MET.O.14

METEOROLOGICAL OFFICE
BOUNDARY LAYER RESEARCH BRANCH
TURBULENCE & DIFFUSION NOTE

T.D.N. No. 54

Shipboard pressure measurements during JASIN 1972.

by N.Thompson.

June 1974

FHI

June 1974

TDN 54

Shipboard pressure measurements during JASIN 1972

by N Thompson

Summary

Shipboard pressure data obtained during the Joint Air-Sea Interaction Experiment in 1972 have been analysed in some detail. The results suggest that typical instrumental errors for the Meteorological Office Precision Aneroid Barometers (PABs) are around 0.2 mb. Random errors associated with effects of ship-induced accelerations on the aneroids were about 0.1 mb. Series of observations obtained for different ship headings relative to wind demonstrated variations of measured pressure with heading of several tenths of a millibar in winds of force 4 or 5 in spite of the barometers being connected to well-exposed static heads. Intercomparisons of pressure readings obtained when ships were adjacent showed inconsistencies due either to short-term barometer drift or more probably reading errors which varied between observers. Comparisons of PAB readings with those from a Kollsman transducer aboard one of the ships (Discovery) revealed a calibration error of about 1.4 mb for the Kollsman instrument and also demonstrated differing standards of observation for the different observers involved in the PAB measurements: thus the scatter in the readings varied systematically with the observer making them, and there was evidence also for systematic differences between means of pressure values obtained by each observer. PAB data from Researcher also demonstrated marked observer-bias, with values obtained by one observer averaging about 0.2 mb higher than from the others.

1. Introduction

The Meteorological programme for the JASIN project is concerned inter alia with the relationships between surface fluxes and large scale mean parameters. One of these latter is the surface geostrophic wind V_g (= $\frac{1}{f}$ p x k : here is the air density, f the coriolis parameter and k the unit vertical vector). There have always been doubts whether the restricted size of the experimental area enclosed by the ships participating in JASIN would allow the measurement of the pressure gradient with sufficient accuracy to provide useful estimates for V_g, and in both the 1970 and 1972 exercises there were special experiments to investigate this point. The planned size of the JASIN array is of the order of 100 km and an error in pressure measurement of 0.1 mb over this distance would produce a wind speed error of 0.8 ms^{-1}, or for a typical geostrophic speed of 10 ms^{-1} a direction error of 5^o. In the context of JASIN it is believed that errors even as small as these are barely acceptable.

In 1970 the pressure experiment was carried out with sensors mounted on meteorological buoys: the results (Royal Society 1971) demonstrated the inadequacy of the sensors for measurements of the required very high accuracy. The 1972 experiment explored again the use of buoys but using different pressure systems supplied and maintained by the University of Miami, and also investigated the possibility of obtaining satisfactory data from ship-board instruments. The present note discusses these ship observations.

The difficulties of making atmospheric pressure measurements of very high accuracy are more acute when the observations are from ships rather than on land. The main errors likely to arise are briefly as follows:

(a) Changes may occur in the sensor calibration and these are detectable usually only on recalibration: since recalibration is not feasible on board ship the nature of the shift (e.g. sudden change or slow drift) is not known and there is uncertainty about which calibration figure to use.

(b) Ship motions (heave, pitch and roll) produce fluctuations in pressure due to change in height of the sensors and to acceleration forces on the transducer and its mounting. The first type of fluctuation can be reduced to negligible amounts either by inserting a suitable constriction in the pipe connecting static head and sensor or alternatively by averaging over several cycles of ship motion. Acceleration forces can also be averaged out provided the mean orientation of the sensor was that in which it was calibrated, but if the instrument is tilted e.g. by incorrect levelling when mounted or by the ship listing due to a strong beam wind then errors may result.

(c) With sensors such as the Meteorological Office Precision Aneroid Barometer (PAB) where manual setting is required and some hysteresis is present, different observers may arrive at a different setting for the same ambient pressure, especially when ship motion is vigorous.

(d) The ship will disturb the airflow from its free-stream pattern and then in spite of using static heads the measured pressure will differ from that in undisturbed flow. If it is assumed that Bernoulli's equation holds for this case then departures of $\pm$ 5 ms^{-1} from a free stream velocity of 10 ms^{-1} produce pressure changes of -0.75 and +0.45 mb: even vel city changes of $\pm 1 ms^{-1}$ cause significant variations ($\pm$ 0.1 mb) at this mean speed.

(e) In a rolling ship with static head above the pressure sensor there will be a net upward force on the air in the pipe connecting the two (Pollard (unpublished) 1971). The mean error introduced is about -0.02 mb for a roll angle of $\pm$ 10 degrees with a period of 6 seconds and static head 15m above the barometer.

2. Experimental design and instrumentation

The pressure sensor used on all ships was the Meteorological Office Precision Aneroid Barometer (PAB). This incorporates a capsule stack whose deflection is measured by a micrometer calibrated in millibars and tenths: contact between micrometer and capsule is indicated by an electrical make and break circuit. The display can be read with a precision exceeding 0.05 mb but there is a dead zone in the micrometer system of about 0.05 mb and a reading resolution better than this is therefore not justified. The instruments were calibrated before and after JASIN in the Meteorological Office Instrument Test Room (at 20°C) against a precision Bourdon gauge at a number of pressures spanning the usual synoptic range (calibrations were given to 0.1 mb). Three PABs were used on each of the three ships in the JASIN array. It was hoped that the multiple pressure observations would allow an improvement in the mean of the accuracy of measurement on each ship as well as providing data for assessing the performance of the aneroids by intercomparison of readings. On all ships the PABs were connected to a standard Meteorological Office static head mounted in a reasonably well- exposed position: these positions and those of the PABs appear in Table 1.

Table 1 BAROMETERS AND STATIC HEADS

Ship	Barometer type, position and approximate mean height above sea level	Static head type, position and mean height above sea level
Weather Adviser	3 PAB's, Met Office 3m	1. Met Office pattern, port side of platform on mainmast, 18m 2. Met Office pattern, stb. side of platform on mainmast, 18m 3. Met Office pattern, on mast above shelter, 15m
Researcher	3 PAB's, Laboratory, 3m	Met Office pattern, stb. side of mast above wheelhouse, 9 m
Discovery	3 PAB's, gravity room 3m 1 PAB, Bridge, 12m Kollsman, either (a) Bridge 11m or (b) Gravity room 2m	1. Met Office pattern, stb side of platform on forecast, 18m 2. Met Office pattern, port side of lookout area of monkey island, 13m 3. Miami (Snyder) pattern, starboard side of monkey island, 13m.

The pressure distribution over any object obstructing the airflow differs from that in the free stream (1(d)) so that aside from any errors introduced by the transducers the pressure observations from ships will always be in error except in very light winds. To obtain some information on these errors additional static heads were mounted on Weather Adviser and Discovery (Table 1). On Adviser an extra head was mounted on the mainmast, at the same level but on the opposite side to the existing head, and another was placed on a mast about 4m above the top of the balloon shelter (aft of the mainmast). Valves were used to connect the selected head to the PABs. On Discovery the extra head was placed on the bridge.

Discovery also carried two further barometers, a PAB mounted above the bridge deck and connected to the bridge Met.Office head, and a Kollsman sensor, mounted either in the gravity room or on the bridge deck and which could be connected to either of the two Met.Office heads or to a University of Miami head on the bridge.

The fluctuations produced by the change in height of the PAB's above sea level due to ship motion were reduced to less than ± 0.1 mb by fitting "damping caps" (constrictions) to the inlet pipes of the barometers.

3. <u>The Observations</u>

The main series of measurements were at 1-hourly intervals on all ships when the PAB's were read twice in the sequence 1-2-3, 1-2-3, using the mainmast static head on Adviser and the foremast head on Discovery. There were additional measurements made on each ship (table 2) with the principal objective the determination of the effect of changes in relative wind direction on the observed pressure. Researcher carried out two series of this type in winds of Force 3 and 5, with the PABs read in the same sequence as for the routine observations. Adviser also carried out two series in similar winds but here observations were made using all three static heads at each heading, each thus producing 18 pressure readings. Two similar series were carried out aboard

Table 2 SPECIAL PRESSURE OBSERVATIONS

Series Number	Ship	Period (GMT)	Barometer and static heads	Notes
1	Researcher	06/1022-06/1110	3 PAB's mast head	Measuring pressure at 16 different headings relative to wind: each PAB read twice at each heading.
2	Researcher	10/1055-10/2055	3 PAB's, mast head	Various different relative headings: PAB's read twice at each heading
3	Adviser	10/1410-10/1535	3 PAB's, all static heads	16 different relative headings PAB's read twice for each static head on each heading
4	Adviser	20/0800-20/0848	3 PAB's, all static heads	" " "
5	Discovery	09/0000-23/0700	Kollsman (bridge) Miami head	100 sec averages every 5 min
6	Discovery	23/1150-23/1950	Kollsman (Gravity room), Mast head	100 sec average every 5 min
7	Discovery	23/2005-24/0315	"	" " "
8	Discovery	24/0320-24/0548	Kollsman (Grav) 3 PAB's Mast head	16 different relative headings. PAB's read 12 times for each heading. 120 Kollsman 1 sec averages at 1.5 sec intervals on each heading: also single 100 sec averages before ship changed heading
9	Discovery	24/0550-25/1515	Kollsman (Grav), mast head	100 sec averages every 5 mins
10	Discovery	25/1520-26/1615	Kollsman (bridge) Miami head	" " "
11	Discovery	26/1620-26/2305	Kollsman (bridge) Bridge Met.O.head	" " "
12	Discovery	26/2318-27/0132	3 PAB's, mast head Bridge PAB, bridge Met.O.head Kollsman (bridge), all three static heads	8 different relative headings, Gravity room PAB's read 12 times for each heading, followed by 18 readings of bridge PAB. 100 sec averages from Kollsman using mast head and bridge Met. Office head (both simultaneous with PAB readings), and Miami head on each heading.
13	Discovery	27/0140-28/0850	Kollsman (bridge), Met.O. bridge and mast head	100 sec average every 5 min.
14	Discovery	28/0855-28/1340	Kollsman (bridge) alternate heads (Met.O., Miami)	" " " "
15	Discovery	28/1340-29/1150	Kollsman (bridge) Miami head	" " " "

Table 2 SPECIAL PRESSURE OBSERVATIONS (continued)

Series Number	Ship	Period (Z)	Barometer and static heads	Notes
16	Discovery Adviser	04/1410- 04/1420	3 PAB's, Mast head 3 PAB's, all heads	Intercomparison. Each PAB read twice on Discovery, 3 times for each head on Adviser.
17	Discovery Researcher	05/1910- 05/1940 05/1855- 05/1955	3 PAB's, Mast head 3 PAB's, Mast head	Intercomparison. Each PAB read twice at 15 minute intervals on both ships.
18	Discovery Researcher	13/1010- 13/1155 13/0955- 13/1255	3 PAB's, mast head 3 PAB's, mast head	Intercomparison in very light winds PAB's read twice at 15 minute intervals
19	Adviser Discovery Researcher	18/0800- 18/0900 18/0740- 18/0855 18/0755- 18/0855	3 PAB's, port mast head 3 PAB's, mast head 3 PAB's, mast head	Intercomparison. PAB's read twice at hourly intervals on Adviser. Read twice at 15 min intervals on Discovery and Researcher
20	Adviser Discovery	27/1810- 27/2010 27/1825- 27/2010	3 PAB's, all heads 3 PAB's (Grav.), mast head. Bridge PAB, bridge head	Intercomparison. PAB's read twice for each head on Adviser at 15 minute intervals. Gravity room PAB's read twice at 15 min intervals, bridge PAB single reading every 15 minutes on Discovery.

Discovery, with 12 readings of each PAB at the various headings. Five intercomparisons of PAB's on different ships were made, in all but one case with only two adjacent ships (Table 2).

On board Discovery the Kollsman sensor was used to obtain extensive data using different static heads, occasionally simultaneously with PAB observations and sometimes sharing static heads with them. Details are also given in Table 2.

4. Results and discussion

(a) PAB readings

(i) General results

Before discussing the results in detail it is appropriate to consider the magnitude of two of the barometry errors described in the introduction. One important cause of uncertainty is the change of calibration revealed after recalibration of the sensors (1(a)). The PAB corrections found before and after JASIN 72 are shown in Table 3. Changes were very small for all three PAB's on Discovery (0.1 mb or less) and in most cases less than 0.2 mb for Adviser but (presumably coincidentally) only one of Researcher's instruments showed a drift of less than 0.2 mb. Because of lack of information on the causes of changes it had to be assumed that they were due to linear drifts with time. Errors are also introduced by the difficulties of averaging out the effects of ship-induced accelerations (1(b)).

Table 3 Barometer corrections

Ship	PAB	Correction (to be added) 980mb	1000mb	1020mb	1050mb	Calibration date
Adviser	1	+0.1	0.0	+0.1	+0.1	15 6 72
		+0.2	+0.2	+0.1	+0.3	19 10 72
	2	+0.1	0.0	0.0	+0.1	2 8 72
		0.0	+0.1	+0.1	+0.1	19 10 72
	3	-0.1	-0.1	-0.1	-0.1	2 8 72
		0.0	0.0	0.0	+0.1	19 10 72
Researcher	1	+0.1	+0.1	+0.1	+0.2	15 6 72
		+0.3	+0.3	+0.3	+0.5	19 10 72
	2	0.0	-0.1	-0.1	+0.1	2 8 72
		+0.3	+0.3	+0.3	+0.4	19 10 72
	3	0.0	0.0	0.0	+0.1	2 8 72
		0.0	-0.1	+0.1	+0.3	19 10 72
Discovery	1	-0.1	0.0	0.0	+0.1	15 6 72
		0.0	+0.1	+0.1	+0.2	19 10 72
	2	-0.1	-0.1	-0.1	-0.1	7 8 72
		-0.1	-0.1	-0.1	-0.1	19 10 72
	3	0.0	0.0	0.0	+0.1	7 8 72
		+0.1	0.0	+0.1	+0.2	19 10 72

They can be reduced by mounting the PAB's on fore and aft bulkheads because the sensitivity to rotation about an axis (A) along this direction is substantially less than for rotation about a horizontal axis at right angles (B). This is demonstrated by Table 4 where typical changes in pressure readings for rotation about both axes are given. Because of the difficulty of finding suitable mounting points for the PABs on the ships it was only possible to use fore and aft bulkheads on Researcher: the other aneroids were mounted athwartships. Observers were instructed to average out as far as possible the fluctuations due to ship motion (heave, pitch and roll) though this was difficult to do in the heavier seas. Systematic errors to be expected from the barometer's sensitivity to tilt would occur as a result of a ship taking up a mean angle of roll due to wind on either beam (1(b)). In the case of Adviser and Discovery the magnitude of the error would be around 0.025 mb per degree of roll, with the sign of the error positive or negative for roll towards port or starboard respectively. The error for Researcher was about 0.005 mb per degree of roll.

Table 4   Sensitivity of PABs to pitch and roll (obtained from static tilt tests)

Angle of pitch (about axis B)	Angle of roll (about A)	Change in reading (mb)
0	0	-
+10	0	0.2
+20	0	0.5
+30	0	0.75
-10	0	-0.3
-20	0	-0.55
-30	0	-0.75
0	+10	0.05
0	+20	0.1
0	+30	0.2
0	-10	-0.05
0	-20	-0.1
0	-30	-0.15

All pressure data recorded during JASIN were "as read", with no corrections applied for height above sea level or for calibration changes. The first step in the analysis was to get all data into computer-compatible format. The routine PAB values and first series (No 5) of Kollsman data were available on digital magnetic tape supplied by IOS but other data had to be punched on tape or extracted from cards before processing. The corrections (for calibration change and for height above sea level) were then applied when the data were processed on an ICL 1905 computer: allowances were made where necessary for variation in ship's draught during the voyage (changes of calibration with temperature were ignored: typical changes are about 0.1 mb for a 10 degrees C variation of temperature).

The ten thousand or so routine pressure values are summarised in Table 5 in the form of mean daily pressure for each PAB. It is immediately clear that there are persistent systematic differences between corrected data from different aneroids and this is demonstrated more clearly in Table 6. Disagreements as large as 0.3 mb occurred between barometers which showed the largest calibration changes with time (e.g. the PABs on Researcher) and in these circumstances an accuracy in measurement of the pressure at the static head of ± 0.1mb clearly cannot be claimed even when using an average of the readings from three PABs. On the other hand the results in Table 6 demonstrate that changes in differences between PAB's are small usually and with the exception of one sensor on Researcher within the range ± 0.1 mb.

The corrected PAB readings (

i = reading number, j = barometer number, k = hour number) showed considerably more scatter than their daily means ( ). If it is assumed that differences between these daily means also apply to the hourly values it is possible then to correct the six observations obtained each hour on each ship to a common reference to give a new set of values . The daily averages of the resulting standard devaitions are given in Table 7.

Table 5 Daily mean pressures (-1000 mb)

Date	Adviser PAB$_1$	Adviser 2	Adviser 3	Discovery 1	Discovery 2	Discovery 3	Researcher 1	Researcher 2	Researcher 3	Means A	Means D	Means R	State of sea (1)
2/9				34.60	34.60	34.74	34.59	34.71	34.68		34.65	34.66	M ⟶ S
3				36.88	36.88	37.03	36.90	37.08	36.99		36.93	36.99	S
4	32.70	32.86	32.89	32.78	32.85	32.99	33.37	33.52	33.55	32.81	32.87	33.48	M
5	24.93	25.12	25.12	25.07	25.13	25.24	25.25	25.43	25.53	25.06	25.15	25.40	M
6	16.30	16.46	16.46	16.01	16.08	16.16	16.14	16.24	16.27	16.41	16.08	16.22	S to M
7	14.79	15.02	15.05	15.16	15.24	15.32	15.31	15.50	15.46	14.95	15.24	15.42	M
8	16.07	16.24	16.27	16.96	17.02	17.10	16.96	17.17	17.17	16.19	17.03	17.10	M ⟶ R
9	19.29	19.53	19.50	19.29	19.32	19.43	20.04	20.31	20.35	19.44	19.35	20.23	R ⟶ M
10	24.10	24.28	24.31	23.86	23.85	23.95	24.37	24.61	24.68	24.23	23.89	24.55	M
11	27.30	27.46	27.50	27.29	27.31	27.39	27.56	27.83	27.90	27.42	27.33	27.76	M
12	29.27	29.47	29.53	29.27	29.29	29.41	29.25	29.51	29.57	29.42	29.33	29.44	M
13	29.34	29.50	29.57	29.47	29.50	29.62	29.36	29.57	29.65	29.47	29.53	29.53	M
14	27.42	27.56	27.61	27.73	27.76	27.86	27.12	27.37	27.43	27.53	27.78	27.31	M
15	25.78	25.95	25.99	25.85	25.87	25.94	23.98	24.23	24.34	25.91	25.89	24.18	S
16	26.49	26.68	26.73	26.24	26.27	26.35	25.72	25.93	26.01	26.63	26.29	25.88	S
17	31.11	31.24	31.33	30.82	30.91	31.04	30.70	30.96	30.93	31.23	30.92	30.86	S
18	30.53	30.72	30.78	30.50	30.57	30.71	30.61	30.87	30.87	30.68	30.59	30.78	M to R
19	24.41	24.60	24.67	23.83	23.90	23.94				24.56	23.89		M
20	19.45	19.67	19.71	19.56	19.64	19.70				19.61	19.63		M ⟶ R
21	18.29	18.50	18.56	16.55	16.60	16.68				18.45	16.61		R
22	16.35	16.59	16.65	13.86	13.98	14.08				16.53	13.97		VR
23	18.47	18.64	18.69	17.68	17.72	17.79				18.60	17.73		VR ⟶ R
24	19.02	19.32	19.34	18.04	18.12	18.19				19.23	18.12		R
25	14.64	14.87	14.95	13.56	13.66	13.69				14.82	13.63		R
26	18.49	18.69	18.72	18.33	18.41	18.46				18.63	18.40		R ⟶ M
27	21.85	22.09	22.09	21.54	21.60	21.63				22.01	21.59		M to R
28	14.54	14.80	14.81	14.42	14.51	14.56				14.72	14.50		M to R
29	03.49	03.65	03.70							03.61			R to VR
30	07.78	07.94	07.93							07.89			VR

Notes: (1) S = slight (wave height 2-4')
M = moderate (wave height 4-8')
R = rough (" " 8-13')
VR = very rough (" " > 13')

Table 6 Intercomparison of mean daily pressures given by each PAB

Date	Adviser			Discovery			Researcher		
	2-1	3-1	3-2	2-1	3-1	3-2	2-1	3-1	3-2
2/9				0.00	0.14	0.14	0.12	0.09	-0.03
3				0.00	0.15	0.15	0.18	0.09	-0.09
4	0.16	0.19	0.03	0.07	0.21	0.14	0.15	0.18	0.03
5	0.19	0.19	0.00	0.06	0.17	0.11	0.18	0.28	0.10
6	0.16	0.16	0.00	0.07	0.15	0.08	0.10	0.13	0.03
7	0.23	0.26	0.03	0.08	0.16	0.08	0.19	0.15	-0.04
8	0.17	0.20	0.03	0.06	0.14	0.08	0.21	0.21	0.00
9	0.24	0.21	-0.03	0.03	0.14	0.11	0.27	0.31	0.04
10	0.18	0.21	0.03	-0.01	0.09	0.10	0.24	0.29	0.07
11	0.16	0.20	0.04	0.02	0.10	0.08	0.27	0.34	0.07
12	0.20	0.26	0.06	0.02	0.14	0.12	0.26	0.32	0.06
13	0.16	0.23	0.07	0.03	0.15	0.12	0.21	0.29	0.08
14	0.14	0.19	0.05	0.03	0.13	0.10	0.25	0.31	0.06
15	0.17	0.21	0.04	0.02	0.09	0.07	0.25	0.36	0.11
16	0.19	0.24	0.05	0.03	0.11	0.08	0.21	0.29	0.08
17	0.13	0.22	0.07	0.09	0.22	0.13	0.26	0.23	-0.03
18	0.19	0.25	0.06	0.07	0.21	0.14	0.26	0.26	0.00
19	0.19	0.26	0.07	0.07	0.11	0.04			
20	0.22	0.26	0.04	0.08	0.14	0.06			
21	0.21	0.27	0.06	0.05	0.13	0.08			
22	0.24	0.30	0.06	0.12	0.22	0.10			
23	0.17	0.22	0.05	0.04	0.11	0.07			
24	0.30	0.32	0.02	0.08	0.15	0.07			
25	0.23	0.31	0.08	0.10	0.13	0.03			
26	0.20	0.23	0.03	0.08	0.13	0.05			
27	0.24	0.24	0.00	0.06	0.09	0.03			
28	0.26	0.27	0.01	0.09	0.14	0.05			
29	0.16	0.21	0.05						
30	0.16	0.15	-0.01						

Table 7 Daily average standard deviations of hourly PAB readings

Date	Standard deviation (mb)		
	Adviser	Discovery	Researcher
2/9		.029	.062
3		.029	.047
4	.081	.029	.064
5	.063	.026	.058
6	.064	.028	.067
7	.076	.038	.059
8	.079	.033	.075
9	.093	.046	.061
10	.081	.045	.048
11	.069	.042	.053
12	.079	.033	.054
13	.066	.034	.055
14	.069	.036	.050
15	.050	.037	.066
16	.075	.028	.049
17	.069	.032	.046
18	.098	.049	.052
19	.077	.035	
20	.072	.039	
21	.083	.059	
22	.112	.100	
23	.096	.055	
24	.083	.042	
25	.090	.029	
26	.081	.045	
27	.069	.045	
28	.100	.049	
29	.086		
30	.075		

In all cases the least scatter was shown by the readings on Discovery, a compliment to the observers, but probably the result also of the greater stability of this ship. Researcher had the more favourable orientation of aneroids and this is perhaps the reasons for a smaller scatter than on Adviser. The standard deviation of the hourly observations corrected for systematic barometer differences was nearly always less than 0.1mb and so a typical non-systematic error after averaging the six corrected readings would be less than 0.1 6. It appears then that the random effects of ship motion and reading errors on the pressure observations were reduced to nearly negligible amounts after averaging. An attempt to assess systematic reading errors is discussed later.

Typical differences between the three pairs of PAB readings obtained hourly on each ship were around 0.2 mb and this value may be used as a very rough guideline in assessing the accuracy with which geostrophic winds may be calculated from the pressure data, provided the errors due to disturbance of local airflow by the ship are ignored or else assumed to be of similar magnitude on each ship. These assumptions are not likely to be justified except in light winds. A ten percent accuracy in geostrophic wind would require pressure differences between ships of the order 2mb. However for most of JASIN the differences between ships (Table 8) were less than this. Clearly

Table 8 Frequency table of mean daily pressure differences between ships

Difference (mb)	3 ships (diff between highest and lowest)	2 ships only
0 - 0.1	2	3
0.1 - 0.2	1	-
0.2 - 0.3	-	2
0.3 - 0.4	4	1
0.4 - 0.5	3	1
0.5 - 0.6	-	-
0.6 - 0.7	1	-
0.7 - 0.8	1	-
0.8 - 0.9	1	1
0.9 - 1.0	1	-
1.1 - 1.2	-	2
1.7 - 1.8	1	1
2.5 - 2.6	-	1

in these circumstances some improvement in the accuracy is required if geostrophic winds of acceptable accuracy are to be calculated. One possibility is by the use of intercalibration data obtained with the ships in close proximity.

(ii) Effect of ship heading on results

Before discussing the JASIN intercalibrations in detail some consideration must be given to the disturbance in the pressure field caused by the ships obstructing the airflow in their vicinity since these effects will be present when an intercomparison takes place. Calculations and measurements of flow velocity around obstacles (e.g. Kondo and Naito 1972) show that velocity deficits occur usually both upwind and downwind of obstacles but excesses appear round the side and above the obstruction. Thus, depending on the positioning of the static heads pressures either above or below the free-stream value may be measured. Variations of $1ms^{-1}$ on a free-stream velocity of $10ms^{-1}$ produce a pressure change around 0.1mb. Ships taking part in any operation such as JASIN 1972 present a variety of hull shapes and correspondingly will influence the airflow in different ways so it is not possible that a single static head position can be found for each which would at least assure pressure errors of similar magnitude for each ship and therefore negligible error differences between ships. The magnitude of the errors will be much reduced if the static head is mounted a considerable distance from the main superstructure (the results of Kondo and Naito for flow across a triangular shaped bank showed velocity perturbations of less than 10% at approximately 3 times the bank height, and these results might be considered a rough guide for a ship lying-to (acrosswind), with the relevant vertical dimension now the average height of the superstructure). It had been the intention to mount the principal static heads very high on each ship in a well-exposed position but it was not found possible to achieve these desirable locations. Nevertheless it was hoped that the heads were placed in positions with fair exposures where actual winds would not depart excessively from those in the undisturbed flow.

Secondary heads in Adviser and Discovery were positioned deliberately in poorly exposed locations in order to obtain some idea of pressure variations over the hulls. Changes in the pressure field caused by the ships are roughly proportional to the square of the wind speed and so ideally investigation of these changes are best carried out in stronger winds. Variations of a few tenths of a millibar might be expected in winds of around 10 ms^{-1} (see above) but since the typical semi-diurnal pressure oscillation is around 0.5mb in stationary synoptic situations it is important that any experiment is carried out within a reasonably short space of time so that for example pressure changes due to variations of relative wind direction may be isolated from any diurnal or synoptic changes. In some cases it was not possible to achieve either of these criteria.

The first experiment of this nature was carried out aboard Researcher in winds of around 10ms^{-1} (Table 2, series 1) and occupied less than one hour. Observations were taken on sixteen different relative wind directions and the initial and final pressures, obtained on the same relative bearing, were identical, suggesting only small synoptic changes. The standard deviation of the observations for each heading was calculated after correcting for mean differences between PABs using averages of all the observations in the series to establish these. Thus six pressure values were used to calculate the SDs on each heading. On average the value was about 0.05 mb and the standard deviation of the means was therefore around 0.05/ 6 0.02mb. The plotted mean value (Figure 1) demonstrate clearly that there are highly significant pressure changes up to 0.25mb with changes of relative wind direction: also a small direction change may produce a relatively large pressure variation. The pressure distribution is consistent with stronger winds at the static head when lying-to rather than aligned alongwind.

The pressure trough is more pronounced with the wind on the starboard beam and this is presumably because of the better exposure of the head for this wind direction than for relative westerlies. There is also an indication of slight asymmetry in the pattern with the highest pressures for wind along the approximate line 020-200 degrees and this is probably due to the asymmetric position of the head. Which of the relative directions provides the "correct" pressure is not of course revealed by the figure and must remain speculative in the absence of further data.

The second experiment aboard Researcher (Table 2, series 2) occupied 10 hours, in winds of only $4ms^{-1}$, so although a considerable number of observations were obtained for a variety of relative ship headings it was not possible to obtain any coherent picture of variations of pressure with heading even after applying a linear trend correction to the observations (Figure 2). The scatter is reduced by selecting data from a more-restricted period but in this case the number of data are then insufficient to draw any firm conclusions (for example the ringed points in the figure refer to data during the first 90 minutes but are too sparse to allow a coherent picture to emerge). Also because of the low wind speeds no large pressure changes were expected to be induced by the ship since perturbations of free stream velocity of 50% would have produced pressure changes of only around 0.1 mb: over a period of 10 hours these would be masked completely by synoptic variations.

The results from the two series of observations for different relative wind directions carried out aboard Adviser are plotted in Figures 3 and 4: a linear trend correction has been applied to reduce the contribution from synoptic changes of pressure. On 10th September the mean wind speed was about $5ms^{-1}$ and here the mean readings from port and starboard static heads on the mainmast agreed within less than 0.1 mb on 16 out of 17 occasions, the maximum difference being 0.19mb from a direction of 060°. The standard deviation of the 6 observations (reduced as before to a common mean pressure) for each static head was around 0.07 mb and the probable error of the mean was therefore about 0.03 mb. Differences between heads of 0.1 mb are thus highly significant. The experiment lasted nearly 90 minutes and some interference from synoptic changes of pressure must be anticipated but it appears that the mast head values are higher with the ship alongwind and lower when acrosswind, in broad agreement with the results from Researcher though the range of about 0.4 mb was higher than found for Researcher in winds twice as strong. Pressures measured using the balloon shelter static head showed very large departures from the others but were reasonably consistent with the corresponding observations on 20th September (Figure 4) with peaks and troughs occurring for broadly similar relative wind directions. The wind was somewhat stronger in this latter case (about 8 ms^{-1}) but even so the port and starboard head values agreed to 0.08 mb or better (there was a small average systematic difference between these observations, the port head value being around 0.02 mb lower when averaged over all wind directions: this was twice the average difference on the earlier occasion). In contrast to the 10th September the mast and balloon shelter heads produced similar variations of pressure with wind direction. The pattern of variation for the mast head is markedly different from that shown in Figure 3 and makes an interpretation of the results very uncertain. There is perhaps an implication that the airflow was relatively stronger when lying-to or headed into wind than the wind astern but the correlations appear rather weak. The probable random error of the mean was around 0.02 mb and the total variations of pressure with heading were about 0.3 mb.

Measured pressures for different ship headings in the case of Discovery are plotted in Figures 5 and 6 after removal of linear trends. The first experiment (Series 8, Table 2) was carried out in winds of about 8 ms^{-1} with both Kollsman and PAB sensors connected to the mast static head (the Kollsman readings are discussed below). The probable random error in the mean of the PAB values was around 0.02 mb for most of the experiment rising to 0.04 mb near the end due to increasing swell (Figure 7). The general shape of the PAB distribution shows no obvious similarities with those obtained from Weather Adviser and Researcher for different headings and is therefore probably the result of synoptic pressure variations (the experiment lasted about 150 minutes and observations from Adviser showed a similar variation of amplitude at around this period: it is unlikely therefore that the broad shape of the distribution is the result of variations of ship heading). (The results from the second experiment are included in the general discussion on the Kollsman observations later in this note).

(iii) Inter-ship calibrations

Attempts to intercalibrate the PABs by taking series of observations with ships in close proximity met with varying degrees of success. Ideally the intercomparisons were required over a wide range of relative headings and wind speeds so that the routine PAB observations taken in any circumstances on the different ships could be corrected to a common standard. Because of the ship programmes and meteorological variability it was clearly impossible to do this and the comparisons which were carried out provided rather limited information. Probably the most consistent series of observations was made by Adviser and Discovery on 27th September (Series 20, Table 2)(Figure 8). Winds were between

6 and 9ms^{-1} and the relative wind direction remained within the range 240 to 270 degrees and 0 to 20 degrees respectively for the whole series. After allowing for time differences between the observations the mean pressure difference was -0.10 ± .05 mb. In another comparison between these ships on 4th September (winds of 8 ms^{-1})(Series 16, Table 2) Adviser's heading relative to wind was 360 degrees and Discovery's 030 degrees. Each PAB was read nine times in the case of Adviser, and twice aboard Discovery with standard deviation of random errors of respectively 0.08 and 0.03 mb: the mean difference was +0.13mb. The change of sign of the difference when compared to the other occasion is consistent with a change of airflow from across to along Adviser. On a third occasion on 18th September (series 19, Table 2) winds were less than 3 ms^{-1} but a significant swell was present and the barometer readings showed considerable scatter especially on Adviser. The measured difference was -0.08 mb but this cannot be considered significant in view of a standard deviation for the Adviser observations (six readings only) of 0.16 mb.

The results of intercomparisons between Discovery and Researcher are given in Figures 9-11. In the first of these, carried out in winds of 5-6 ms^{-1} (Series 17, Table 2), three sets of simultaneous observations were taken while Researcher was lying-to (090 degrees relative) but for Discovery the relative headings were 270, 360 and 030 degrees. In all cases Researcher values were lower, the average difference being 0.08 mb. Figure 1 suggests that on the basis of a square-law dependence on wind speed of the ship's influence on pressure there would be a difference of around -0.06 mb between Researcher observations for relative directions of 090 degrees and 360 degrees at 5 ms^{-1}. The results on 5th September suggest therefore that if the ships had both been headed directly into wind the measured pressures on each would have agreed very closely. Similar observations made on 18th September (Series 19, Table 2) in generally lighter winds but again with considerable variations in relative heading for Discovery gave a mean difference of 0.05 mb, Researcher's figures again being the lower. An observation from Adviser during this period while adjacent was about 0.08 mb lower than Discovery's. The idea that the observations aboard Discovery and Researcher are closely compatible, with significant differences partly explicable in terms of different relative headings is destroyed apparently by an inspection of Figure 11 which shows results from 13th September (Series 18, Table 2). Here the relative wind speeds were very low so the disturbing effects of ships on the pressure field should have been negligible. However while the standard deviations of Discovery's observations were less than 0.05 mb (each PAB was read twice at each observation time and the SD was calculated as before for each set of six readings after correcting to a common standard using the observed daily mean differences between the PAB's) those from Researcher showed much more scatter, typical SDs being around 0.15 mb. On the other hand reference to Figure 12 suggests that most of the contribution to the SDs of the Researcher observations was non-random since the spread of the two individual observations made with each PAB at each time was small usually (the spread is shown by the vertical bars). There is perhaps an indication of systematic calibration changes over a short period of time in this case therefore. Table 5 supports the view that on a daily basis there can occur significant changes in the differences between PABs, and Table 9 (routine PAB observations aboard Researcher, 13th September) suggests that changes may occur on a much shorter time scale.

Table 9 Researcher observations on 13 September

Time	PAB 1	PAB 2 (-1029 mb)	PAB 3	2 - 1	3 - 1	3 - 2
00	.72	.91	1.13	.19	.41	.22
01	.55	.83	.75	.28	.20	-.08
02	.34	.55	.59	.21	.25	.04
03	.11	.23	.35	.12	.24	.12
04	.09	.29	.42	.20	.33	.13
05	.11	.28	.45	.17	.34	.17
06	.01	.28	.35	.27	.34	.07
07	.13	.35	.52	.22	.39	.17
08	.42	.71	.72	.29	.30	.01
09	.65	1.01	1.11	.36	.46	.10
10	.85	.88	1.15	.03	.30	.27
11	.75	1.21	1.05	.46	.30	-.16
12	.53	.75	.67	.22	.14	-.08
13	.85	.98	1.08	.13	.23	.10
14	.79	.93	.92	.14	.13	-.01
15	.55	.73	.82	.18	.27	.09
16	.29	.45	.55	.16	.26	.10
17	.09	.21	.22	.12	.13	.01
18	.09	.23	.32	.14	.23	.09
19	.09	.18	.35	.09	.26	.17
20	-.01	.15	.25	.16	.26	.10
21	.19	.31	.47	.12	.28	.16
22	.31	.65	.65	.34	.34	.00
23	.26	.53	.59	.27	.33	.06

The extreme differences between PABs 1 and 2 on this day occurred at 1000 and 1100 and were observations actually included in the intercomparison with Discovery! Three observers took pressure observations during the intercomparison and it is feasible then that the systematic changes in differences between PABs are due to different ways adopted by individual observers in smoothing out fluctuations induced by ship motion. Interestingly the observations from Researcher most in apparent discord with those from Discovery (1010-1110, and perhaps 1210) were all made by the same observer whereas those in closest agreement (1125-1155) were made by two others. The extensive series of observations obtained with the Kollsman sensor aboard Discovery allow this possibility of observer bias to be explored in more detail below.

(b) Kollsman readings

The Kollsman device has the advantage of automatic averaging and readout of observations. The shortest averaging time used was 1 second and this gave an opportunity of investigating the effects of ship motion on the output. During each of a number of 3-minute periods on 24th September (Table 2, series 9) about 120 1-sec averages were obtained and the typical range of measured pressure was found to be 1.0 mb. Swell was only moderate at the time (less than 3m) and therefore it appears that the Kollsman output is significantly affected by acceleration forces on the transducer. However, all the Kollsman data which will be discussed here were either 100 -second averages or alternatively averages of 1-sec long observations taken at 1.5 sec intervals over periods of about 3 minutes and so the effects of acceleration or height displacements would have been reduced to insignificant amounts by this smoothing.

Figure 5 shows a comparison of Kollsman and PAB observations obtained using the same static head during the first of Discovery's series of special pressure measurements involving different ship headings relative to wind. The broad details of the shape of the PAB plot have been discussed already and the point of interest here is the disparity between this plot and that for the Kollsman data. Most obvious is the difference of about 1.4mb between observations from the two types of sensors, a difference confirmed (at least approximately) by data obtained on other occasions. Clearly the Kollsman sensor had not been properly calibrated (the Meteorological Office standard against which the PABs were checked is accurate to around 0.1mb and is checked against NPL working standards every three months). It must be hoped that the Kollsman's error was systematic and did not reflect either uncertainty in short-term stability or in slope of its calibration curve. After elimination of the systematic difference between the sets of recordings the residual maximum difference between averaged PAB and Kollsman observations were $\pm$ 0.04 mb except for the last two pairs. Here the difference increased to about -0.15mb, because of, it is believed, increased difficulties in reading the PAB's due to an increase in swell. The trend corrections used in the plots in Figure 5 were derived therefore from the Kollsman data.

Figure 6 shows the results of Kollsman measurements using all three static heads in turn in a wind of about 4 ms^{-1}. The observations were taken over a period of about two hours when significant synoptic changes were occurring and the linear trend correction which was applied almost certainly failed to eliminate these entirely from the results. The basic shape of the distributions was probably not a consequence therefore of the varying ship's heading. The second Met.Office head was mounted on the port guard rail of the lookout area on the monkey island and the Miami head was positioned on the sternward rail of the island. Differences between pressures measured using these heads were usually less than 0.05 mb. In all but one case the mast static head gave higher pressures which is consistent with the stronger flow being in the region closer to the superstructure of the ship. Typical differences between mast and bridge head readings were less than 0.05mb.

Table 10 shows the differences between Kollsman and mean PAB readings for different headings on the same occasion, with both types of sensors connected to the mast head, and also differences when the Kollsman and the single PAB on Discovery's bridge were connected to the bridge (Met.Office) head.

Table 10 Comparisons between barometers on same static head, Discovery, 26/9 - 27/9/72

Relative wind (Approx)	(Mast Head) Kollsman - Av. PABs (mb)		(Bridge Head) Kollsman - Bridge PAB (mb)	
		Diff. from mean		Diff. from mean
360	-1.211	.001	-1.155	.040
315	-1.210	.002	-1.277	-.082
270	-1.177	.035	-1.173	.022
225	-1.226	-.014	-1.249	-.054
180	-1.194	.018	-1.106	.089
135	-1.209	.003	-1.187	.008
090	-1.225	-.013	-1.168	.027
045	-1.240	-.028	-1.149	.046
000	-1.221	-.009	-1.287	-.092

The probable random error in the first case for the PAB mean was less than 0.02mb (36 readings at each heading, standard deviation about 0.09mb after correcting for systematic differences between PABs), and this is consistent with the observed small variations in the pressure differences between the two sensor types. A similar scatter was found for observations with the single PAB but the differences between the meaned values and the Kollsman showed substantially more variation than in the first case (Table 10). The reason for this is not clear.

Data obtained on 28th (series 14, Table 2), provided a further opportunity to study the effects of different positions of static heads on measured pressure. Here all three heads were used in turn, usually at 5-minute intervals. The relative wind speed changed markedly during the period, from around 15ms^{-1} during the first part to 6 ms^{-1} towards the end. Mean pressures for the two wind speeds are given in Table 11. The results confirm others discussed earlier, with relatively small differences between bridge-mounted heads but significantly higher pressure at mast head particularly in the period with strong wind. As expected the difference between mast and bridge-head values is roughly proportional to the square of the wind speed and its magnitude suggests that (if

Bernoulli's equation can be applied) the wind over the bridge-head is around 20% higher than at the mast head.

Table 11 Kollsman observations using three static heads 28th Sept (Series 14)

Mean Wind Speed (ms^{-1})	Relative direction (degrees)	Mean Pressure (mb)		
		Bridge (Met O) Head	Miami Head (bridge)	Mast Head
15	010	1012.18	1012.10	1012.72
6	010	1013.05	1013.04	1013.14

During the period from 9th to 23rd September (series 5, Table 2) Kollsman readings were taken at 5-minute intervals using the Miami head, and although the data cannot be compared directly therefore with the routine PAB observations in order to assess for example the relative stability of the two types of transducer, they do provide an opportunity to investigate the effects of observer bias on the PAB data. Thus in spite of differences between the two sets of data varying with time due to, for example, varying ship heading or relative wind speed, the number of hourly observations are large enough (350) for these variations to be distributed reasonably uniformly between the 3 observers involved in the PAB observations. The results are given in Table 12 in the form of means and standard deviations of differences between Kollsman and PAB readings for each of the three observers involved in the PAB observations. Observer 2 made observations with the smallest standard deviation and was presumably the most effective in averaging out the effects of ship motion on PAB readings. Data obtained by Observer 3 had the largest scatter but otherwise were closely comparable in the mean with those from 2. In contrast Observer 1 produced data which showed systematically higher values for each of the PAB's, suggesting that he was using a reading technique somewhat different from that adopted by the other two observers.

Table 12 Observer bias in PAB results (9 - 23 September)

PAB	Differences between PAB and Kollsman readings (mb)					
	Observer 1		Observer 2		Observer 3	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	1.349	.236	1.309	.216	1.288	.252
2	1.394	.249	1.345	.227	1.347	.278
3	1.491	.236	1.439	.219	1.437	.264
Means	1.411	.240	1.364	.211	1.357	.265

During the period 23-25 Sept (Series 6, 7 and 9, Table 2) the Kollsman and PAB's were connected to the mast static head and the resulting observations allowed a further investigation of observer bias. The results appear in Table 13.

Table 13 Observer bias in PAB results (23-25 September)

Differences between mean PAB and Kollsman readings (mb)					
Observer 1		Observer 2		Observer 3	
Mean	S.D.	Mean	S.D.	Mean	S.D.
1.324	.061	1.321	.056	1.342	.067

Again the scatter was smallest for Observer 2 and largest for 3 but in contrast to the results given above the highest average was obtained by the latter. However because of the relatively small number of data the largest difference between the means is significant to no better than about the 30% level.

(In para 4(a) (iii) it was pointed out that one of the intercomparisons involving Researcher and Discovery produced some fairly strong evidence for substantial barometer errors caused apparently by the way in which one of the observers smoothed out the effects of ship motion as he noted the PAB readings. In Table 14 the mean value of the routine observations obtained by each observer aboard Researcher during JASIN are listed. Each mean was calculated from about 120 observations, spread more or less evenly throughout the 24 hour periods (6-hour shifts were worked) so the differences between means are expected to be affected insignificantly by normal diurnal pressure variations. Observer 2 appears to have read about 0.2mb higher than the other two: he also made the anomalous observations in the intercomparison between Discovery and Researcher which therefore appears to be subject to observer bias rather than short-term sensor drift).

Table 14 Mean values of Researcher observations for each observer

Observer	1	2	3
Mean (mb)	1026.38	1026.60	1026.46

5. Conclusions

Wind speeds were generally low during JASIN 72 and it was not possible therefore to carry out all the shipboard pressure experiments in conditions ideal for revealing the ship's disturbance to the local pressure field but a number of useful results have emerged. In particular, the Met Office PAB appears not to be reliable to better than about 0.2mb in absolute terms. However the relative accuracy, found by comparing the daily mean values for each PAB on each ship separately, was with the exception of one sensor on Researcher within the range $\pm$ 0.1 mb.

Intercalibrations with ships in close proximity are clearly useful in giving data which may be used to reduce relative pressure errors between ships but necessarily demand that the ships involved take up orientations with respect to wind which are used in the routine observations since the ship-induced perturbation to the pressure field has been demonstrated to vary significantly with relative heading. However the perturbation depends on wind speed also and a range of wind speed would usually be achieved during an intercalibration only by ships heading into wind at various speeds, thus limiting the chosen relative direction to 360 degrees. On the other hand the present results support the idea that the perturbation is roughly proportional to the square of the wind speed and so provided the intercalibrations are carried out to include observations in zero relative wind then the corrections for the different headings could be deduced for speeds other than occurring at the time of intercalibration. Clearly the intercalibration needs to be carried out in the shortest possible time (to avoid complications due to synoptic changes) and in strong winds (where perturbations are large).

The results have demonstrated fairly conclusively that observers differ in the way they smooth out the effects of ship motion on the PAB values, at best producing different amounts of scatter and at worst systematic differences in the mean. The solutions here (in the absence of modifications to provide automatic averaging and readout) are to establish a uniformity of reading standard by training, to have all observers participating in intercalibrations, and to mount PAB's with fore-and-aft orientations to decrease effects of ship motion. The results from Discovery demonstrated that in a larger ship, even with athwartship orientation of PAB's the observer differences can be as small as 0.05 mb on average.

The Kollsman sensor on Discovery appeared to function satisfactorily (unlike the surviving Kollsman device on the buoys which suffered from inadequate temperature compensation): however it was surprising to find a calibration error greater than 1mb. There was no evidence of any drift; for example the mean difference between PAB's and Kollsman for series 5, and for series 6, 7 and 8 were respectively 1.38 and 1.33 mb: the small disparity in these values is explicable in terms of the two different positions of static head used in series 5. The 100-sec averaging capability of the device was invaluable though it should be pointed out that the multiple-recording technique used for the PAB's can also be very successful in reducing fluctuations of pressure due to ship accelerations.

As anticipated the experiments have not given much useful information on the most advantageous placing of the static heads. It is believed that the effects of ship's influence cannot be satisfactorily reduced by any particular, and conclusively predictable, placing of the static head in which case the best chance of accurate pressure measurements may come from applying corrections to observations using the air velocity at the static head and an estimated "free stream" velocity at the same height in Bernoulli's equation. The first velocity might be measured fairly easily with a small cup anemometer and the second could be obtained with sufficient accuracy from an upward extrapolation of speed measured on an adjacent meteorological buoy. The type of buoy is stressed here because such an anemometer would have to be well exposed in order to measure speeds to within the required few percent, and thus the buoy would have to be relatively uncluttered.

Acknowledgements

Installation of the PAB's and static heads was carried out by D. Winters and D. R. Davies.

Thanks are due to the Captains and crews of Discovery, Researcher and Weather Adviser for their co-operation and to the observers for their diligence in obtaining the PAB data.

Professor Kraus provided the Kollsman sensors and made available data obtained by them.

IOS supplied on magnetic tape all the routine meteorological data from JASIN (including PAB observations).

Miss S. A. Matthews carried out most of the data processing.

Particular note should be made of the efforts of Dr R. T. Pollard including co-ordinating the Kollsman and PAB measurements on Discovery, and arranging the supply of Kollsman data and the reformatting of data on magnetic tapes.

Reference

Kondo J and Naito G 1972 Disturbed wind fields around the obstacle in sheared flow near the ground surface, J Met Soc Jap 50 pp 346 - 354

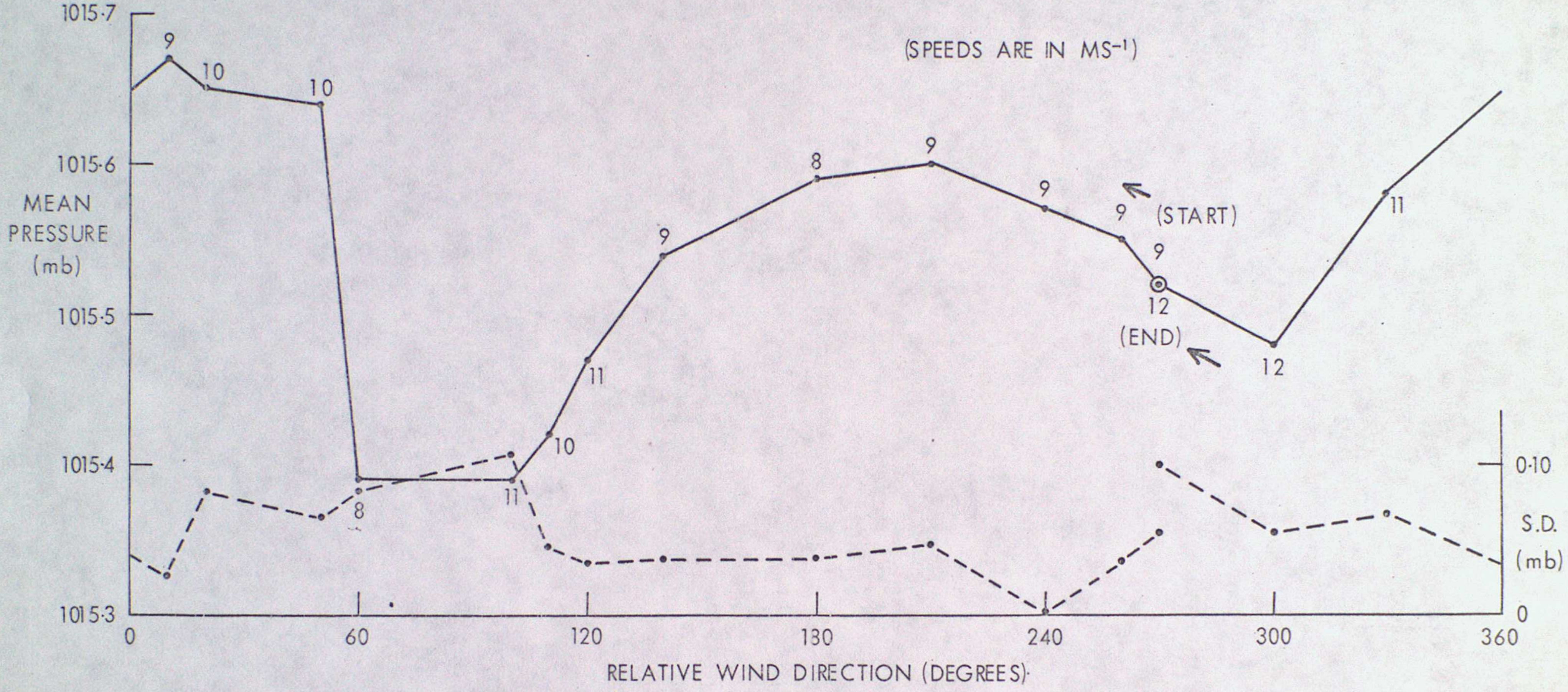

FIGURE 1 VARIATION OF PRESSURE WITH RELATIVE WIND DIRECTION RESEARCHER 6/9/72 1022–1110Z

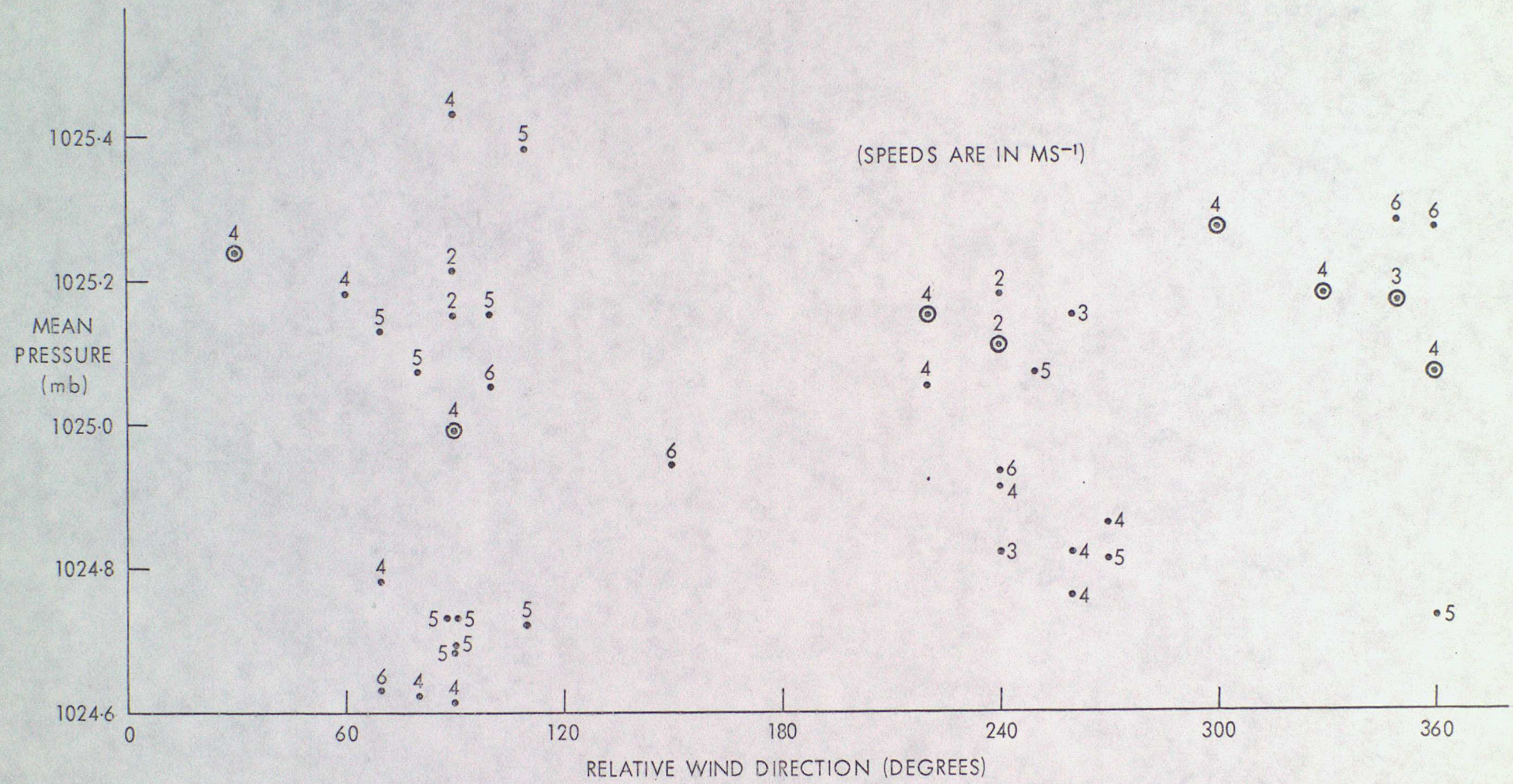

FIGURE 2 VARIATION OF PRESSURE WITH RELATIVE WIND DIRECTION RESEARCHER 10/9/62 1055–2055Z

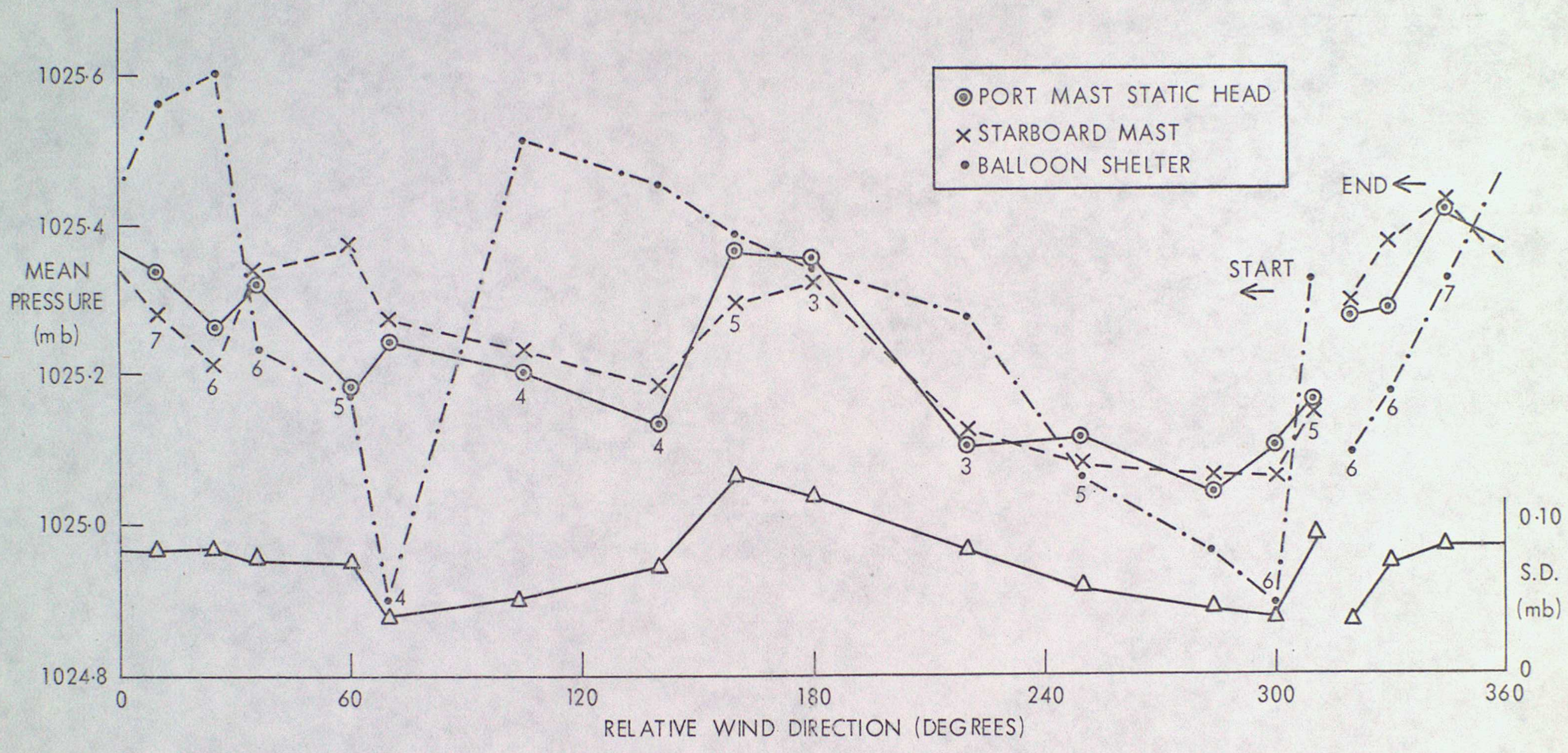

FIGURE 3 VARIATION OF PRESSURE WITH RELATIVE WIND DIRECTION WEATHER ADVISER 10/9/72 1410–1535Z

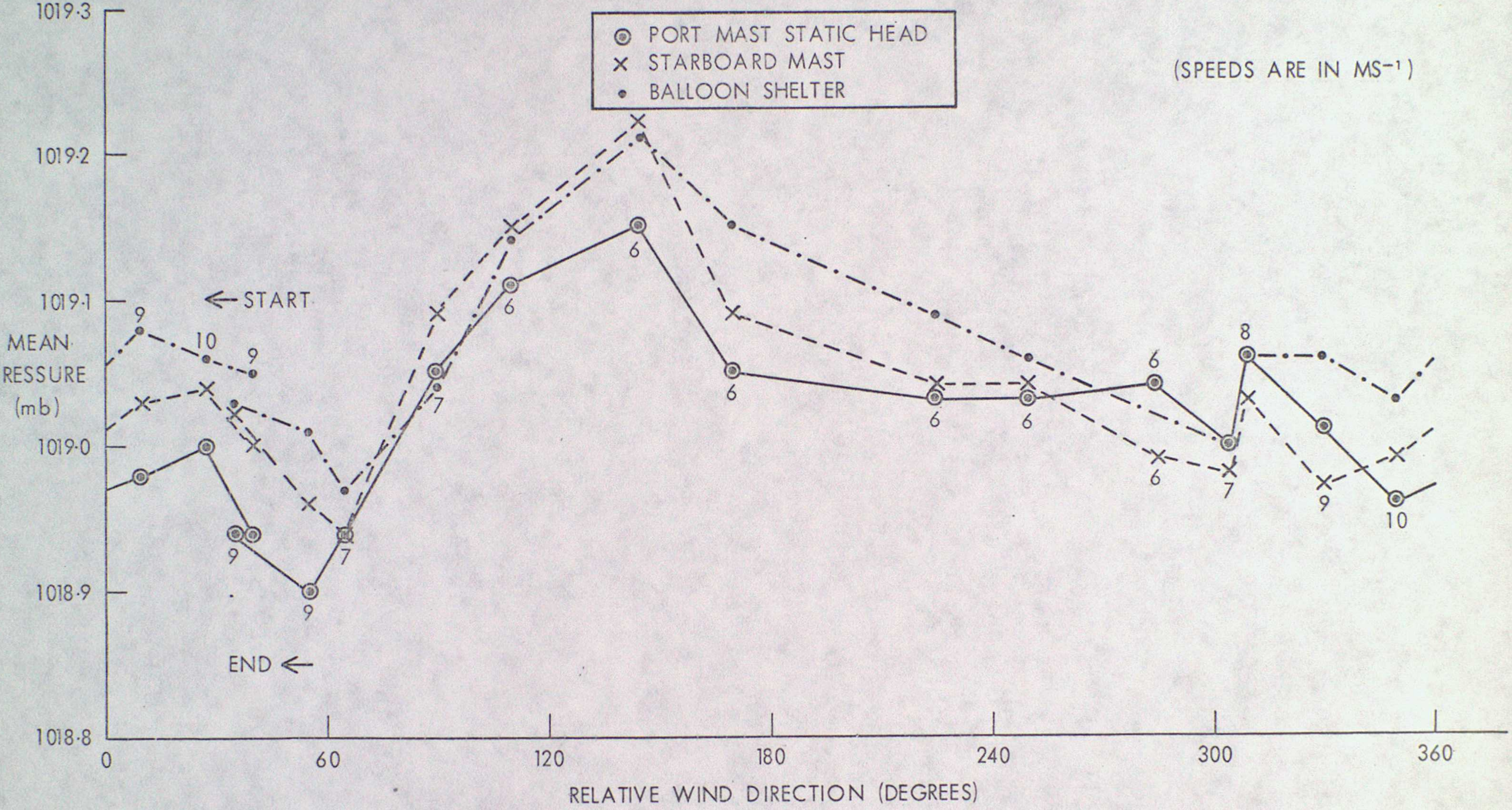

FIGURE 4 VARIATION OF PRESSURE WITH RELATIVE WIND DIRECTION WEATHER ADVISER 20/9/72 0800–0848Z

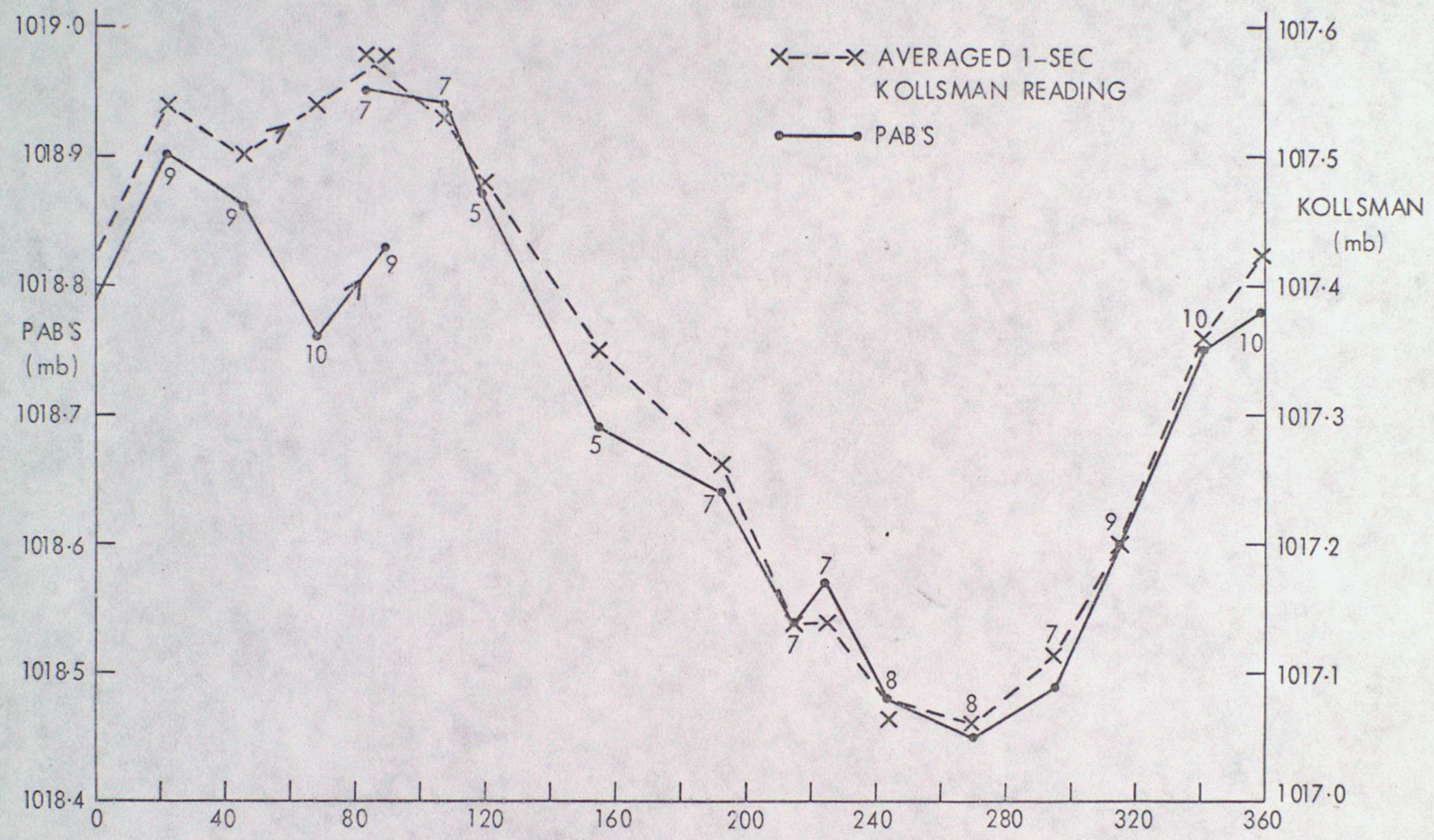

FIGURE 5 VARIATION OF PRESSURE WITH RELATIVE WIND DIRECTION

DISCOVERY 24/9/72 0320–0548Z

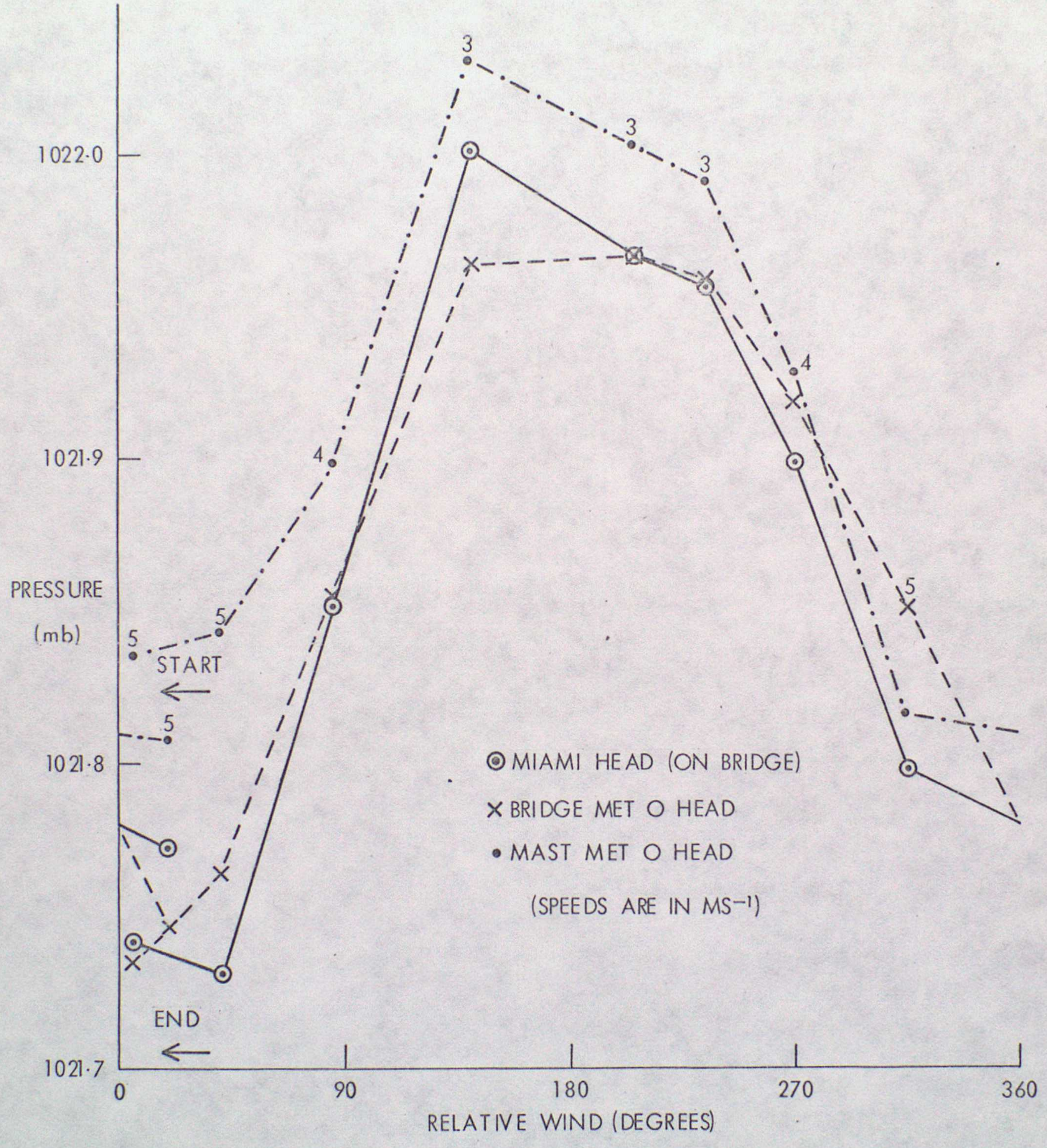

FIGURE 6 KOLLSMAN PRESSURE READINGS
DISCOVERY 26/9/72 2320 TO 27/9/73 0132Z

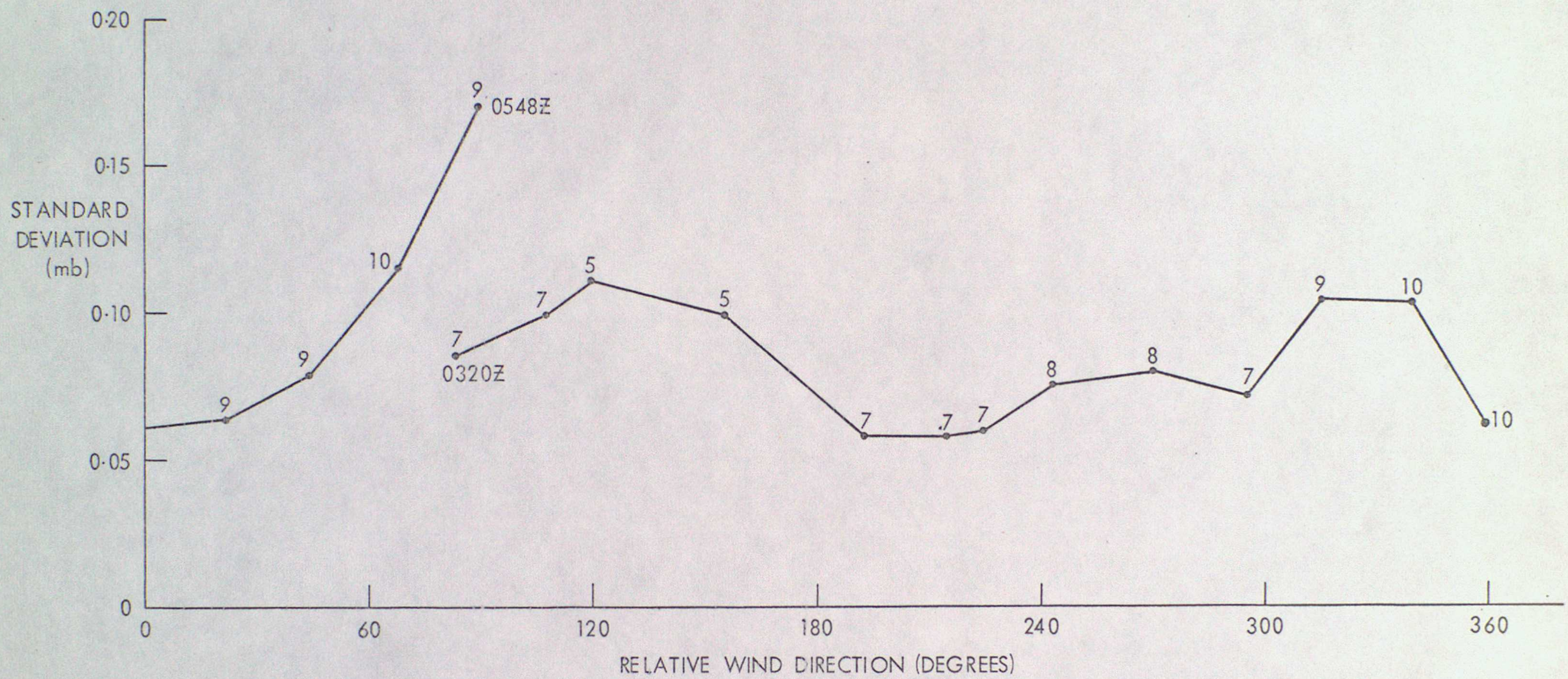

FIGURE 7 STANDARD DEVIATION OF PAB READINGS DISCOVERY 24/9/72 0320–0548Z

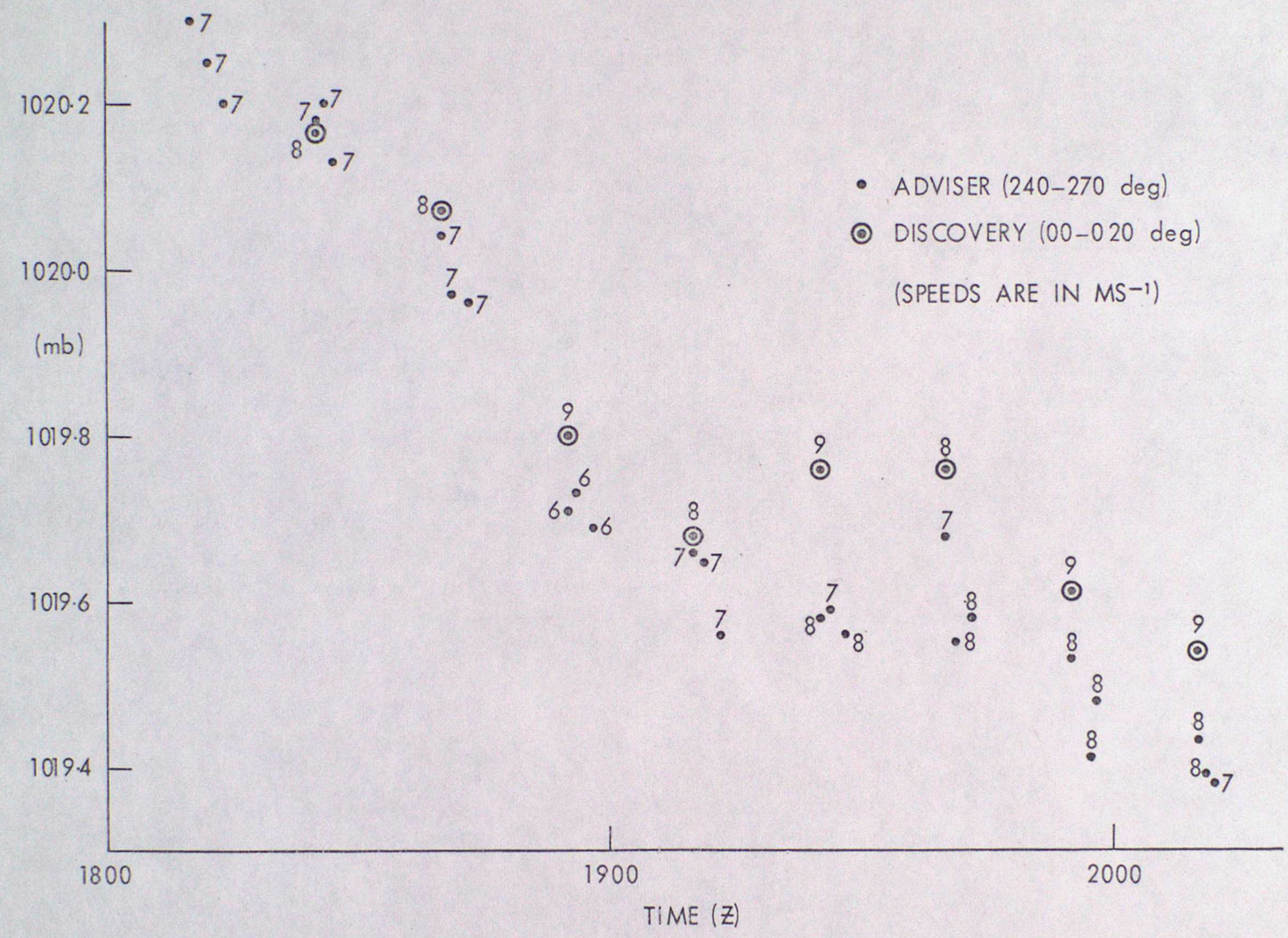

FIGURE 8 ADVISER/DISCOVERY COMPARISONS 27/9/72

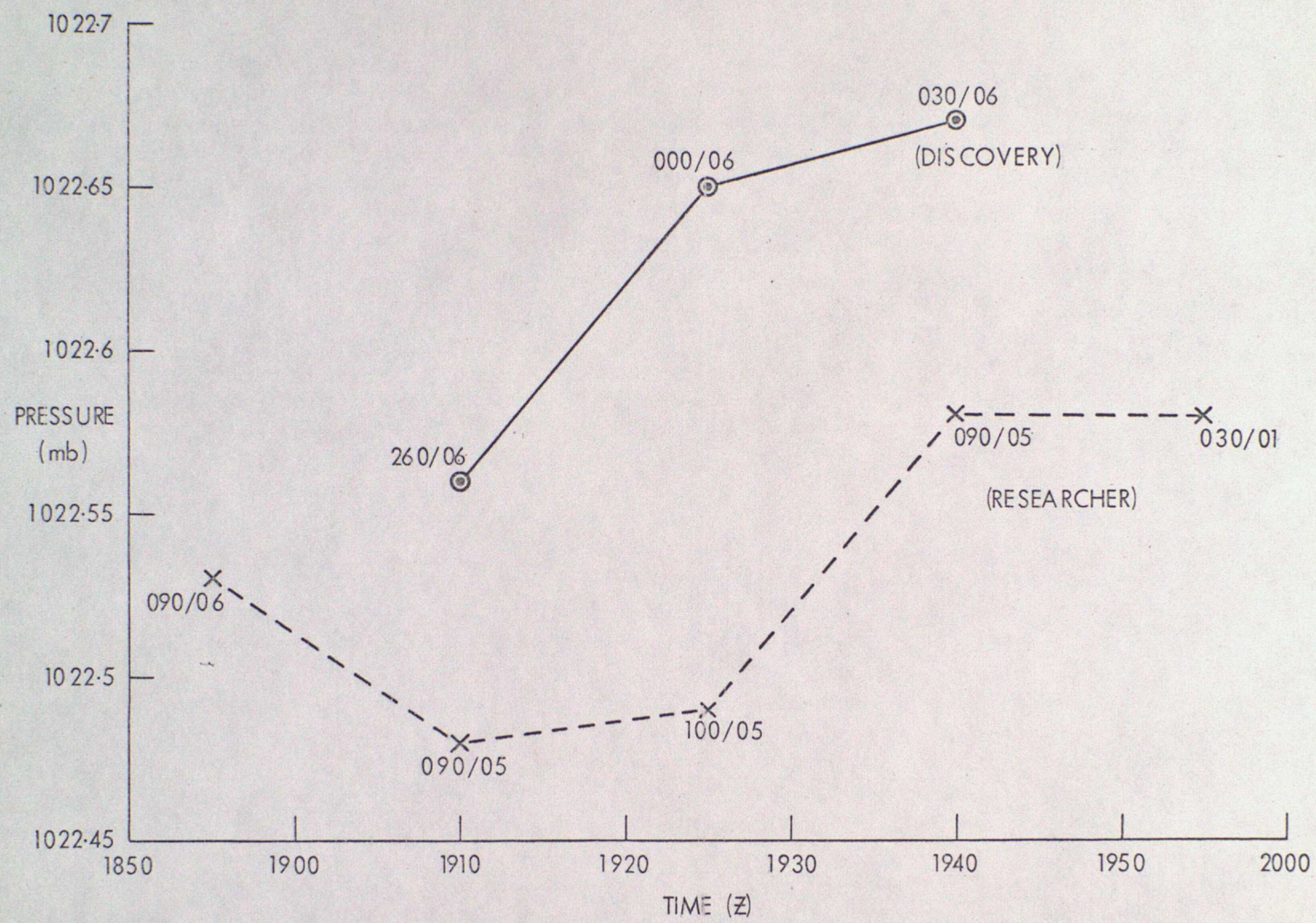

FIGURE 9 DISCOVERY/RESEARCHER COMPARISONS 5/9/72 1855–1955Z

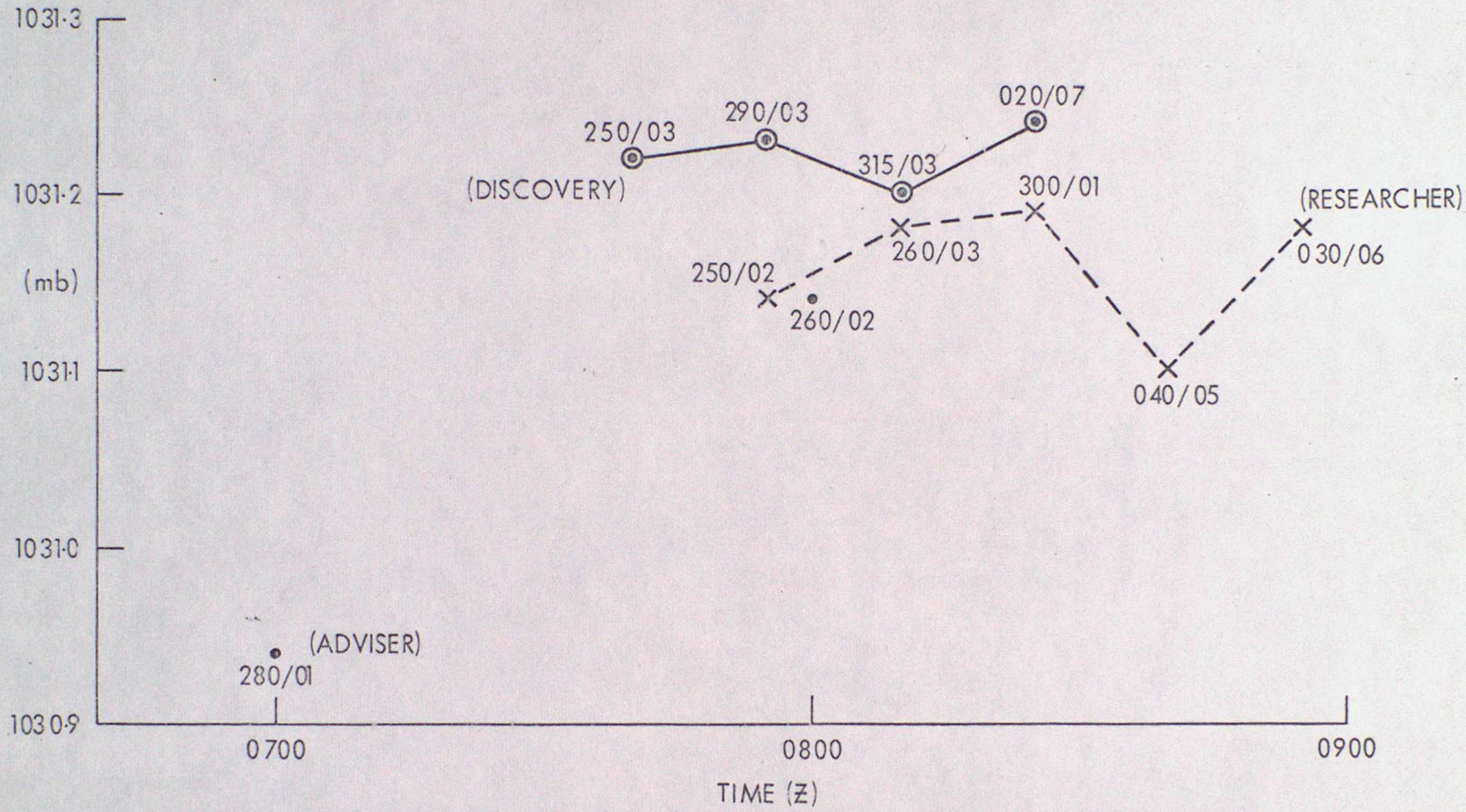

FIGURE 10 3–SHIP COMPARISONS 18/9/72

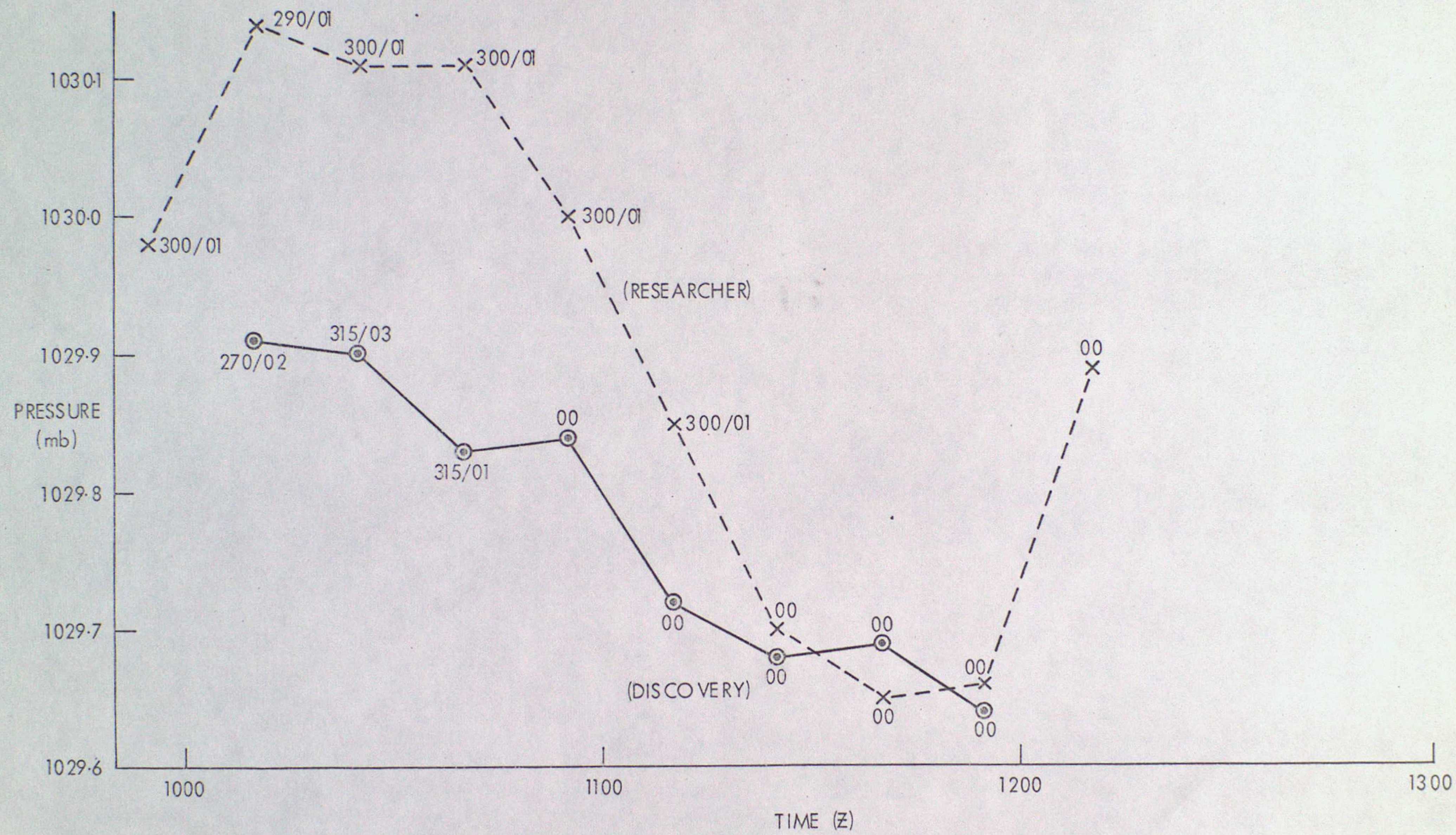

FIGURE 11 DISCOVERY/RESEARCHER COMPARISONS 13/9/72

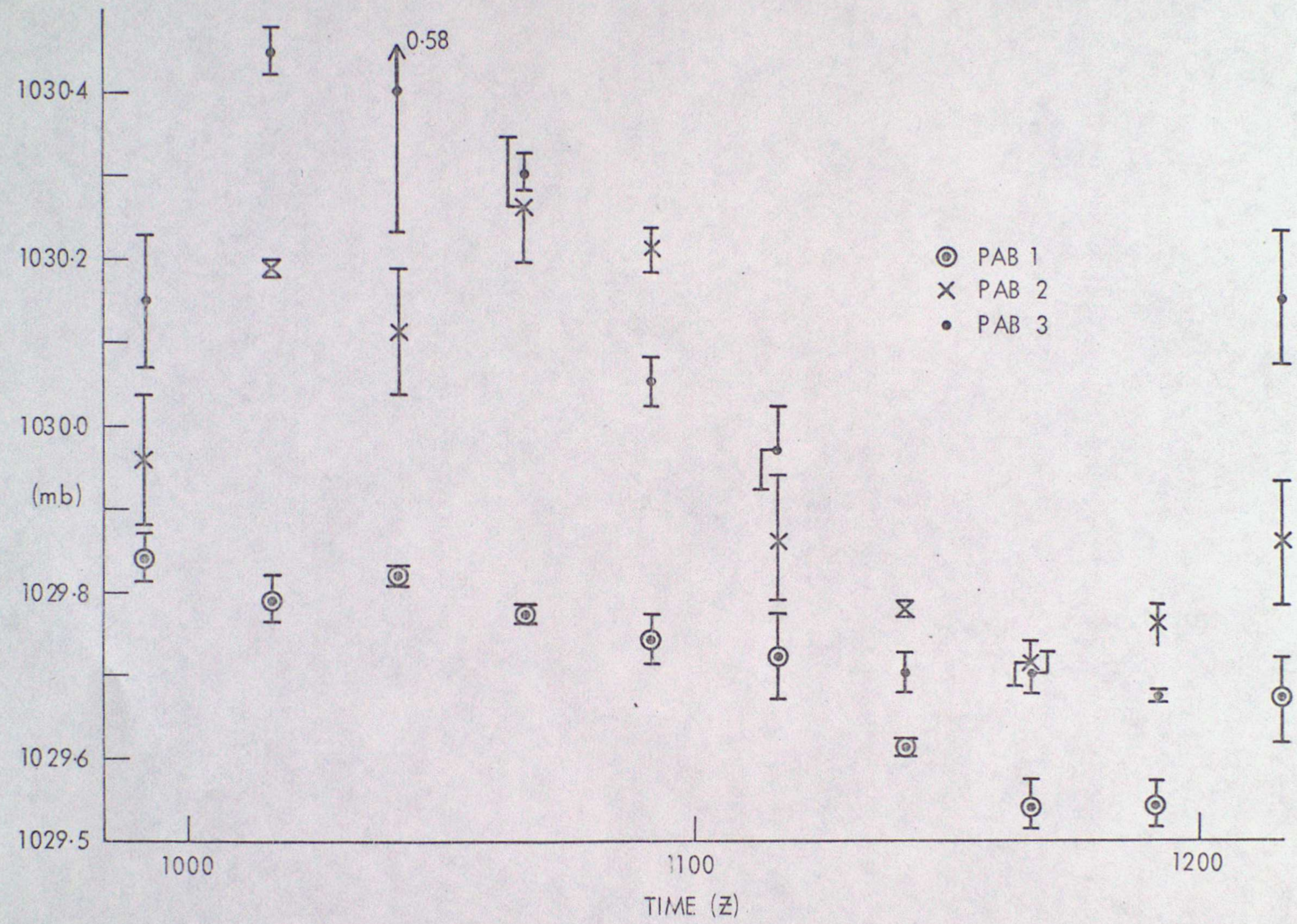

FIGURE 12 RESEARCHER DATA DURING INTERCOMPARISONS ON 13/9/72