S(\rho)]^2}} = \sqrt{D_s(\rho)} = 1.7k\sqrt{L}C_n\rho^{5/6}$$

From propagation studies and direct meteorological measurements one has found that typically $2\cdot10^{-8} \leqslant D_n \leqslant 4\cdot10^{-7}\ m^{-1/3}$.

Taking $C_n = 5.10^{-8}\ m^{-1/3}$ with $\lambda = 0.11$ m, $L = 3000$ m we find for baseline 5 with $\rho = 2400$ m a phase fluctuation

$$\overline{\Delta S} = 0.174 \text{ radian} = 10 \text{ degrees}.$$

Considering the limits of C_n the actual value of ΔS may be as low as $4°$ and as high as $80°$.

These values are of the same order of magnitude as observed.

Sometimes one uses a gaussian correlation function (which has only one characteristic scale length ℓ) for the refractivity fluctuations. This is not in accordance with the facts but the advantage is that in the formula for the phase fluctuations at a point the refractivity fluctuations $\overline{\Delta N^2}$ appear directly and not the quantity C_n which depends on ΔN via some empirical constants whose numerical values are difficult to determine.

In the case where $L \ll k\ell^2/q$ (with L = 3 km and ℓ = 60 m this is true) one obtains for the phase fluctuations at a point

$$\overline{S^2} = \sqrt{\pi}\ \overline{\Delta N^2}\,\ell k^2\ L\cdot 10^{-12}$$

Direct measurements of $\overline{\Delta N^2}$ give values typically between 10^{-2} and 1 (N-units)^2 (Straiton). With the same values for L, k and ℓ = 60 m we find

$$\overline{S^2} \sim 10.10^{-6}\ (\text{rad})^2 \quad \text{or} \quad 0.2 \lesssim \bar{S} \lesssim 2 \quad (\text{degrees})$$

if $\overline{\Delta N^2}$ varies between the two limits just given.

Taking the fluctuations uncorrelated at the two antennas we find for

$$\Delta S = \sqrt{2}\ \bar{S} \approx 0.3 \text{ to } 3 \text{ degrees.}$$

which is about an order of magnitude less than we found earlier with the better theory.

SUMMARY

For the sample used in the analysis the phase scatter increased with time. It is difficult to separate equipment and atmospheric effects. Some correlation is found between the phase scatter and temperature. The scatter in phase appears to be correlated with specific humidity. But other influences must also be present, strongly changing between day and night. There is no clear correlation with refractivity. The refractivity lies between 255-315 (average 275) in day-time and 270-315 (av. 290) N-units in night.

Large discontinuities in phase are in about half of all cases connected with abrupt meteorological variations. Frontal activity in or near our region correlates with large phase jumps in about 70 percent of their occurrence. Also the rms phase scatter increases with frontal activity, although not very striking.

The phase fluctuations predicted from the theory of turbulence is of the order of 10 degrees. The observed phase scatter is of the same order.

No one to one correspondence between phase stability and simple, locally measured meteorological characteristics has been found. Although some correlation is found with humidity and frontal activity, no quantitative conclusion about expected interferometer performance can be inferred from the knowledge of these phenomena.

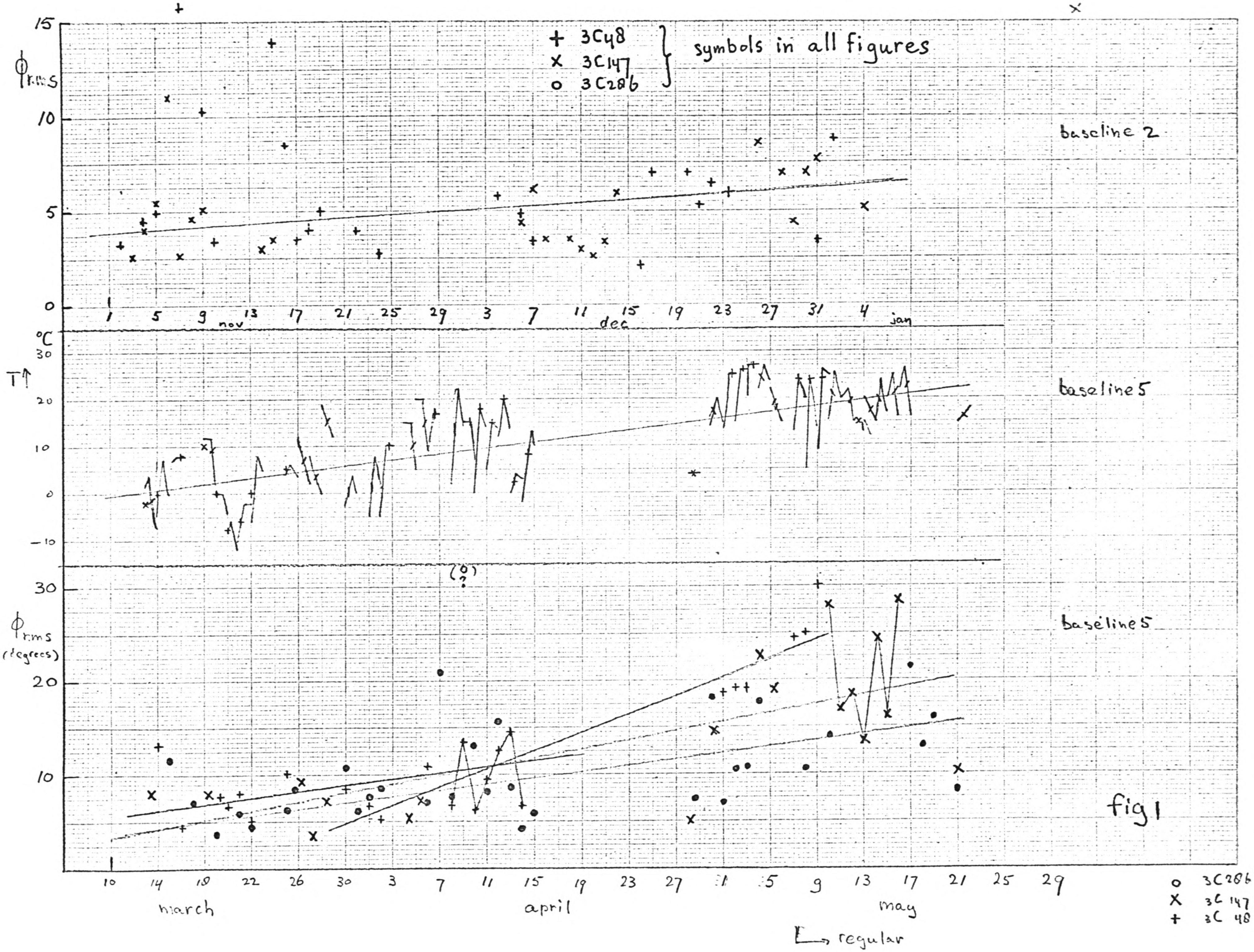
Also the knowledge of meteorological quantities would not suffice to make a decision as to the quality of a prospective site for a Very Large Array. It can be concluded that a dry site with little frontal activity will be desirable.

Some uncertainty in the present results could be removed, if one were cercertain that none of the phase fluctuations is caused by instrumental effects. Therefore, it may be worthwhile to repeat a similar investigation as this one on a block of data obtained after installation of the phase lock system.

Literature cited.

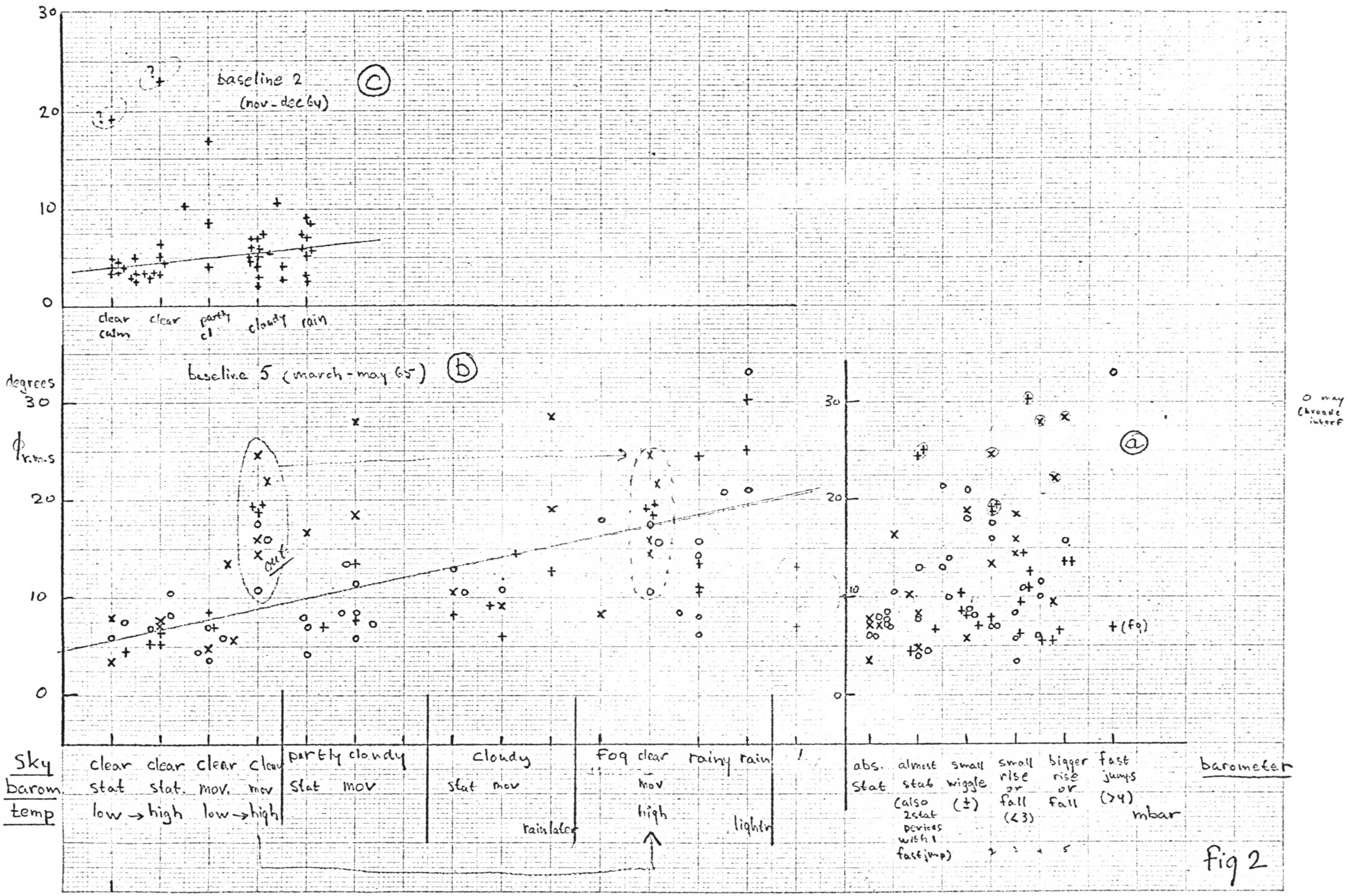
V. I. Tatarski - Wave Propagation in a Turbulent Medium

A. W. Straiton - The Measurement of Refractivity, in Advances in Radio Research Volume 1.



+ 3C48
x 3C147
o 3C286
symbols in all figures
ϕ_{rms}
baseline 2
nov
dec
jan
°C
T↑
baseline 5
baseline 5
ϕ_{rms} (degrees)
march
april
may
o 3C286
x 3C147
+ 3C48
regular

fig 1



baseline 2
(nov - dec 64)
(c)
clear calm
clear
partly cl
cloudy
rain
baseline 5 (march - may 65)
(b)
degrees
$\phi_{r.m.s}$
out
(a)
o may (broadc. interf)
Sky
barom.
temp
clear stat low → high
clear stat.
clear mov. low → high
clear mov
partly cloudy stat mov
cloudy stat mov rain later
fog
clear mov high
rainy
rain lighter
abs. stat
almost stab (also 2 stat devices with 1 fast jump)
small wiggle (±)
small rise or fall (<3)
bigger rise or fall
fast jumps (>4)
mbar
barometer
+ (fog)

Fig 2

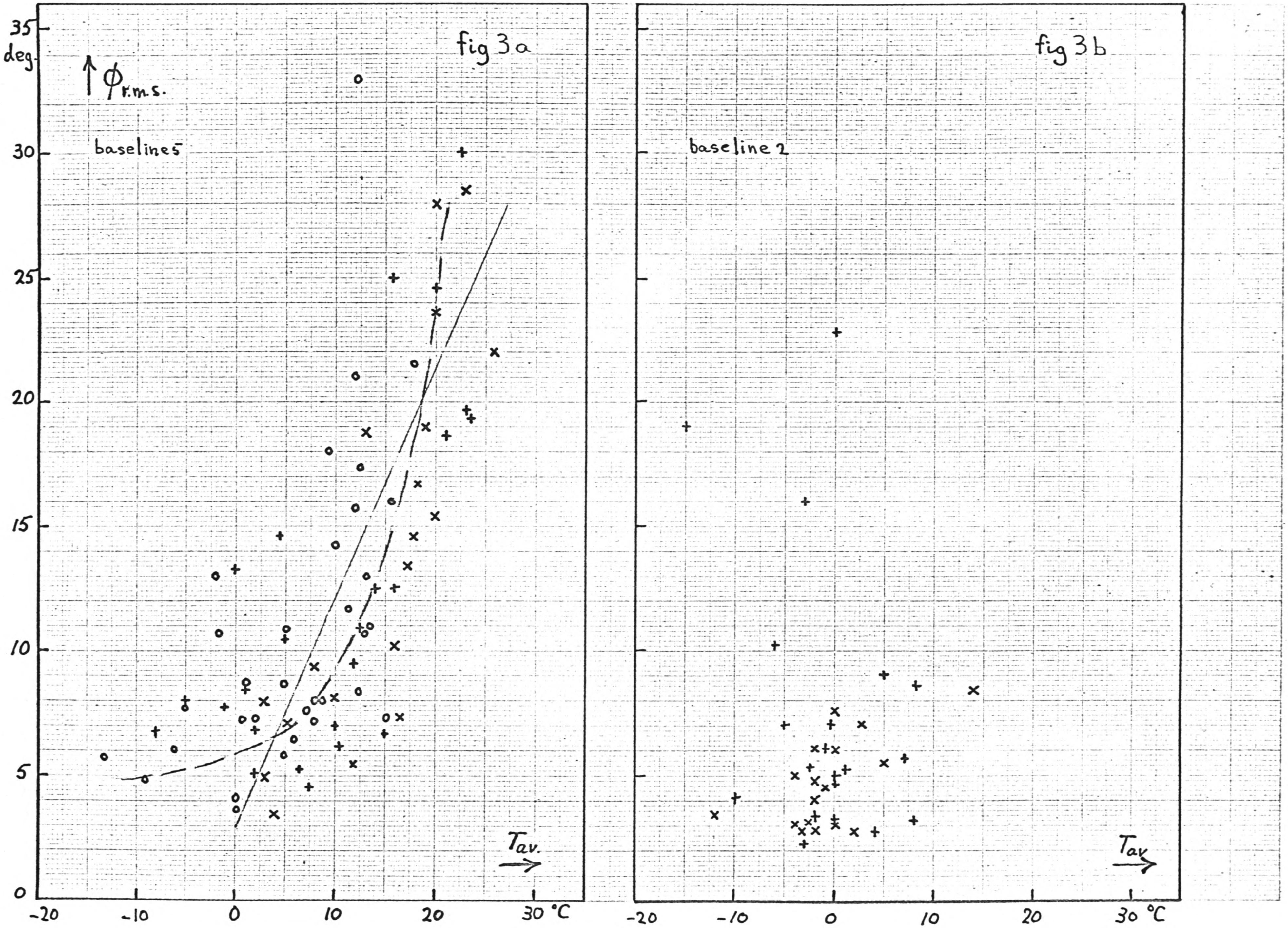


fig 3a
deg.
$\phi_{r.m.s.}$
baselines 5
$T_{av.}$
°C
fig 3b
baseline 2
T_{av}
°C

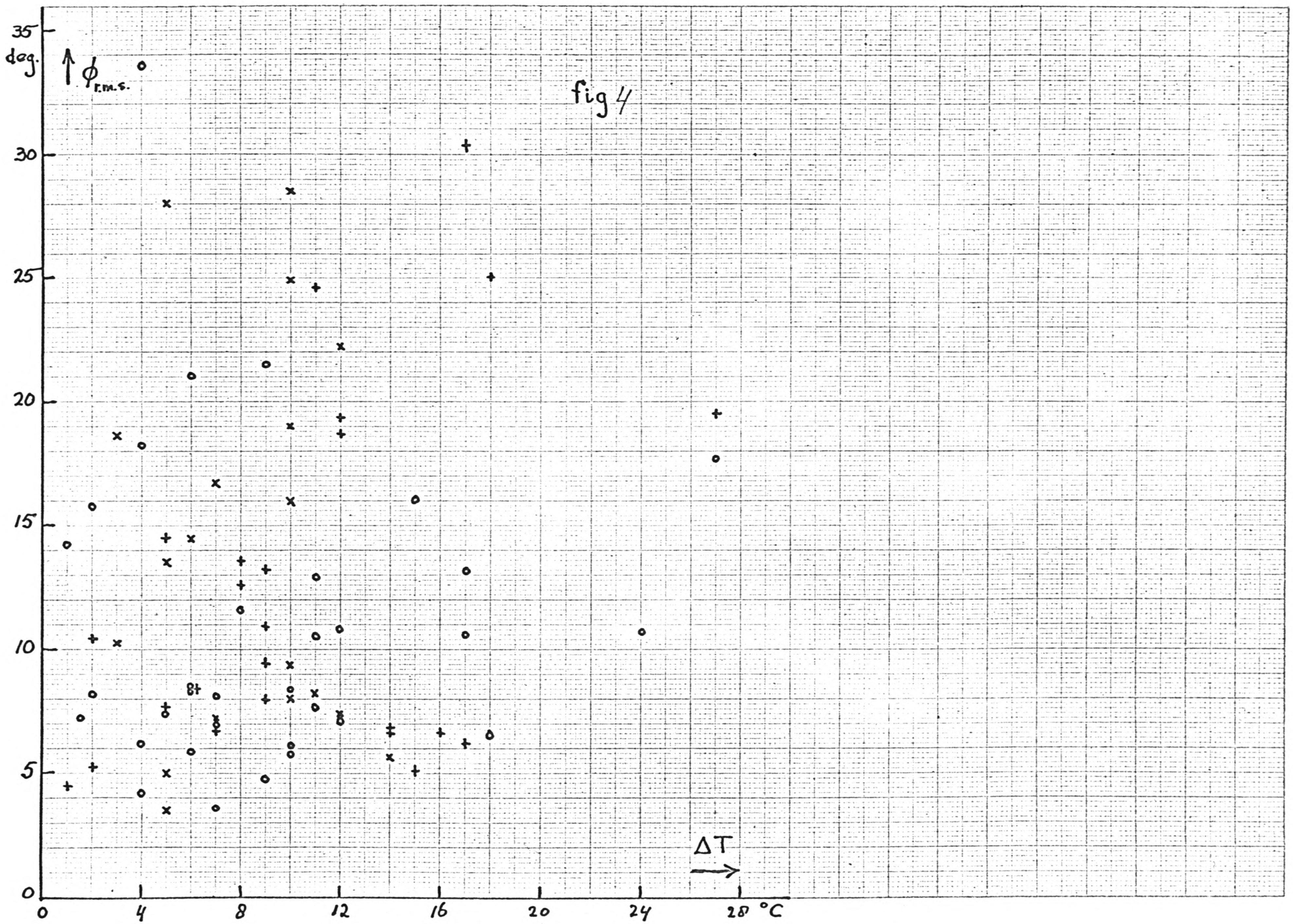


fig 4
35
deg.
$\phi_{r.m.s.}$
30
25
20
15
10
5
0
0
4
8
12
16
20
24
28 °C
ΔT

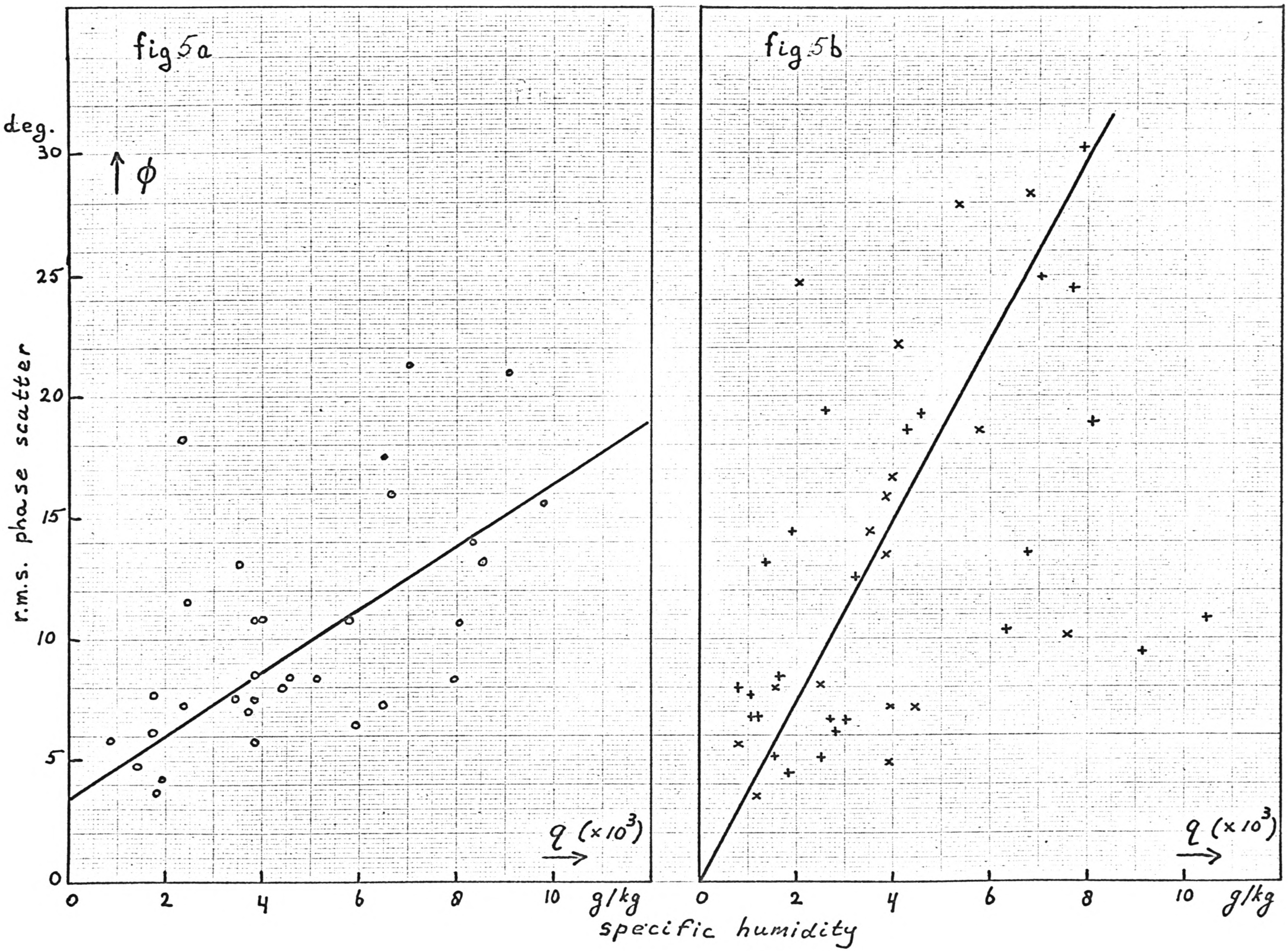


fig 5a
fig 5b
deg.
φ
r.m.s. phase scatter
0
5
10
15
20
25
30
0
2
4
6
8
10
g/kg
q (×10³)
specific humidity

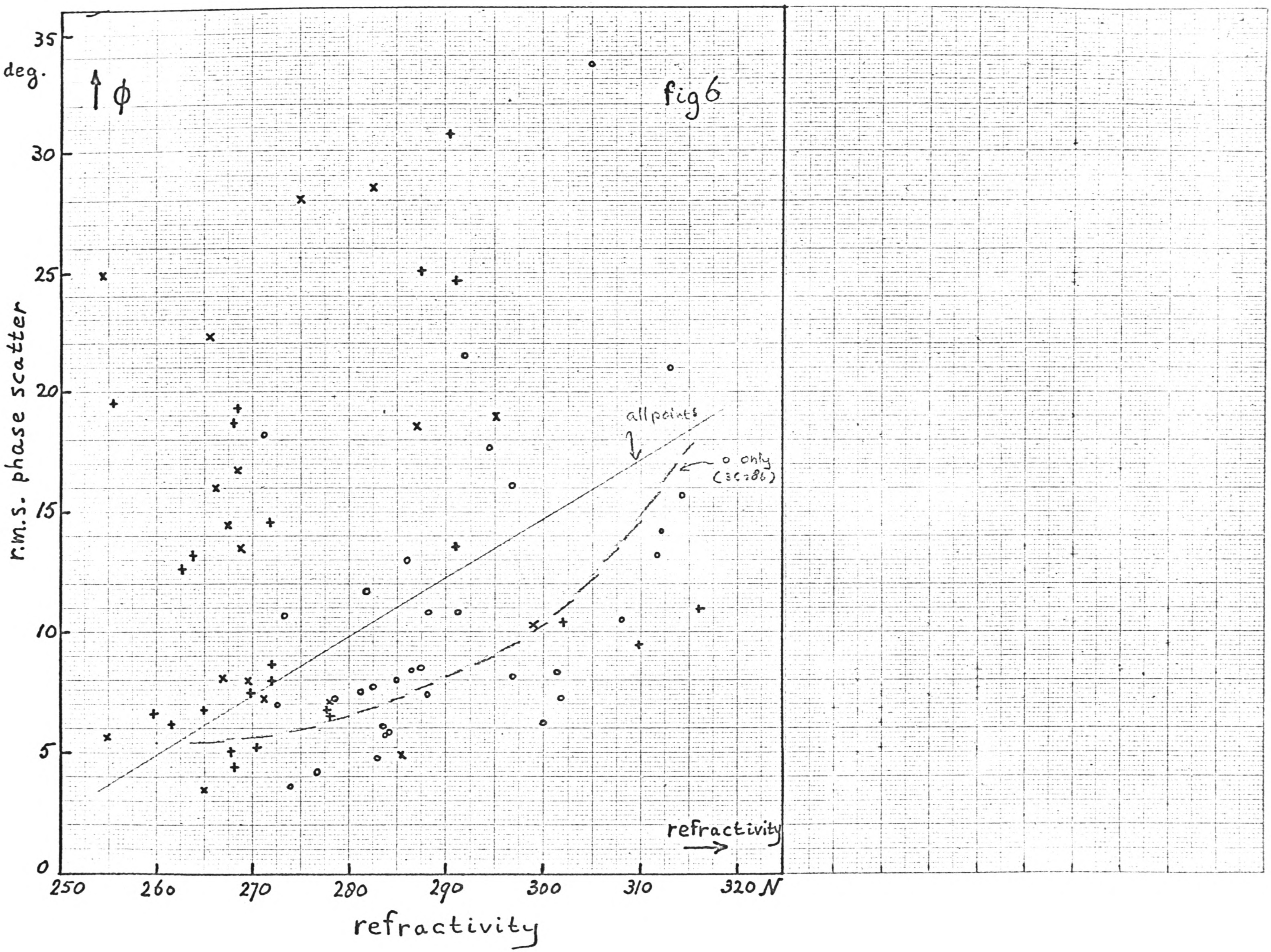
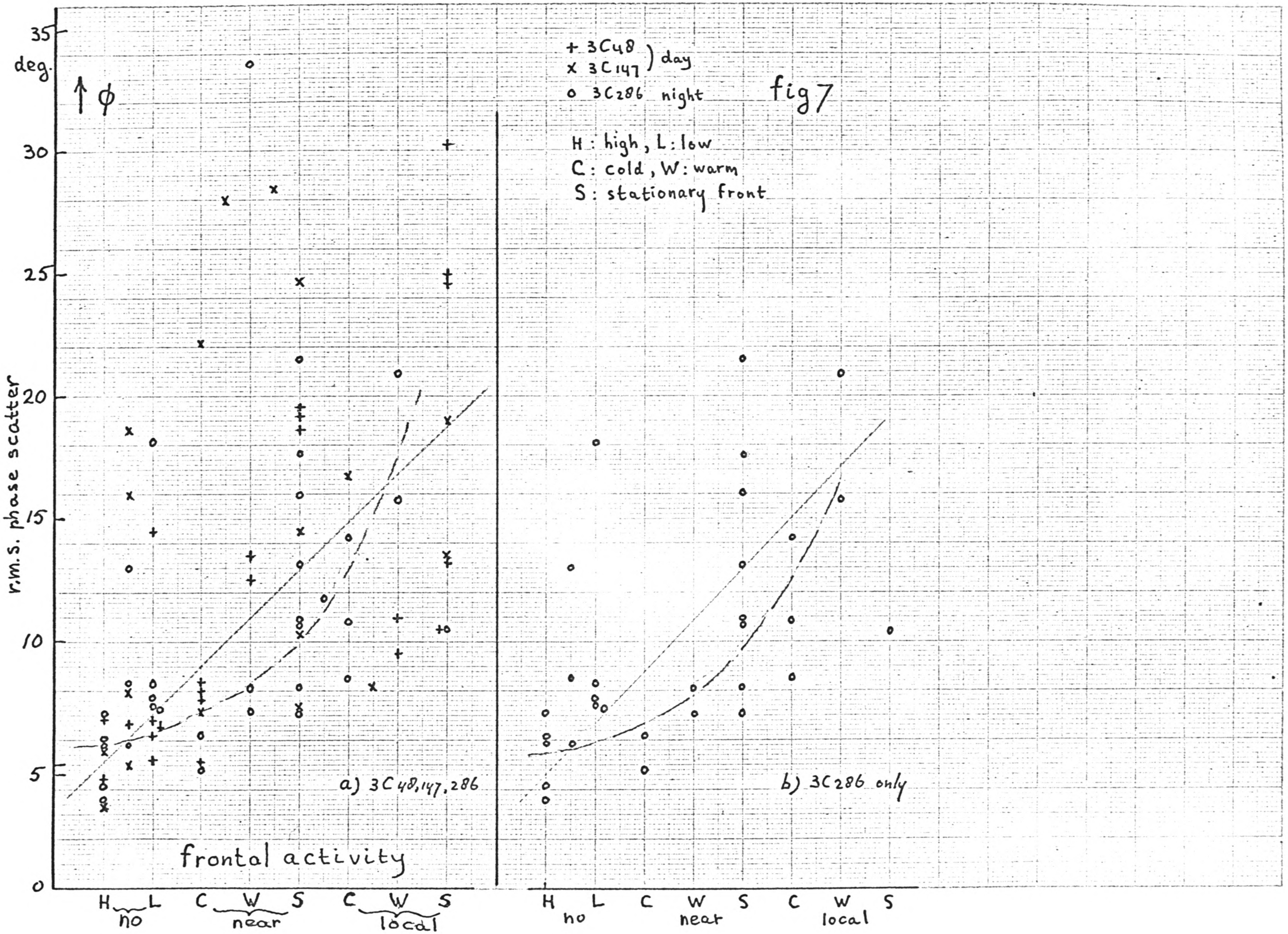


fig 6
deg.
φ
r.m.s. phase scatter
35
30
25
20
15
10
5
0
250
260
270
280
290
300
310
320 N
refractivity
all points
o only
refractivity



+ 3C48) day
x 3C147
o 3C286 night
fig 7
H: high, L: low
C: cold, W: warm
S: stationary front
35 deg.
↑ φ
r.m.s. phase scatter
30
25
20
15
10
5
0
a) 3C48,147,286
b) 3C286 only
frontal activity
H L C W S C W S
no near local
H L C W S C W S
no near local