METEOROLOGICAL OFFICE

INVESTIGATIONS DIVISION TECHNICAL NOTE NO. 10

# Optimum averaging time for reports of along and across - runway wind components to aviation (M. J. O. Dutton)

PART I : Winter 1973 - 1974

PART II : Summer 1973

PART III : Summer 1973 + Winter 1973 - 1974.

This note is a combination of three separate reports on the same subject. The 'Introduction', 'Data' and 'Analysis' sections of PARTS I and III are very similar, as is the general format of the sections describing the results, including the tables and figures. PART II presents only the results of the analysis of summer data with tables and figures in the same format as those in PARTS I and III.

PART I — WINTER 1973-1974

## Introduction

In two earlier studies, by Hardy[1] and Dutton[2], samples of turbulent wind conditions at Heathrow during Summer 1973 and Winter 1973-74 were analysed to determine what is the optimum averaging period to use for a wind report supplied to an aircraft pilot shortly before touchdown or take-off, as a forecast of the wind at touchdown or take-off. Both studies looked only at the magnitude of the total vector error in the wind report and illustrated how the optimum averaging period not only varied with the lag between the supply of the report and its use, but was also dependent on the relative importance of errors of different magnitudes. Results of the Winter study, which were similar to those from the Summer study, showed that:-

(a) Differences between the reported mean wind and the actual wind some time later can be most significantly reduced if the time lag between the wind observation and touchdown or take-off is reduced to a minimum.

(b) A 5 to 10-minute averaging period minimises the root-mean-square (r.m.s.) difference for all lags except the shortest (½-minute) when a ½ to 1-minute average is best.

(c) For lags greater than 3 or 4 minutes a 5 to 10-minute average minimises the number of departures exceeding a 10 kt threshold; for shorter lags a 1 to 4-minute average is best. In general the higher the threshold and the shorter the lag the shorter the averaging period necessary to minimise the frequency of departures exceeding that threshold.

(d) A 2-minute averaging period, recommended by the International Civil Aviation Organization[3] (ICAO), reduces the frequency of the very large departures (greater that 15 kt or so), particularly for the shorter lags, although the resultant errors in excess of 10 kt are about 25% more frequent than with a 5 to 10-minute averaging period if the lag is 3-minutes or more.

In the study of Winter turbulent cases the question was posed as to whether the results for orthogonal components of the vector error, across and along the runway direction for example, would be different; some evidence was presented tentatively suggesting that the optimum averaging period for reducing the frequency of error components in excess of 10 knots may be significantly shorter for the across-runway component than for the along-runway component. An aircraft's airspeed, which determines its lift, is normally only negligibly affected by variations in the lateral (across-runway) wind component, changes in the longitudinal (along-runway) component being much more important from this point of view during landing and take-off phases. This report presents the results of a re-analysis of the Winter 1973-74 wind data, considering separately these longitudinal and lateral components of the vector error.

## The data.

The basic data comprised series of 30-second wind averages recorded by the Digital Anemograph Logging Equipment (DALE) operating in conjunction with a Meteorological Office Mk 5 wind system[4] at Heathrow from 20 December 1973 to 25 March 1974. (Total of 1775 hours with a few gaps in the record). In the subsequent selection of turbulent periods the prime objective was to include all occasions when vector differences between 30-second winds up to 20 minutes apart exceeded 10 knots in magnitude; the final turbulent sample comprised 47 periods totalling 287 hours.
Detailed information on runway useage during the selected periods was obviously necessary since wind components along and across the direction of the runway in use were required for this analysis; this information was obtained from Air Traffic Control arrival/departure records held by the Civil Aviation Authority.

## The Analysis

The object of the investigation was to compare, on a large number of occasions, the wind which might be supplied to the pilot with the wind which he would actually have encountered some minutes later at touchdown or take-off. The departure or error is defined as the magnitude of the difference between the forecast wind component (along or across-runway) and the actual or encountered component, that affecting the aircraft at or near touchdown or take-off. The forecast or reported wind was taken as the observed wind averaged over a period of time varying from 30 seconds to 10 minutes (simple arithmetic averaging of the East-West and North-South components of the winds was used) and the actual wind was taken as the 30-second wind average some time (lag) later; this lag, which represents the interval between the wind observation and the aircraft touchdown on take-off, was also varied from 30 seconds to 10 minutes.

For all the 47 sample periods totalling 287 hours the errors at every time step, for 20 averaging periods and 20 lags, were evaluated and various statistics of these errors were computed. 916 minutes of data were 'lost' in computing initial means and final lags so that in fact 271 hours and 43 minutes of 30-second wind data were used.

## Results

### (a) Root-mean-square errors

Figure 1 ((a) and (b)) shows the variation of rms error as a function of averaging period for various lags from 30 seconds to 10 minutes. Although the variation is similar for both components, the optimum averaging time from the point of view of minimising the rms error is consistently slightly shorter for the across-runway component. For lags of 2 minutes or more a 5 to 10-minute average appears to be the optimum for the along-runway component while a 4 to 8-minute average is better for the across-runway component.

### (b) Percentages of errors exceeding various thresholds

Figures 2, 3 and 4 show the variation with averaging period, for various lags, of percentages of errors (out of a total of 40,802) exceeding 6 kt, 10 kt and 14 kt respectively.

(i) 6 kt threshold (figure 2)

There appears to be no consistent difference between the two components except that there are generally more across-runway errors exceeding this threshold especially for the larger lags.

(ii) 10 kt threshold (figure 3)

For lags of 1 minute or more a shorter optimum averaging period is indicated in the case of the across-runway component; at the shortest lag of ½-minute a 1 to 2-minute average is best for both components.

(iii) 14 kt threshold (figure 4)

Here a short averaging period is favoured for most lags in the case of the across-runway component and errors exceeding this threshold are a lot more frequent for this component than for the along runway component (up to ten times more frequent for a 10-minute lag). For lags of 2 minutes or more a 4 to 10-minute average minimises the frequency of these large errors for the along-runway component while for shorter lags the numbers of cases are too small to reveal any significant trend.

(iv) Higher thresholds

The numbers of along-runway errors exceeding higher thresholds are too small for any significant conclusions to be drawn. The results for the across-runway component at higher thresholds show that the higher the threshold the shorter the averaging period necessary to minimise the number of errors exceeding that threshold.

Table 1 lists percentage frequencies of component errors exceeding thresholds of 6, 10, 14 and 20 kt for lags and averaging periods of 2, 5 and 10 minutes. Tables 2a and 2b contain estimates of the true overall percentage frequencies of errors in excess of 10 kt and 14 kt for a lag of 5 minutes. The figures in brackets are the reciprocals of the true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 10 kt or more and 14 kt or more is encountered; the figures for "magnitude of total vector" are taken from the original[2] analysis. Table 2a reveals that errors in the along-runway component of 10 kt or more occur with only about a quarter of the frequency of total vector errors of the same magnitude; the equivalent relative frequency for errors of 14 kt or more (table 2b) is about 1/15th.

Basic theoretical considerations (steady-state conditions)

Define the error or departure, $\Delta u_{\Delta t,\tau}$, in forecast (reported) wind component for lag $\Delta t$ and averaging period $\tau$ as:-

$$\Delta u_{\Delta t,\tau} = u_{30}(t+\Delta t) - u_{\tau}(t) \qquad (1)$$

where $u_{\tau}(t)$ is the wind component averaged over time $\tau$ seconds at time t (i.e. up to and including time t).

Restrict $\Delta t$ and $\tau$ to $30 \leqslant \Delta t \leqslant 600$ sec
and $30 \leqslant \tau \leqslant 600$ sec

Define $$S^2_{\Delta t,\tau} = \frac{1}{N}\sum\left(\Delta u_{\Delta t,\tau}\right)^2 \qquad (2)$$

and $$\sigma^2_{\tau} = \frac{1}{N}\sum\left(u_{\tau} - \bar{u}\right)^2 \qquad (3)$$

(i.e. mean square error and variance of wind component respectively).
We now assume steady-state conditions so that

$$\frac{\partial}{\partial t}(\sigma_{\tau}) = 0$$

and that the N $u_{\tau}$'s are normally distributed about the mean value
(i.e. that the wind component fluctuations are random)
We can then write

$$S^2_{\Delta t,\tau} = \sigma^2_{30} + \sigma^2_{\tau} - 2\rho_{\Delta t,\tau}\sigma_{30}\sigma_{\tau} \qquad (4)$$

Where $\rho_{\Delta t,\tau}$ is the correlation between $u_{\tau}(t)$ and $u_{30}(t+\Delta t)$, a function of $\Delta t$ and $\tau$. $S^2_{\Delta t,\tau}$, the mean square error, is therefore made up of three terms.

(i) $\sigma^2_{30}$ - independent of $\Delta t$ and $\tau$
(ii) $\sigma^2_{\tau}$ - independent of $\Delta t$
(iii) $-2\rho_{\Delta t,\tau}\sigma_{30}\sigma_{\tau}$ - dependent on both $\Delta t$ and $\tau$

Characteristics of $S^2_{\Delta t,\tau}$ for (typical) steady-state conditions

Values for $S^2_{\Delta t,\tau}$ have been obtained for a single 18-hour period during which conditions approximated to steady-state. (in this particular context $\Delta u_{\Delta t,\tau}$ is the error in total wind speed, not the component error as initially defined above). The following characteristics of $S^2_{\Delta t,\tau}$ were evident (see figure 5)

(i) For all $\tau$. $S^2_{\Delta t,\tau}$ increases as $\Delta t$ increases, with maximum overall variation ( $\Delta t$ = 30s to $\Delta t$ = 600s) at $\tau$ = 30s and minimum variation at $\tau$ = 600s.

(ii) (a) For $\Delta t$ = 30s. $S^2_{\Delta t,\tau}$ remains approximately constant or increases slightly as $\tau$ increases

(b) For $\Delta t > 30$s. $S^2_{\Delta t,\tau}$ decreases with increasing $\tau$ up to $\tau \approx$ 360s, then remains approximately constant or increases slightly as $\tau$ increases further.

(figure 5 shows the results for the particular 18-hour period taken from the winter sample).

Figure 6 shows the variation, with $\Delta t$ and $\tau$, of $\rho_{\Delta t,\tau}$ and $\sigma_\tau$ for the same 18-hour period, and shows that $\rho_{\Delta t,\tau}$ has the following characteristics

(i) For all $\tau$. $\rho_{\Delta t,\tau}$ decreases as $\Delta t$ increases. In equation (4) the last term on the RHS, $2\rho\sigma_{30}\sigma_\tau$ is the only lag-dependent term and therefore determines the variation of $S_{\Delta t,\tau}$ with $\Delta t$ for a given $\tau$.

(ii) (a) For $\Delta t$ = 30s. $\rho_{\Delta t,\tau}$ decreases as $\tau$ increases. The term $2\rho\sigma_{30}\sigma_\tau$ in equation (4) obviously decreases with increasing $\tau$ at about the same rate as or slightly more rapidly than $\sigma^2_\tau$, since $S^2_{\Delta t,\tau}$ remains approximately constant or increases slightly as $\tau$ increases.

(b) For $\Delta t > 30$s. $\rho_{\Delta t,t}$ increases with increasing $\tau$ up to a maximum at $\tau \approx$ 180s, then decreases as $\tau$ increases further.

Although the above argument applies to stationary conditions it can be seen that the variation of rms error with lag and averaging period for the 18-hr period examined (figure 5) is similar to that evident for the entire winter sample (figure 1, and figure 1 of reference 2). This is almost certainly because the latter, as already pointed out, was dominated by periods of roughly steady-state conditions. We can therefore say with reasonable confidence that the general characteristics of $\rho_{\Delta t,\tau}$ for the winter sample as a whole are also similar to those derived for the steady-state 18-hr sample.

## REFERENCES

1. HARDY, R. N. A note on the optimum averaging time of wind reports for aviation. Met Mag, London, 103, 1974 pp99-105

2. DUTTON, M.J.O., Optimum averaging time of wind reports for aviation (to be published in Met Mag).

3. Montreal, International Civil Aviation Organization, Report of the 8th Air Navigation Conference, Montreal. DOC 9101 AN-CONF/8, Montreal 1974

4. ELSE, C.V. The Meteorological Office Mk 5 wind system Met Mag, London, 103, 1974, pp 130-139.

TABLE 1 PERCENTAGE FREQUENCIES OF ERRORS EXCEEDING VARIOUS THRESHOLDS

(Winter)

| Averaging Period (Minutes) | Lag (Minutes) | ALONG-RUNWAY COMPONENT Threshold (kt) 6 | 10 | 14 | 20 | ACROSS-RUNWAY COMPONENT Threshold (kt) 6 | 10 | 14 | 20 |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 2 | 2.18 | 0.101 | 0.015 | 0.0 | 2.57 | 0.169 | 0.040 | 0.006 |
| | 5 | 2.71 | 0.190 | 0.015 | 0.003 | 3.32 | 0.374 | 0.101 | 0.040 |
| | 10 | 3.91 | 0.316 | 0.034 | 0.003 | 4.69 | 0.613 | 0.196 | 0.068 |
| 5 | 2 | 1.66 | 0.080 | 0.012 | 0.0 | 1.98 | 0.209 | 0.052 | 0.019 |
| | 5 | 2.19 | 0.150 | 0.012 | 0.0 | 2.70 | 0.334 | 0.104 | 0.052 |
| | 10 | 3.39 | 0.291 | 0.025 | 0.003 | 3.82 | 0.515 | 0.181 | 0.074 |
| 10 | 2 | 1.64 | 0.098 | 0.012 | 0.003 | 2.05 | 0.255 | 0.074 | 0.025 |
| | 5 | 2.21 | 0.156 | 0.015 | 0.003 | 2.63 | 0.337 | 0.141 | 0.049 |
| | 10 | 3.19 | 0.255 | 0.022 | 0.0 | 3.80 | 0.534 | 0.199 | 0.083 |

(1 case = 0.0031%)

TABLE 2a ESTIMATED TRUE PERCENTAGE FREQUENCIES OF ERRORS ≥ 10 kt FOR A LAG OF 5 MINUTES

(Winter)

Figures in brackets are reciprocals of true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 10 kt or more is encountered.

| | Averaging period (minutes) | | |
|---|---|---|---|
| | 2 | 5 | 10 |
| Along-runway Component | 0.0291 (3400) | 0.0230 (4400) | 0.0239 (4200) |
| Across-runway Component | 0.0572 (1800) | 0.0511 (2000) | 0.0516 (1900) |
| Magnitude of Total Vector | 0.1230 (800) | 0.1070 (900) | 0.1025 (1000) |

TABLE 2b ESTIMATED TRUE PERCENTAGE FREQUENCIES OF ERRORS ≥ 14 kt FOR LAG OF 5 MINUTES

(Winter)

Figures in brackets are reciprocals of true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landing in which one error of 14 kt or more is encountered.

| | Averaging period (minutes) | | |
|---|---|---|---|
| | 2 | 5 | 10 |
| Along-runway Component | 0.0023 (43500) | 0.0018 (55600) | 0.0023 (43500) |
| Across-runway Component | 0.0155 (6500) | 0.0159 (6300) | 0.0216 (4600) |
| Magnitude of Total Vector | 0.0300 (3300) | 0.0295 (3400) | 0.0337 (3000) |

FIGURE 1

Heathrow (Winter 1973-74)

Variation of r.m.s. errors with lag and averaging period

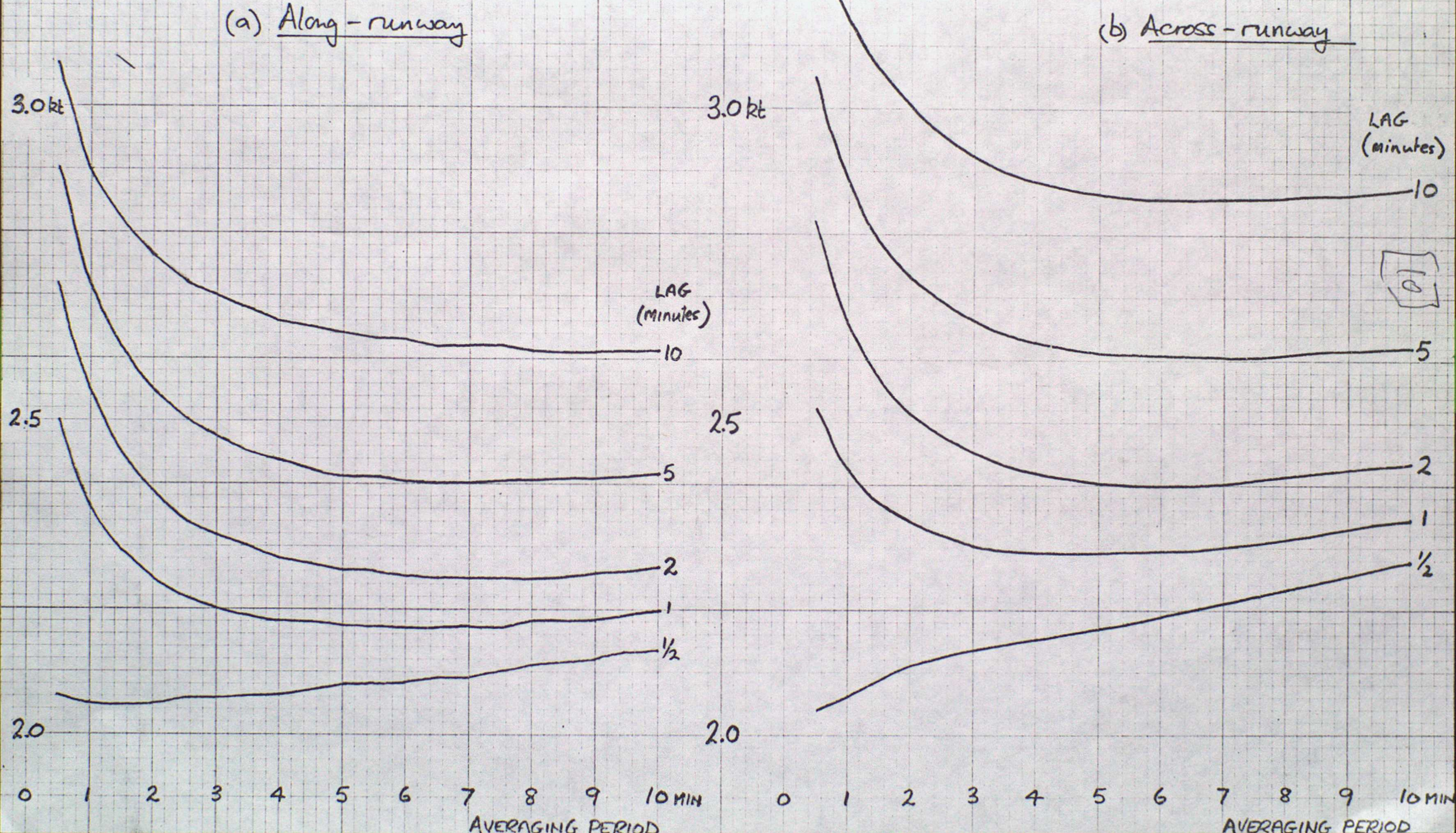
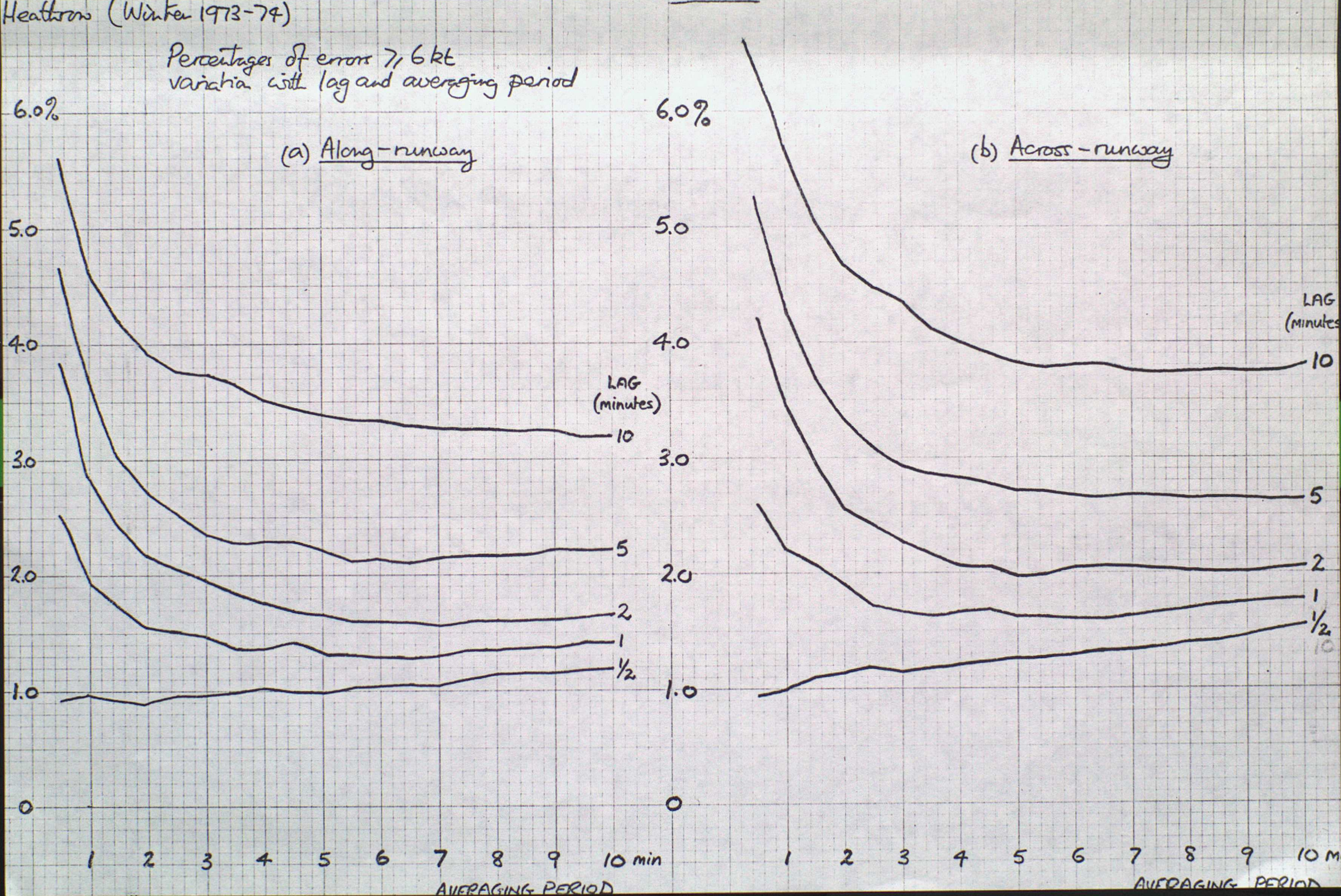


FIGURE 2



Heathrow (Winter 1973-74)
Percentages of errors ≥ 6 kt
variation with lag and averaging period
(a) Along-runway
6.0%
5.0
4.0
3.0
2.0
1.0
0
LAG (minutes)
10
5
2
1
½
1 2 3 4 5 6 7 8 9 10 min
AVERAGING PERIOD
(b) Across-runway
6.0%
5.0
4.0
3.0
2.0
1.0
0
LAG (minutes)
10
5
2
1
½
1 2 3 4 5 6 7 8 9 10 m
AVERAGING PERIOD

FIGURE 3

Heathrow (Winter 1973-74)

Percentages of errors ≥ 10 kt variation with lag and averaging period

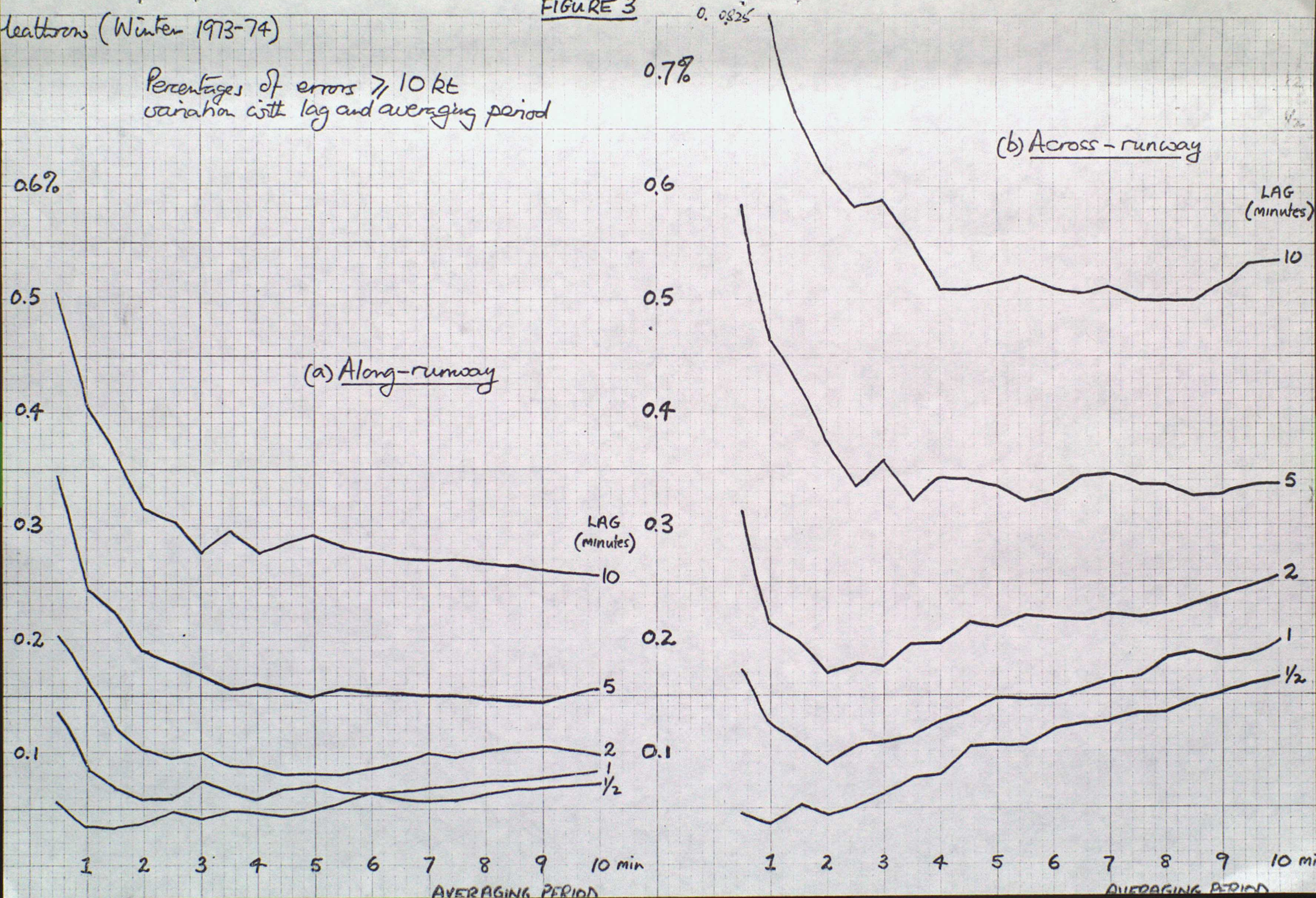
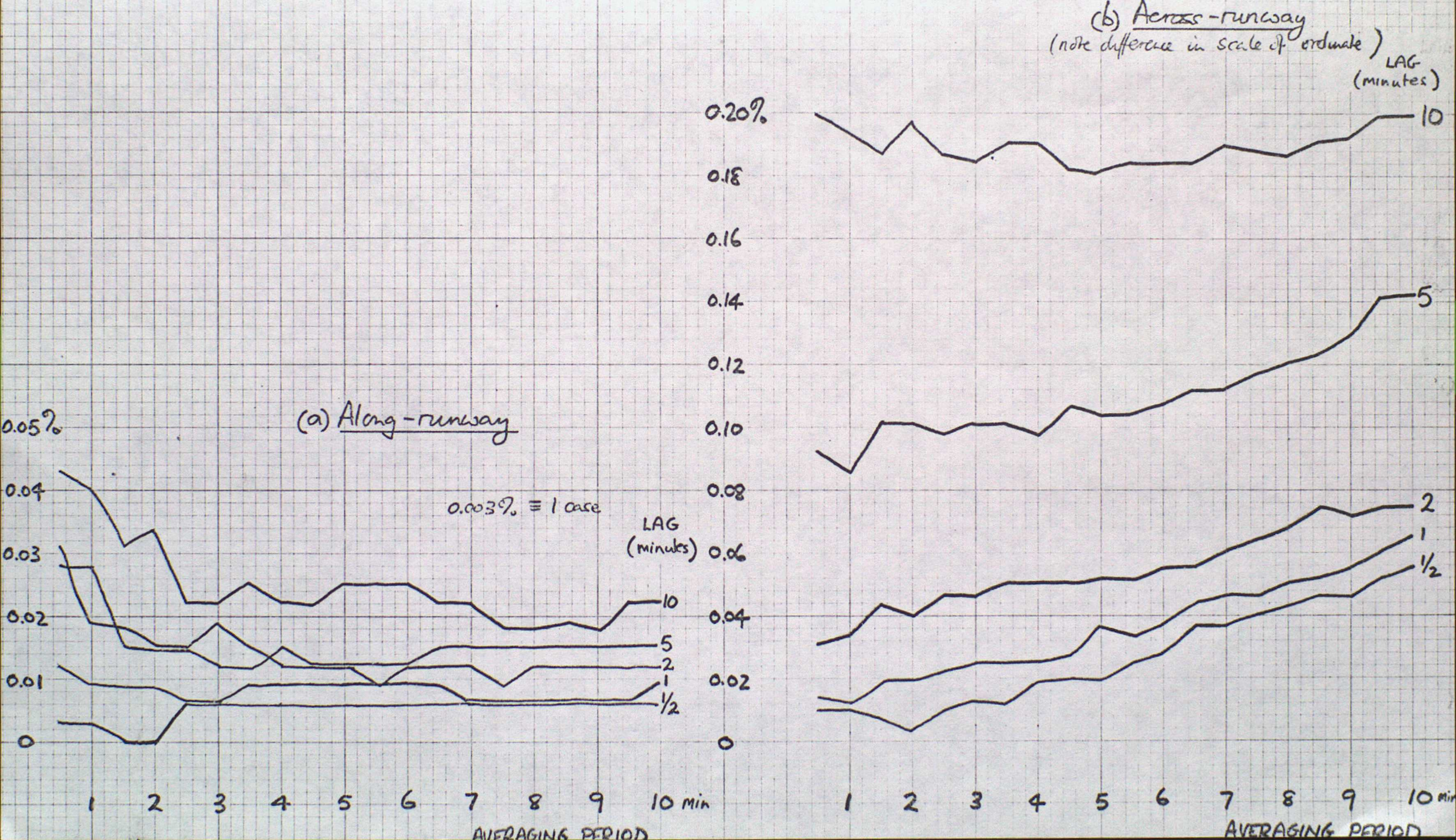


FIGURE 4

Heathrow (Winter 1973-74)

Percentages of errors ≥ 14 kt
variation with lag and averaging period



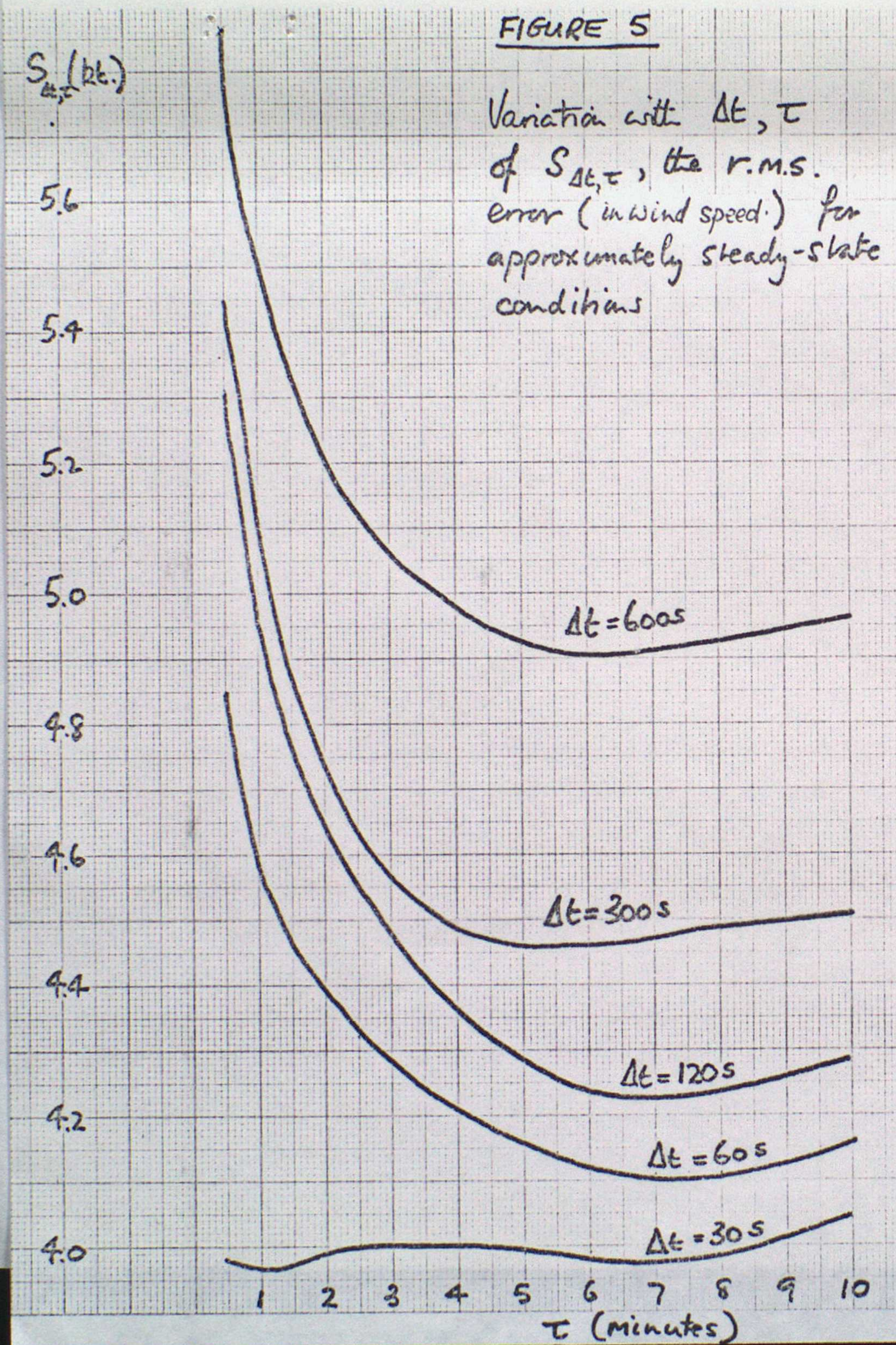


FIGURE 5
Variation with Δt, τ of $S_{\Delta t,\tau}$, the r.m.s. error (in wind speed) for approximately steady-state conditions
$S_{\Delta t,\tau}$ (kt.)
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
Δt = 600s
Δt = 300s
Δt = 120s
Δt = 60s
Δt = 30s
1 2 3 4 5 6 7 8 9 10
τ (minutes)

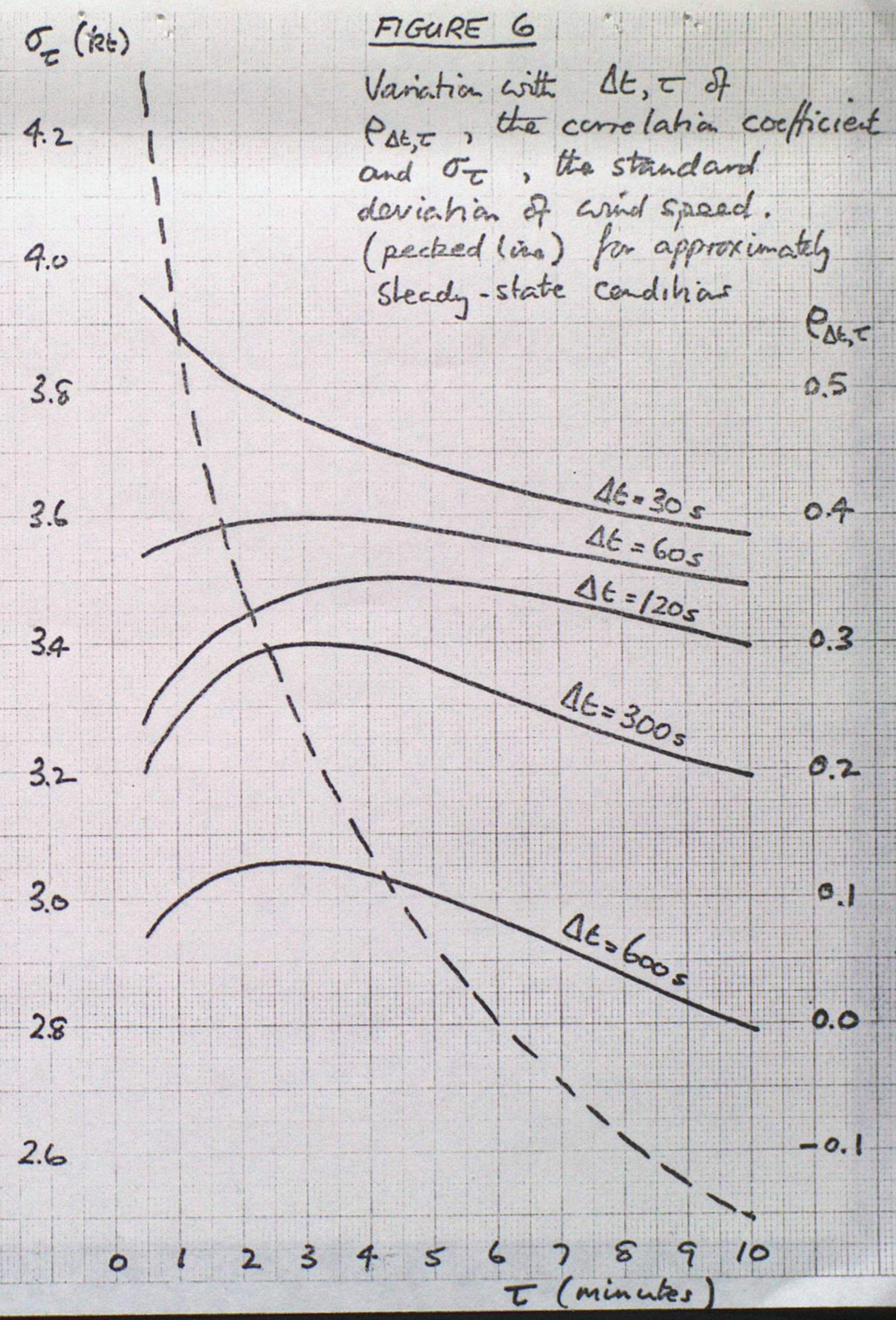



FIGURE 6
Variation with Δt, τ of $\rho_{\Delta t,\tau}$, the correlation coefficient, and $\sigma_\tau$, the standard deviation of wind speed (pecked line) for approximately steady-state conditions
$\sigma_\tau$ (kt)
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
$\rho_{\Delta t,\tau}$
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
Δt = 30s
Δt = 60s
Δt = 120s
Δt = 300s
Δt = 600s
0 1 2 3 4 5 6 7 8 9 10
τ (minutes)

PART II

SUMMER 1973

In this part only the results of the analysis of data gathered during Summer 1973 are presented, in the form of tables and figures with the same format as those in PART I.

A description of the summer data can be found in Hardy's 1974 Meteorological Magazine paper (referred to in PART I); a brief description of the data is also included in the 'Data' section of PART III.

TABLE 1 PERCENTAGE FREQUENCIES OF ERRORS EXCEEDING VARIOUS THRESHOLDS

(Summer)

| Averaging Period (minutes) | Lag (Minutes) | ALONG-RUNWAY COMPONENT Threshold (kt) 6 | 10 | 14 | 20 | ACROSS-RUNWAY COMPONENT Threshold (kt) 6 | 10 | 14 | 20 |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 2 | 2.50 | 0.232 | 0.049 | 0.0 | 2.88 | 0.244 | 0.049 | 0.012 |
| | 5 | 3.73 | 0.439 | 0.195 | 0.012 | 5.33 | 0.842 | 0.171 | 0.0 |
| | 10 | 5.30 | 0.952 | 0.452 | 0.073 | 7.33 | 1.599 | 0.439 | 0.098 |
| 5 | 2 | 1.93 | 0.317 | 0.085 | 0.0 | 2.90 | 0.427 | 0.085 | 0.012 |
| | 5 | 3.06 | 0.561 | 0.244 | 0.024 | 4.58 | 0.866 | 0.208 | 0.012 |
| | 10 | 4.38 | 0.952 | 0.476 | 0.110 | 6.82 | 1.660 | 0.537 | 0.110 |
| 10 | 2 | 2.25 | 0.452 | 0.208 | 0.012 | 3.32 | 0.598 | 0.195 | 0.0 |
| | 5 | 3.01 | 0.610 | 0.330 | 0.061 | 4.87 | 1.159 | 0.281 | 0.049 |
| | 10 | 4.09 | 0.915 | 0.513 | 0.134 | 6.67 | 1.794 | 0.549 | 0.159 |

(1 case = 0.0122%)

TABLE 2a

## ESTIMATED TRUE PERCENTAGE FREQUENCIES OF ERRORS ≥ 10 kt FOR A LAG OF 5 MINUTES

(Summer)

Figures in brackets are reciprocals of true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 10 kt or more is encountered.

| | Averaging period (minutes) | | |
|---|---|---|---|
| | 2 | 5 | 10 |
| Along-runway | 0.0439 | 0.0561 | 0.0610 |
| component | (2300) | (1800) | (1600) |
| Across-runway | 0.0842 | 0.0866 | 0.1159 |
| component | (1200) | (1200) | (900) |
| Magnitude of | 0.1680 | 0.1765 | 0.2090 |
| Total Vector | (600) | (600) | (500) |

TABLE 2b

## ESTIMATED TRUE PERCENTAGE FREQUENCIES OF ERRORS ≥ 14 kt FOR A LAG OF 5 MINUTES

(Summer)

Figures in brackets are reciprocals of true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 14 kt or more is encountered.

| | Averaging period (minutes) | | |
|---|---|---|---|
| | 2 | 5 | 10 |
| Along-runway | 0.0195 | 0.0244 | 0.0330 |
| Component | (5100) | (4100) | (3000) |
| Across-runway | 0.0171 | 0.0208 | 0.0281 |
| Component | (5800) | (4800) | (3600) |
| Magnitude of | 0.0450 | 0.0575 | 0.0760 |
| Total Vector | (2200) | (1700) | (1300) |

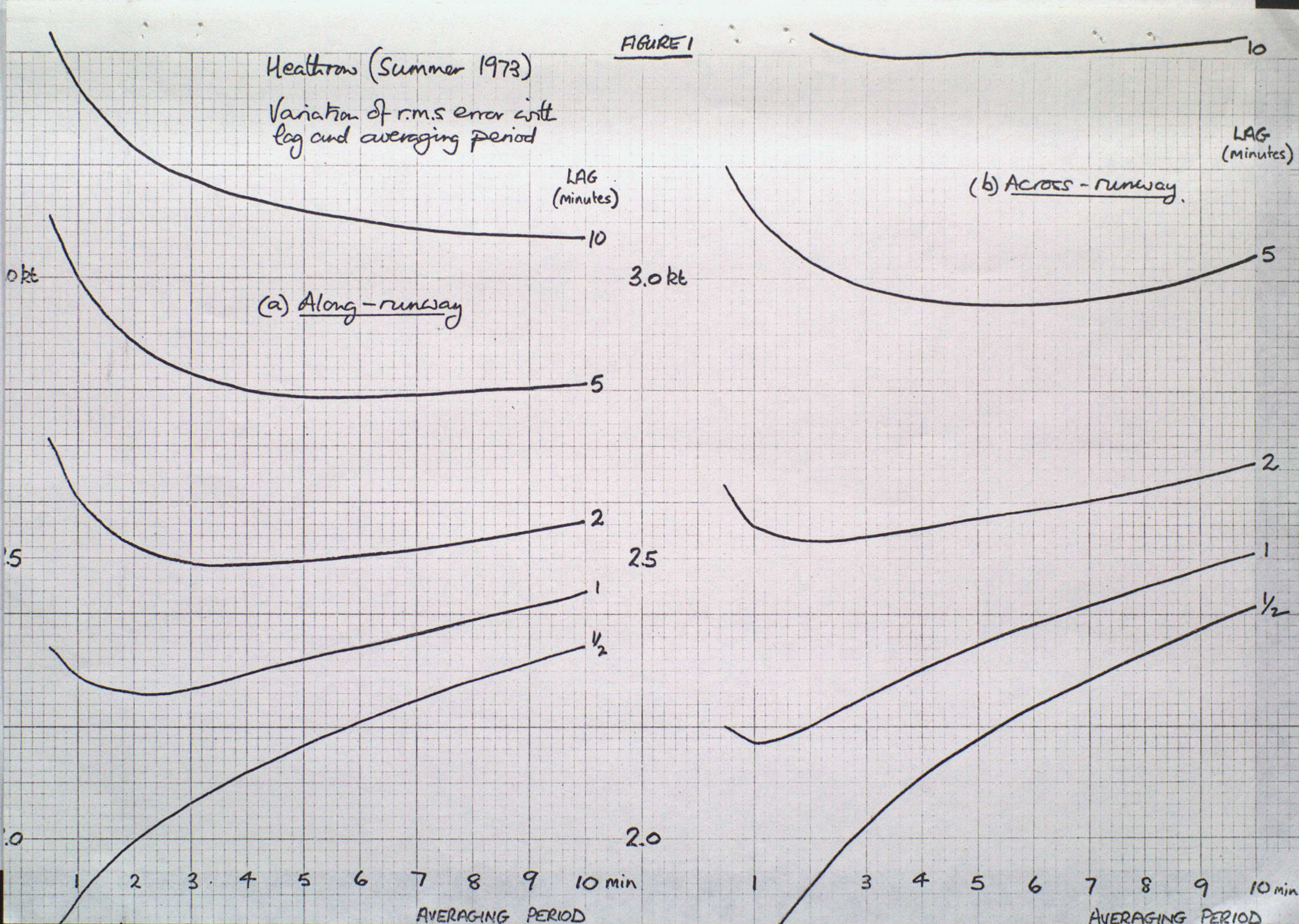
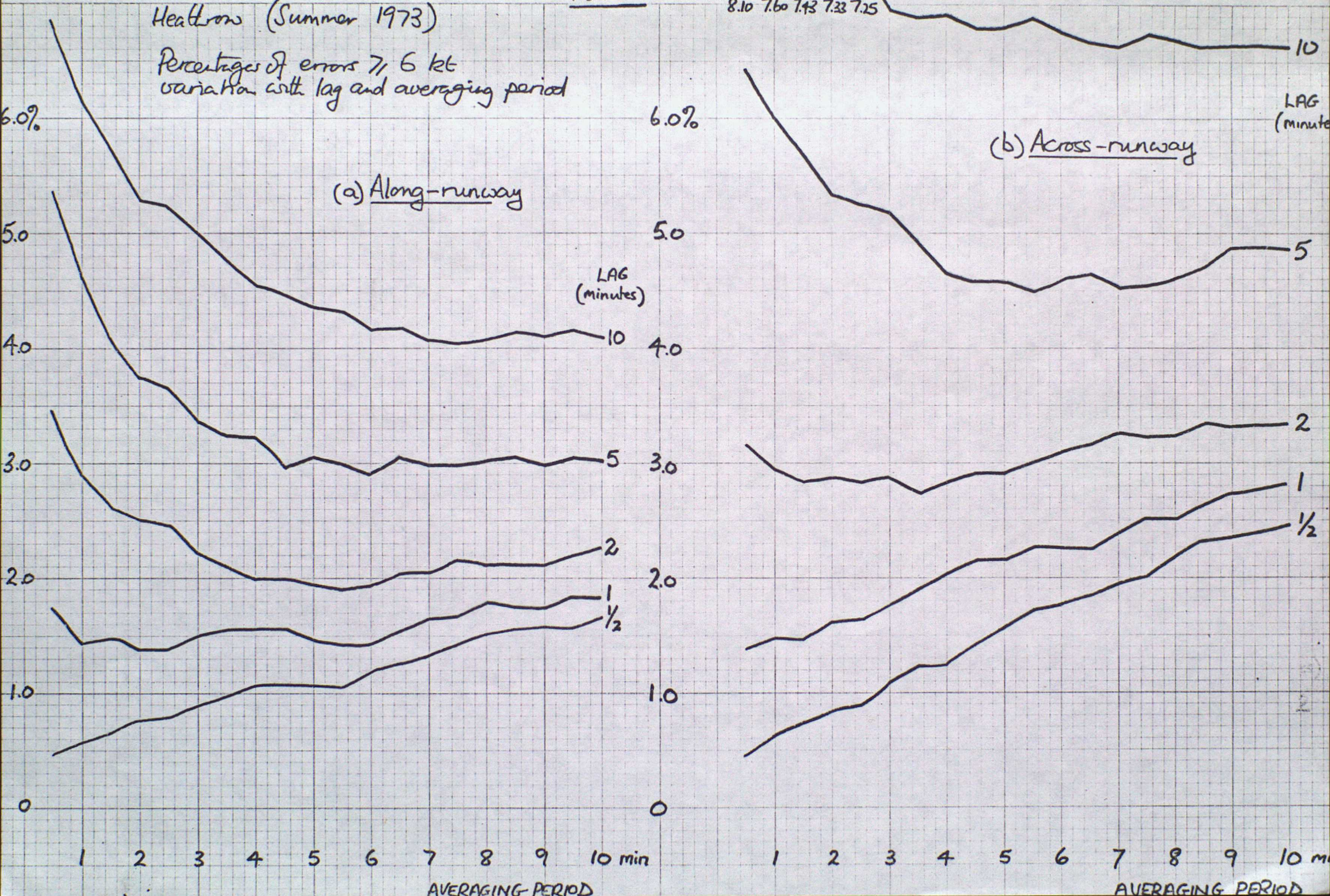


FIGURE 1
Heathrow (Summer 1973)
Variation of r.m.s error with lag and averaging period
(a) Along-runway
(b) Across-runway
LAG (minutes)
10
5
2
1
½
3.0 kt
2.5
2.0
1 2 3 4 5 6 7 8 9 10 min
AVERAGING PERIOD

FIGURE 2



Heathrow (Summer 1973)
Percentages of errors ≥ 6 kt
variation with lag and averaging period
(a) Along-runway
(b) Across-runway
LAG (minutes)
LAG (minute
6.0%
5.0
4.0
3.0
2.0
1.0
0
10
5
2
1
½
8.10 7.60 7.43 7.33 7.25
1 2 3 4 5 6 7 8 9 10 min
AVERAGING PERIOD

FIGURE 3

Heathrow (Summer 1973)

Percentage of errors ≥ 10 kt
variation with lag and averaging period

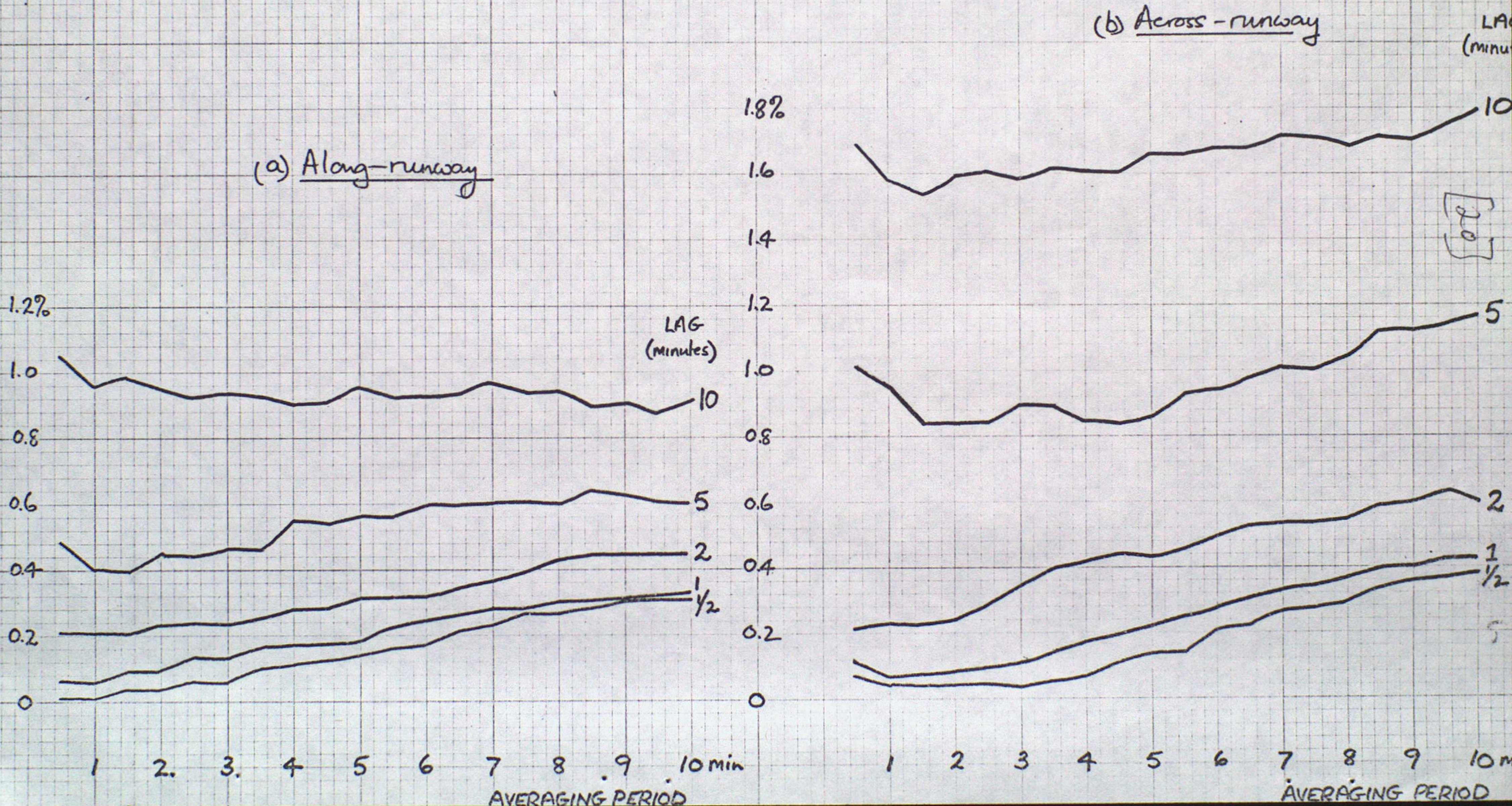
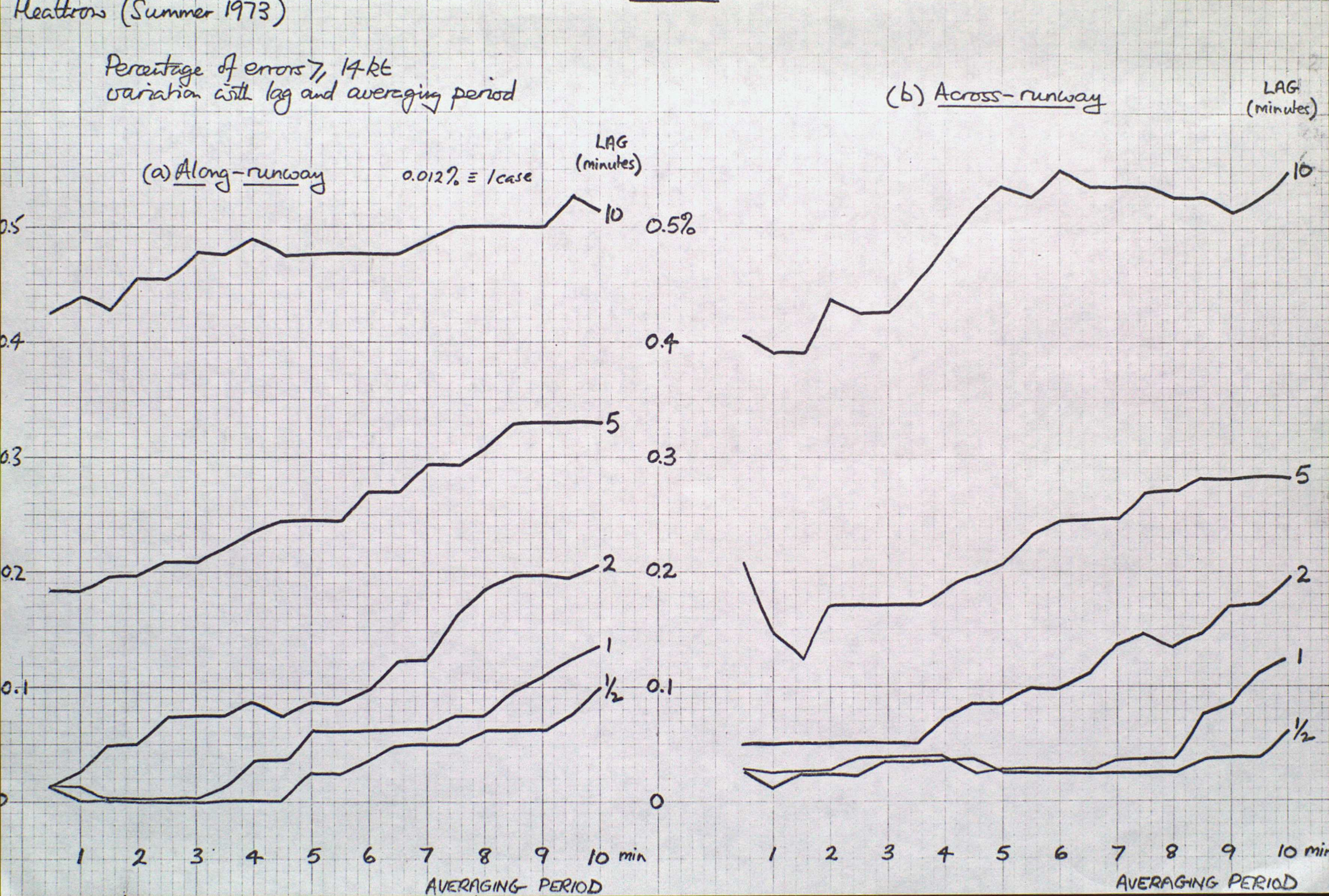


FIGURE 4


Heathrow (Summer 1973)
Percentage of errors >, 14kt
variation with lag and averaging period
(a) Along-runway
0.012% ≡ 1 case
LAG
(minutes)
10
5
2
1
½
.5
.4
.3
.2
0.1
0
1
2
3
4
5
6
7
8
9
10 min
AVERAGING PERIOD
(b) Across-runway
LAG
(minutes)
10
5
2
1
½
0.5%
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10 min
AVERAGING PERIOD

## PART III SUMMER 1973 AND WINTER 1973-1974

### Introduction

In two earlier studies, by Hardy[1] and Dutton[2], samples of turbulent wind conditions at Heathrow during summer 1973 and winter 1973-74 were analysed to determine what is the optimum averaging period to use for a wind report supplied to an aircraft pilot shortly before touchdown or take-off, for use as a forecast of the wind at touchdown or take-off. Both studies considered only the magnitude of the total vector error in the wind report and illustrated how the optimum averaging period not only varied with the lag between the supply of the report and its use, but was also dependent on the relative importance of errors of different magnitudes. Results showed that the root-mean-square (rms) error could normally be minimised by using an averaging period of 5-10 minutes but to reduce the frequency of errors in excess of a 10 knot or higher threshold a shorter averaging period was better; in general the shorter the lag and the higher the threshold, the shorter the averaging period necessary to minimise the frequency of errors exceeding that threshold. The results suggested that the original (1967) provisional recommendation of the International Civil Aviation Organisation[3] (ICAO) for the use of a 2-minute average, a recommendation which they recently confirmed[4], appeared to be a satisfactory compromise, at least for summer and winter in southern England.

In the study of winter turbulent cases the question was posed as to whether the results for orthogonal components of the vector error, across and along the runway direction for example, would be different; some evidence was presented to suggest tentatively that the optimum averaging period for reducing the frequency of error components in excess of 10 knots may be significantly shorter for the across-runway component. An aircraft's airspeed, which determines its lift, is normally only negligibly affected by variations in the lateral (across-runway) wind component, changes in the longitudinal (along-runway) component being much more important from this point of view during landing and take-off phases. This report presents the results of a re-analysis of the combined summer 1973 and winter 1973-74 wind data, considering separately these longitudinal and lateral components of the vector error.

### The Data

The basic data comprised series of 30-second wind averages recorded by the Meteorological Office Mk5 wind system at Heathrow during the periods 3 May-7 August 1973 and 20 December 1973-25 March 1974. During the former period wind recording only took place when "the mean wind reached 15kt, when cumulonimbus cloud or moderate precipitation was reported or when fronts were forecast in the area". 266 hours of wind data were collected of which 100 hours (42 periods) were punched onto cards after scrutiny for wind changes; the final selection of periods for analysis included the 32 most turbulent periods totalling 78 hours 41 minutes. Over the winter 1775 hours of wind data (about 75% of total time) were recorded by the Digital Anemograph Logging Equipment (DALE) which was operational by that time. Statistics of these recorded wind data proved useful in selecting for analysis a total of 287 hours (47 periods) of wind data. Initially the periods selected included all occasions with 10-minute mean wind speed greater than 15kt, rapid changes of wind speed and/or direction or reports of heavy showers or cumulonimbus clouds (total of 362 hours); in the final selection of turbulent periods for analysis the prime objective was to include all occasions when vector differences between 30-second winds up to 20 minutes apart exceeded 10kt. Detailed information on runway useage during the selected periods was obviously necessary since wind components along and across the direction of the runway in use were required for this analysis; this information was obtained from Air Traffic Control arrival/departure records held by the Civil Aviation Authority.

## Analysis

The object of the investigation was to compare, on a large number of occasions, the wind which might be supplied to the pilot with the wind which he would actually have encountered some minutes later at touchdown or take-off. The departure or error is defined as the magnitude of the difference between the forecast wind component (along or across-runway) and the actual or encountered component, that affecting the aircraft at or near touchdown or take-off. The forecast or reported wind was taken as the observed wind averaged over a period of time varying from 30 seconds to 10 minutes (simple arithmetic averaging of the east-west and north south components of the 30-second winds was used) and the actual wind was taken as the 30-second wind average some time (lag) later; this lag, which represents the interval between the wind observation and the aircraft touch-down or take-off, was also varied from 30 seconds to 10 minutes.

For all the 79 sample periods totalling 366 hours the across-runway and along-runway error components at every time step, for 20 averaging periods and 20 lags, were evaluated and various statistics of these errors were computed. About 26 hours of data were 'lost' in computing initial means and final lags so that in fact about 340 hours of 30-second wind data were used.

## Results and Discussion

(a) Root-mean-square errors

Figure 1 ((a) and (b)) shows the variation of rms erros as a function of averaging period for various lags from 30 seconds to 10 minutes. Although the variation is very similar for both components, the optimum averaging time from the point of view of minimising the rms error is consistently slightly shorter for the across-runway component. For lags of 2 minutes or more a 5 to 10-minute average appears to be the optimum for the along-runway component, while a 4 to 8-minute average is better for the across-runway component.

(b) Percentages of errors exceeding various thresholds

Figures 2, 3 and 4 show the variation with averaging period, for various lags, of percentages of errors (out of a total of 40,802) exceeding 6kt, 10kt and 14kt respectively.

(i) 6kt threshold (figure 2)

There appears to be no consistent difference between the two components except that there are generally more across-runway errors exceeding this threshold especially for the longer lags.

(ii) 10kt threshold (figure 3)

For lags of 2 minutes or more a shorter optimum averaging period is indicated in the case of the across-runway component; at shorter lags a 1 to 2-minute average is best for both components.

(iii) 14kt threshold (figure 4)

Here a short averaging period is favoured for most lags for both components but again there is a tendency for the optimum averaging period to be shorter for the across-runway component. In addition the frequency of errors exceeding this threshold is a more sensitive function of averaging period for the across-runway component. In general the frequencies for the latter component are about double those for the along-runway component.

(iv) Higher thresholds

The results for higher thresholds show that, for both components, the higher the threshold the shorter the averaging period necessary to reduce the number of errors exceeding that threshold. In addition the ratio, for a given lag and averaging period, of the number of across-runway errors to the number of along-runway errors exceeding the threshold increases with increasing threshold value. At a threshold of 20kt this ratio is about 3 or 4, and across-runway errors exceeding at 24kt threshold appear to be about an order of magnitude more frequent than along-runway errors of the same magnitude.

Table 1 lists percentage frequencies of errors exceeding thresholds of 6, 10, 14 and 20kt for lags and averaging periods of 2, 5 and 10 minutes. Tables 2a and 2b contain estimates for summer, winter and combined summer/winter, of the true overall frequencies of errors in excess of 10kt and 14kt for a lag of 5 minutes. The figures in brackets are the reciprocals of the true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 10kt or more and 14kt or more is encountered. The figures for "magnitude of total vector" are taken from the original[1,2] analyses.

As far as the variations of optimum averaging period with lag and error threshold are concerned the results for the summer and winter samples are essentially similar and from this point of view the results for the combined sample described above should therefore be broadly representative of both summer and winter conditions at Heathrow. There are however some interesting differences between winter and summer results which should be mentioned here and which are particularly evident in the estimated true frequencies of large along-runway and across-runway errors listed in tables 2a and 2b. On the evidence of these summer and winter samples errors $\geqslant$ 14kt in the along-runway component are an order of magnitude more frequent in summer than in winter; across-runway errors $\geqslant$ 14kt are in contrast only marginally more frequent in summer. It is also interesting that while in winter across-runway errors $\geqslant$ 14kt are much more probable than along-runway errors $\geqslant$ 14kt, in summer along and across-runway errors exceeding this threshold are almost equally probable. Furthermore the winter results show that the higher the threshold the smaller the ratio of along-runway to across-runway errors exceeding that threshold (ratio $\approx$ 1/8 at the 14kt threshold) while for the summer sample the reverse is true, the ratio increasing with increasing threshold ($\approx$ 1 at the 14kt threshold).

The differences between the summer and winter turbulent samples themselves, including the criteria used in their selection, have been described here and in a previous report[2]. Briefly, the summer sample contained a higher proportion of cases incorporating large and rapid changes in wind speed or direction or both. In a study of such 'events' at Bedford over a period of 4 years, Burnham and Colmer[5] showed that they were normally associated with convective activity and occurred mainly in spring and late summer; on average only about 12% occurred in the 4-month period November to February, while more than half occurred in the 3-month period March to May. The winter sample was in contrast dominated by a high proportion of periods approximating to steady-state during which the wind speed was generally high (with roughly constant direction) producing a high level of short period turbulence; there were relatively few cases with large and rapid wind direction shifts and when these did occur, usually in association with the passage of active cold fronts or thunderstorms, they were normally accompanied by quite large increases in wind speed. In both summer and winter samples alike the largest errors occurred in non-stationary situations where it is obvious that a short averaging period and, more importantly, a short lag are desirable if their frequency is to be reduced. On the other hand in strong wind steady-state conditions when short period fluctuations of the 30-second wind about a relatively stable long period mean can be large, a longer averaging period is usually superior.

The 'combined' overall frequencies in table 2a show that for the two seasons combined, errors in the more important along-runway component of 10kt or more (about 1 in 2500) occur with about a half of the frequency of across-runway errors (about 1 in 1300) and about a quarter of the frequency of total vector errors (about 1 in 700) exceeding the same threshold; the equivalent relative freqneucies for errors of 14kt or more (table 2b) are about two thirds and one third respectively.

## Conclusions

The results of this study and others[1,2] has shown that, for Heathrow (and similar terrain in Southern England) the 2-minute averaging period, recommended by ICAO for this purpose, is particularly effective for reducing the frequency of errors exceeding a threshold of about 10 to 14kt (10kt for summer months, 14kt for winter months), but that its use inevitably results in increased rms error and frequency of errors in the range 0-10kt, which a 5 to 10-minute mean reduces more efficiently. The results have also illustrated well that, whatever the averaging period (within the $\frac{1}{2}$ to 10-minute range), the use of as short a lag as possible is of paramount importance. During lengthy periods of strong winds when there are no large abrupt changes of mean wind speed and/or direction, conditions quite frequently experienced during the winter months, the use of a 5 to 10-minute average has proved markedly superior to a shorter period average. On the other hand when there are frequent large variations in mean wind speed and/or direction such as those associated with the passage of major fronts (synoptic scale) or with convective activity including meso-scale squall-lines, the use of a short averaging period of $\frac{1}{2}$ to 3 minutes is favoured. These results apply to both along and across-runway wind components and to the vector error magnitude.

Overall it seems that the ICAO-recommended 2-minute average wind provides an adequate compromise, particularly when the lag between the supply of the wind report and its use is less than 5 minutes. It also appears to be more effective for reducing large across-runway errors than for reducing large along-runway errors.

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4. Montreal, International Civil Aviation Organization. Report of the 8th Air Navigation Conference, Montreal.Doc 9101,AN-CONF/8,Montreal 1974.
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TABLE 1 PERCENTAGE FREQUENCIES OF ERRORS EXCEEDING VARIOUS THRESHOLDS

(Summer + Winter)

| Averaging Period (Minutes) | Lag (Minutes) | ALONG-RUNWAY COMPONENT Threshold (kt) 6 | 10 | 14 | 20 | ACROSS-RUNWAY COMPONENT Threshold (kt) 6 | 10 | 14 | 20 |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 2 | 2.25 | 0.128 | 0.022 | 0.0 | 2.63 | 0.184 | 0.042 | 0.007 |
| | 5 | 2.92 | 0.240 | 0.052 | 0.003 | 3.73 | 0.468 | 0.115 | 0.032 |
| | 10 | 4.19 | 0.444 | 0.118 | 0.017 | 5.22 | 0.811 | 0.245 | 0.071 |
| 5 | 2 | 1.71 | 0.128 | 0.027 | 0.0 | 2.16 | 0.253 | 0.059 | 0.017 |
| | 5 | 2.37 | 0.233 | 0.059 | 0.005 | 3.00 | 0.441 | 0.125 | 0.044 |
| | 10 | 3.59 | 0.424 | 0.115 | 0.025 | 4.42 | 0.745 | 0.253 | 0.081 |
| 10 | 2 | 1.76 | 0.169 | 0.052 | 0.005 | 2.31 | 0.324 | 0.098 | 0.020 |
| | 5 | 2.37 | 0.248 | 0.079 | 0.015 | 2.95 | 0.502 | 0.169 | 0.049 |
| | 10 | 3.37 | 0.387 | 0.120 | 0.027 | 4.38 | 0.787 | 0.270 | 0.098 |

(1 case = 0.0025%)

Table 2a ESTIMATED TRUE PERCENTAGE FREQUENCIES OF ERRORS ≥ 10 kt FOR A LAG OF 5 MINUTES

Figures in brackets are reciprocals of true frequencies (rounded to the nearest hundred) and represent the average number of take-off/landings in which one error of 10 kt or more is encountered

| | Averaging Period (Minutes) | Winter* | Summer* | Combined |
|---|---|---|---|---|
| Along-runway component | 2 | 0.0291 | 0.0439 | 0.0365 |
| | | (3400) | (2300) | (2700) |
| | 5 | 0.0230 | 0.0561 | 0.0395 |
| | | (4400) | (1800) | (2500) |
| | 10 | 0.0239 | 0.0610 | 0.0424 |
| | | (4200) | (1600) | (2400) |
| Across-runway component | 2 | 0.0572 | 0.0842 | 0.0707 |
| | | (1700) | (1200) | (1400) |
| | 5 | 0.0511 | 0.0866 | 0.0688 |
| | | (2000) | (1200) | (1500) |
| | 10 | 0.0516 | 0.1159 | 0.0837 |
| | | (1900) | (900) | (1200) |
| Magnitude of total vector | 2 | 0.1230 | 0.1680 | 0.1455 |
| | | (800) | (600) | (700) |
| | 5 | 0.1070 | 0.1765 | 0.1417 |
| | | (900) | (600) | (700) |
| | 10 | 0.1025 | 0.2090 | 0.1558 |
| | | (1000) | (500) | (600) |

*The winter and summer figures are taken from the results of separate analyses of winter and summer samples.

TABLE 2b ESTIMATED TRUE PERCENTAGE FREQUENCIES OF ERRORS ≥ 14 kt FOR LAG OF 5 MINUTES

Figures in brackets are reciprocals of true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 14 kt or more is encountered.

| | Averaging Period (Minutes) | Winter* | Summer* | Combined |
|---|---|---|---|---|
| Along-runway component | 2 | 0.0023 | 0.0195 | 0.0109 |
| | | (43500) | (5100) | (9200) |
| | 5 | 0.0018 | 0.0244 | 0.0131 |
| | | (55600) | (4100) | (7600) |
| | 10 | 0.0023 | 0.0330 | 0.0177 |
| | | (43500) | (3000) | (5700) |
| Across-runway component | 2 | 0.0155 | 0.0171 | 0.0163 |
| | | (6500) | (5800) | (6100) |
| | 5 | 0.0159 | 0.0208 | 0.0184 |
| | | (6300) | (4800) | (5400) |
| | 10 | 0.0216 | 0.0281 | 0.0248 |
| | | (4600) | (3600) | (4000) |
| Magnitude of total vector | 2 | 0.0300 | 0.0450 | 0.0375 |
| | | (3300) | (2200) | (2700) |
| | 5 | 0.0295 | 0.0575 | 0.0435 |
| | | (3400) | (1700) | (2300) |
| | 10 | 0.0337 | 0.0760 | 0.0548 |
| | | (3000) | (1300) | (1800) |

* The winter and summer figures are taken from the results of separate analyses of winter and summer samples.

FIGURE 1

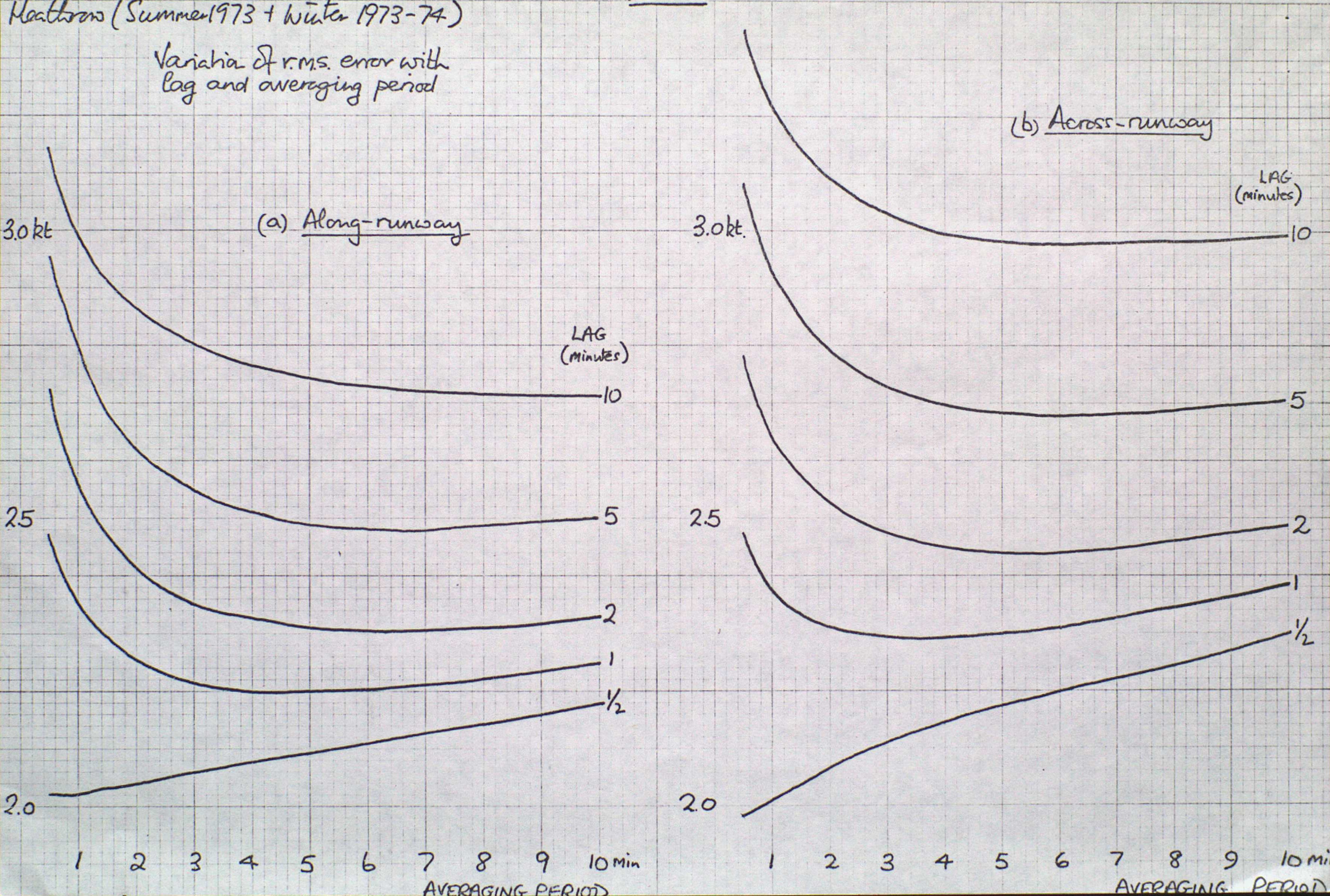
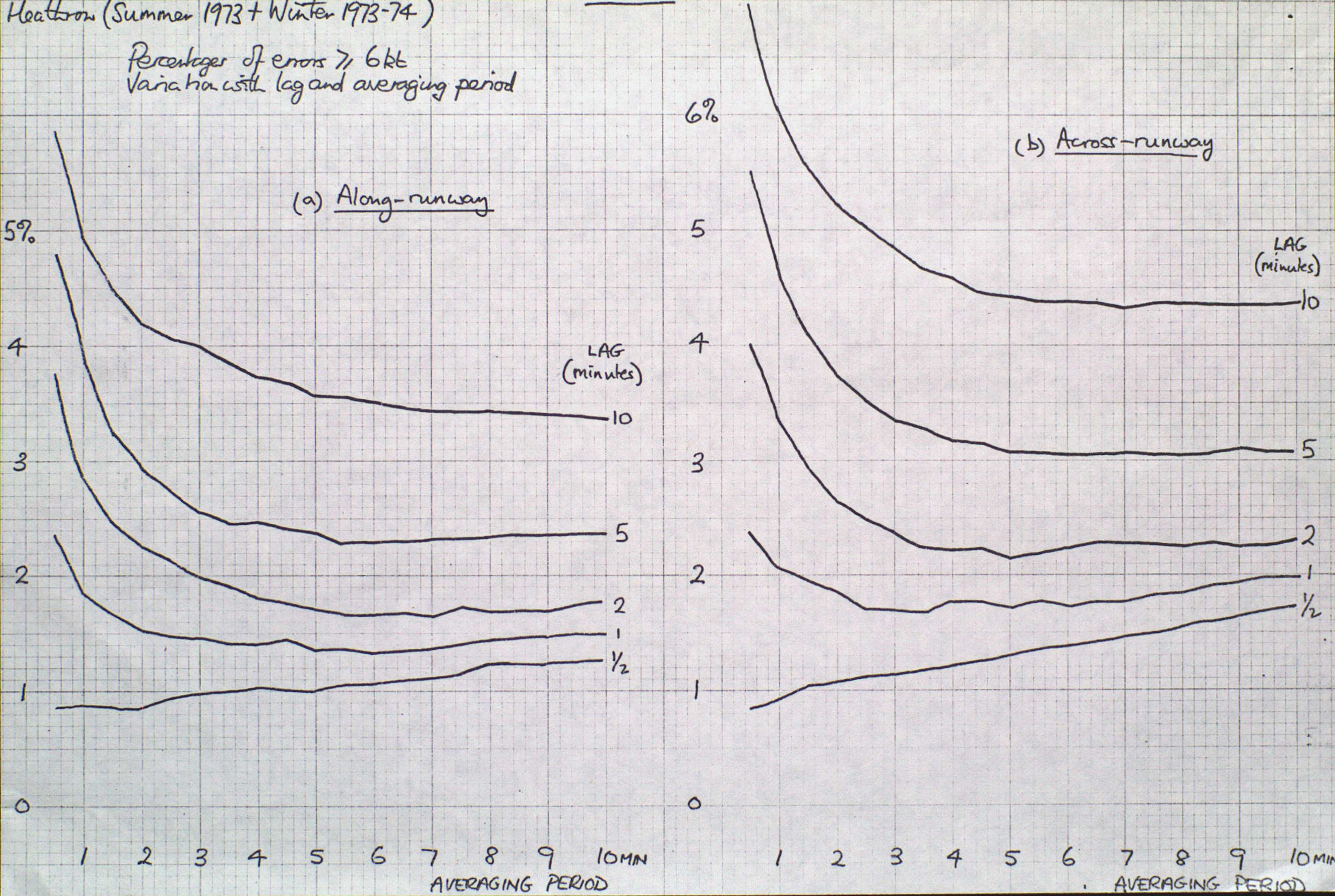

Heathrow (Summer 1973 + Winter 1973-74)
Variation of r.m.s. error with lag and averaging period
(a) Along-runway
3.0 kt
2.5
2.0
LAG (minutes)
10
5
2
1
½
1 2 3 4 5 6 7 8 9 10 min
AVERAGING PERIOD
(b) Across-runway
3.0 kt.
2.5
2.0
LAG (minutes)
10
5
2
1
½
1 2 3 4 5 6 7 8 9 10 min
AVERAGING PERIOD

FIGURE 2



Heathrow (Summer 1973 + Winter 1973-74)
Percentages of errors ≥ 6 kt
Variation with lag and averaging period
(a) Along-runway
5%
4
3
2
1
0
LAG (minutes)
10
5
2
1
½
1 2 3 4 5 6 7 8 9 10 MIN
AVERAGING PERIOD
(b) Across-runway
6%
5
4
3
2
1
0
LAG (minutes)
10
5
2
1
½
1 2 3 4 5 6 7 8 9 10 MIN
AVERAGING PERIOD

FIGURE 3

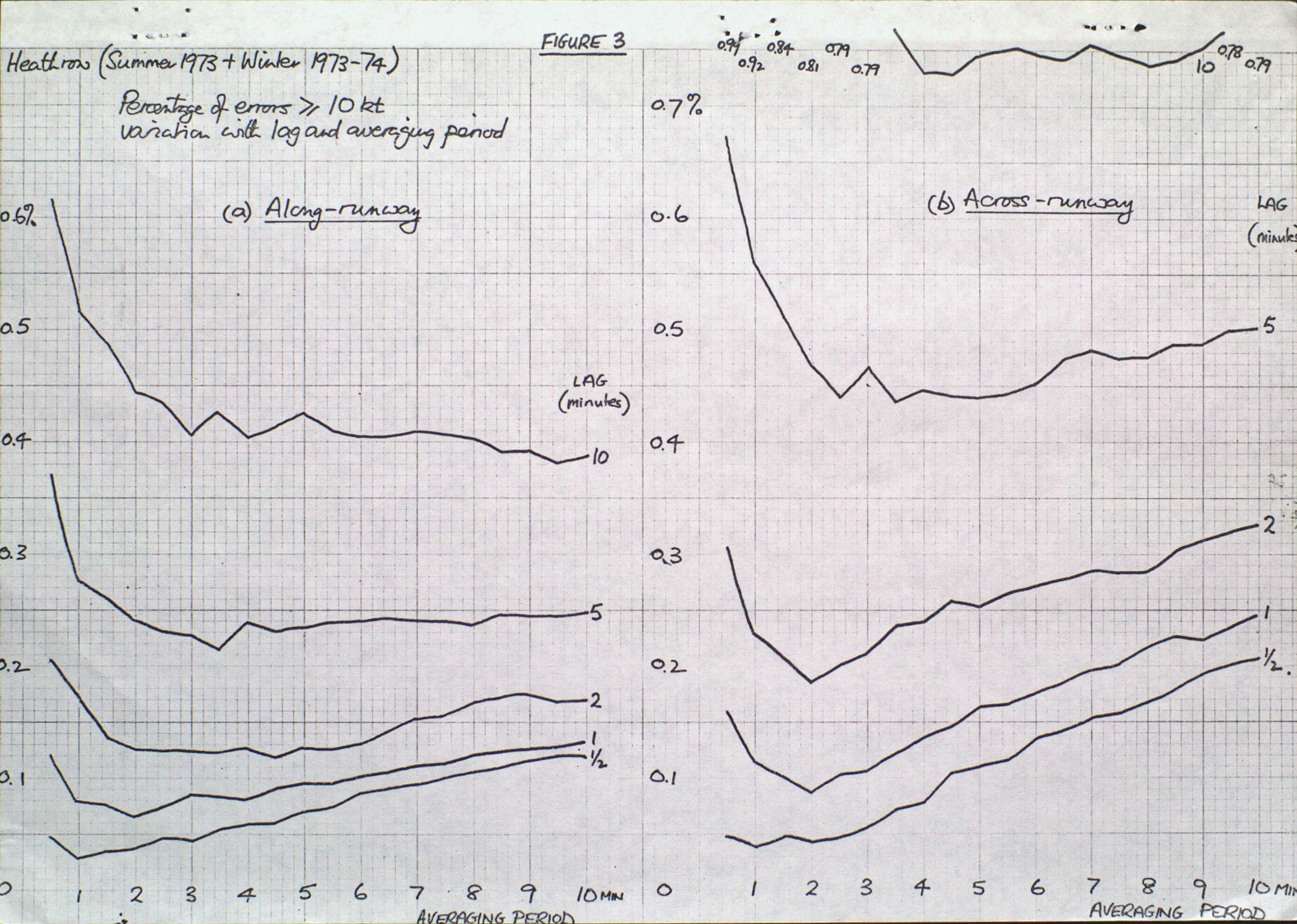
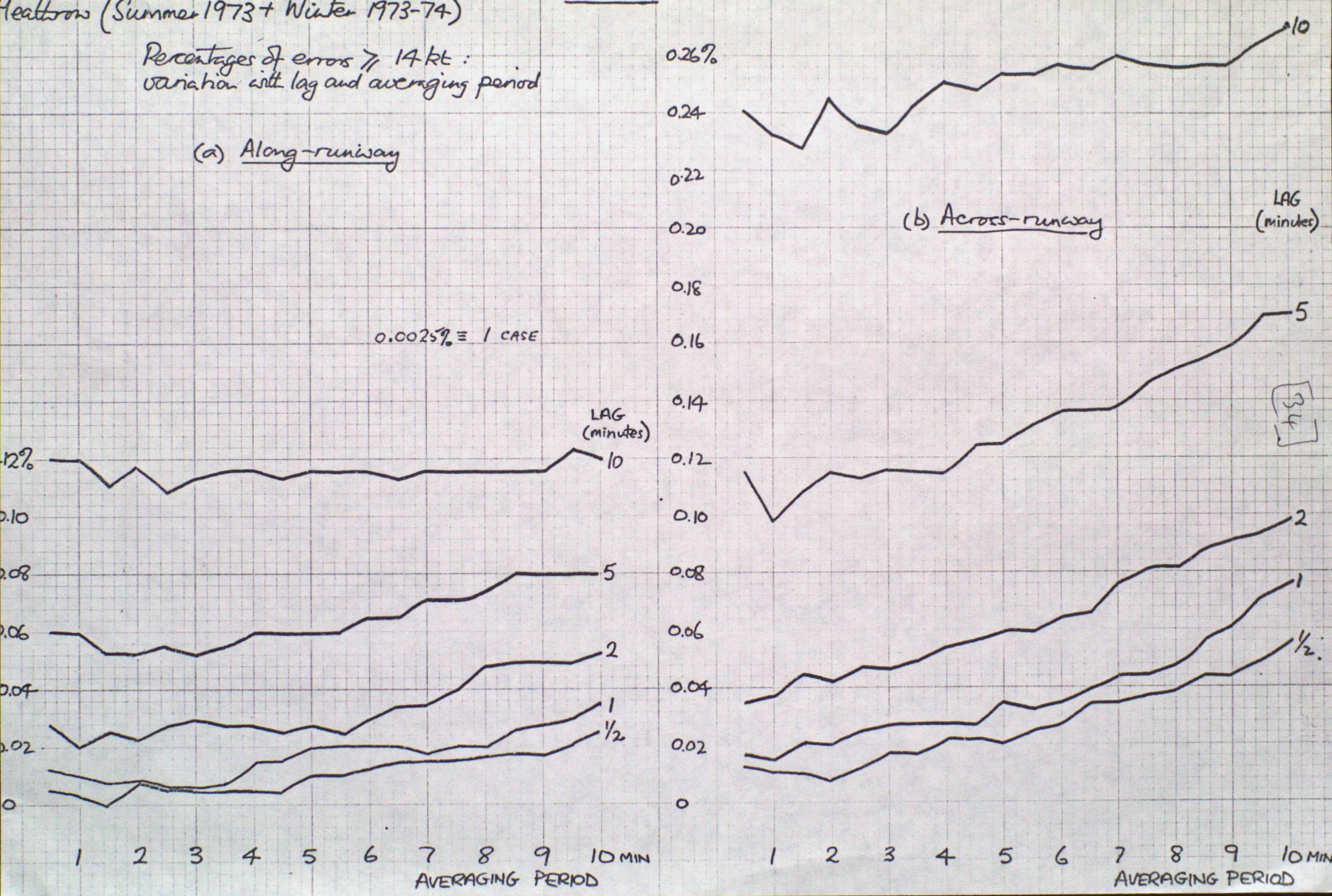

Heathrow (Summer 1973 + Winter 1973-74)
Percentage of errors ≥ 10 kt
variation with lag and averaging period
(a) Along-runway
(b) Across-runway
LAG (minutes)
0.7%
0.6%
0.6
0.5
0.4
0.3
0.2
0.1
0
10
5
2
1
½
0.94
0.92
0.84
0.81
0.79
0.79
0.78
0.79
1
2
3
4
5
6
7
8
9
10 MIN
AVERAGING PERIOD

FIGURE 4


Heathrow (Summer 1973 + Winter 1973-74)
Percentages of errors ≥ 14 kt : variation with lag and averaging period
(a) Along-runway
0.0025% ≡ 1 CASE
LAG (minutes)
10
5
2
1
1/2
.12%
0.10
0.08
0.06
0.04
0.02
0
1
2
3
4
5
6
7
8
9
10 MIN
AVERAGING PERIOD
(b) Across-runway
LAG (minutes)
10
5
2
1
1/2
0.26%
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
1
2
3
4
5
6
7
8
9
10 MIN
AVERAGING PERIOD
34