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Statistical Survey of Wind Sensor Colocations

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"What is truth?" - Pontius Pilate (John 38:18)

1.0 INTRODUCTION

This report describes the statistical analyses of various wind sensor colocations drawn from radiosonde, aircraft, ASDAR, and satellite data collected since October 1977. Two quantities were primarily used for analysis: the monthly mean wind speed difference (BIAS) between two sensors in a particular type of colocation, and the monthly root mean square vector difference (RMSVE) between these two sensors. Further analyses were made of the BIAS and RMSVE as a function of separation distance (or difference in observation time) between the colocated sensors, altitude of the colocations, and time. A rough comparison among sensors is given, along with a greater in-depth study of colocations involving Japanese satellite data.

For a number of reasons which are given in this report, it might be considered both futile and foolish to make any bold statements about the quality of various sensors, either in an absolute sense or relative to each other. If one sensor were "perfect" (as radiosondes might be considered), it could be used to calibrate the others. As it is, an attempt at meaningful comparison is apt to be drowned in a sea of caveats. Despite these problems, several techniques were used to provide clues that might aid in evaluating these sensors.

2.0 HISTORY AND METHODOLOGY OF DATA COLLECTION

Collection of colocated data began in October 1977 when aircraft and radiosonde reports were gathered and paired after testing for a proximity threshold of 1 hour observation time and within 3 latitude degrees (333 km) of each other. ASDAR-RAOB colocations were tabulated separately as ASDAR data became available. In September 1978, satellite colocations with RAOBS and aircraft were included. There were four satellites: GOES-A, GOES-B, a Japanese geostationary satellite and a European geostationary satellite (hereafter called EURSAT). The European satellite ceased to function in November 1979. In January 1979 the colocation "window" was expanded to 3 hours, 3 degrees. Colocations between observations of the same type sensor began in December 1979.

Data saved on tape consists of the position and altitude (pressure level) of one of the two colocated sensors. Only the differences in temperature, u- and v-wind components, wind speed, and wind vector were stored on tape. Finally, the actual horizontal and temporal separation between the two sensors were recorded, along with a numerical code identifying the type of colocation. In October 1979 the average wind speed of the two colocated sensors was included in the data collection.

RAOB data was interpolated (linearly with respect to log p) to the level reported by the sensor colocated with it. Where two single-level sensors were involved, a vertical proximity of 2000 feet or less was required. The actual vertical separation was not recorded. The standard atmosphere was used to adjust the temperature of one sensor to the level of the other; however, little has been done so far in compiling temperature statistics. Single level reports having climatologically unrealistic temperatures for the reported location were deleted. Temperature differences between two colocated sensors exceeding 25°C were also summarily tossed, as were wind speed differences exceeding 50 m/sec. No other quality control techniques were used.

3.0 OBSTACLES TO SENSOR EVALUATION

The purpose of evaluating a sensor is to determine whether it provides sufficiently accurate data to be useful to analysts and forecasters. A related purpose is to isolate the cause of any problem that exists and correct it if possible. When colocations are used as a means of evaluation, a sensor being tested should be colocated precisely with another sensor that is perfect, so that the BIAS and RMSVE for the test sensor is with respect to the true wind. Since such ideal conditions do not occur, any difference between the two sensors' wind measurements can be due to a variety of causes (table 1) which are difficult to isolate. A simple straight forward evaluation of such colocations would tend to be inconclusive or misleading.

There are a few additional pitfalls inherent in the sampling. The most obvious of these is the large variation of sample size for different types of colocations, ranging from fewer than 30 per month for some aircraft versus satellite colocations to more than 6,000 per month for aircraft versus RAOB. These numbers are for the 3°, 1 hour "window" from which most statistics given in this report are drawn. In some instances opening the window to 3°, 3 hours would have greatly enlarged a pitifully small sample to a statistically reliable size.

Another tricky aspect of sampling is that (for example) 500 pairs of colocations within the 3°, 1 hour window may in fact include 5 pairs within 1° and 1 hour--or 50, or 450. Obviously a set containing 450 pairs within 1° and 1 hour is going to produce better results than a set containing only 5 such pairs. Fortunately, such skewed distributions are rare. Finally, one must consider the distribution of the colocations.

There is little or no overlap in the regions covered by the four satellites in this study. Due to the size of the "window" required to obtain a reasonable sample, wind shear is very much a factor in this study, and one satellite may cover a more strongly sheared region than another. Colocations involving aircraft, RAOBs, and ASDAR may have the same problem, though to a lesser degree.

4.0 ANALYSIS TECHNIQUES USED

Certain analysis techniques were used in attempts to alleviate some of the problems discussed earlier. The basic strategy was to try to isolate some of the variables that are responsible for wind speed differences between colocated sensors, then piece the results together to develop some kind of overall picture. This method appears to have had some limited success. A description of these techniques follow:

4.1 Adjacent gridpoints of an operational wind analysis field were treated as "colocated sensors" and the RMSVE calculated as a function of the separation distance between gridpoints (Fig. 1). The purpose of this technique was to determine the probable overall RMSVE value of a real wind field, i.e., the "meteorological" contribution to wind vector differences between colocated sensors. This value appears to be roughly 5 m/sec, or 25% of the mean wind, for colocations having a horizontal separation of 3° (333 km) and under.

4.2 The BIAS for a sufficiently large number of colocated sensors of the same type (i.e., GOES-A vs GOES-A) should be zero. Non-zero values are random fluctuations the magnitude of which should be in some degree inversely proportional to the sample size. These fluctuations were used to construct an empirically derived set of "confidence limits" for BIAS as a function of sample size. The resulting graph (Fig. 2) should give a pretty good idea of what the significance threshold of BIAS would be for a given set of colocations between different types of sensors. For example suppose that an aircraft-satellite pairing has 80 colocations and a mean speed difference of 2.58 m/sec. The graph indicates that for 80 colocations, a difference of up to 3.4 m/sec can occur by chance; therefore a difference of only 2.58 m/sec is not significant.

4.3 Monthly tabulations of BIAS and RMSVE were obtained from "window boxes" ranging from 1°, 1 hr to 3°, 3 hr (Fig. 3). If the wind vector differences were only meteorological, the RMSVE should increase with increasing window size. What kind of "window box" distribution might we expect? Disregarding the temporal variation, consider Fig. 4, in which we have a wind field with parallel flow and uniform speed shear across the flow (as might be found in a small area on one side of a jet stream). Here V everywhere is zero, du/dx=0, and du/dy=2 m/sec/deg. If every point is "colocated" with the center, the RMSVE varies linearly with the radius of the circle (i.e., the maximum separation), with a value of Y*(du/dy)/2, where Y = R. In this example RMSVE=1 m/sec for 1°, 2 m/sec for 2°, and 3 m/sec for 3°. The technique described in 4.1 and accompanying Fig. 1 suggest that this model is valid for colocations with 3° separation at least in a smoothed wind field. A big fly in the ointment, however, is that there are often not enough colocations in the 1°, 1 hr. "box" to make this technique useful.

4.4 RMSVE and BIAS statistics of colocations between different sensors (see Figs. 5-10 for time series graphs) are the "meat and potatoes" of this study and will readily reveal differences between sensors. However no further conclusion may be revealed with these statistics alone, and even the degree of apparent difference may be modified when viewed against the background of other analyses.

4.5 RMSVE statistics of "same sensor" colocations is a good test of the internal integrity of a system. See Figs. 11 and 12 for time-series graphs. There is no real "BIAS" to bloat the RMSVE values, and a large RMSVE cannot be blamed on "the other sensor". Unfortunately it was not practical to test RAOBS in this manner.

4.6 "Proportional" BIAS and RMSVE values were computed since October 1979. Here the BIAS and RMSVE values were divided by the "observed" wind speed (average of the two sensors). All other factors being equal, wind speed error (BIAS) should increase with wind speed, and RMSVE is increased by strong winds due to the greater significance of small directional differences.

Theoretically, RMS(VE/S) should be more accurate than RMSVE/$\overline{S}$. However, RMSVE/$\overline{S}$ was computed first, and a comparison sample of RMS(VE/S) showed little difference, at least in the relationship between sensors. Hence the RMSVE/$\overline{S}$ data shall be used in the discussion.

4.7 Special techniques used to evaluate colocations involving Japanese satellites will be described later, during discussion of that evaluation and its results.

5.0 RESULTS OF ANALYSES

5.1 BIAS: Figs. 5(a, b, c, d) each show a time series of BIAS values for a satellite vs RAOB, aircraft vs satellite, and aircraft vs RAOB (within the domain of the satellite). The sample sizes are not given here but only the BIAS values of Japanese satellite or European satellite (EURSAT) vs RAOB or aircraft are significant, with a few minor exceptions. EURSAT is now defunct so only limited data is available. An in-depth discussion of the Japanese satellite BIAS will be given in the next chapter.

5.2 RMSVE of sensors vs RAOB: Fig. 6 shows a time series of RMSVE of various sensors vs RAOB. Remember that colocations having a high BIAS will have inflated RMSVE values. Above 500 mb ASDAR appears to have the best agreement with RAOBS, with other aircraft having a parallel RMSVE values about 3 m/sec higher. Japanese satellites show a February maximum as a result of high BIAS values; if the standard deviation were taken instead of RMS, Japanese satellites would probably have the lowest values along with ASDAR. The remaining satellites appear to have net values between those for aircraft and ASDAR. The limited EURSAT data available is for an earlier time period but the mean value of about 14 m/sec is close to the GOES-A and GOES-B values for that period.

Below 500 mb (Fig. 7) aircraft make a relatively poor showing, but the sample size (<20) is too small to be significant. Japanese satellites also have relatively high RMSVE, with the usual winter maximum. ASDAR, GOES-A, and GOES-B are pretty close together.

When the RMSVE is expressed as a percentage of the mean wind, a different pattern appears (Fig. 8). ASDAR is still best above 500 mb but the rest are fairly close together although GOES-A is a little worse. For the Japanese satellite, the winter maximum is replaced by a summer maximum. EURSAT data of this type was available only for October and November 1979. The values of 68 and 71 percent, respectively, were at least 10 points higher than for any other colocation at that time.

Below 500 mb (Fig. 9) ASDAR again wins by a wide margin. Ignoring aircraft (due to the low sample size), we see that the time-series lines run fairly parallel with GOES-A, GOES-B, and Japanese satellites finishing in order after ASDAR. This is not too much different from the non-proportional RMSVE below 500 mb.

It should be noted briefly that RMSVE/S values above 500 mb for satellites versus aircraft (Fig. 10) are very similar to those for satellites versus RAOBs. The number of colocations per month generally ranges from 50 to 400.

Two things should be pointed out in digesting these results. The first is that the results simply imply the degree of agreement with RAOBS which means little unless RAOBS are (or are assumed to be) the best wind measuring systems available. The second relates to the numerical values of RMSVE/$\overline{S}$ which appear to be rather high, especially below 500 mb. Actually they are fairly reasonable. Using Fig. 4 in the example given in 4.3, consider what happens if the wind is calm at the center. This gives the lowest possible mean absolute wind speed and the resulting RMSVE/$\overline{S}$ is 2.00 (i.e. 200%). This is the highest possible value that can be obtained legitimately.

In a region of light winds and small scale features such as the tops of subtropical ocean stratus decks measured by satellites, these conditions may be approached. Because of the way $\overline{S}$ is computed, using wind measured by both sensors, the value of $\overline{S}$ computed from Fig. 4 would be halfway between the actual mean wind if the u component were uniformly positive or negative. If $\overline{S}$ in the example is 6 m/sec RMSVE/$\overline{S}$ at 3° is 0.50 (50%). This is close to the medium value for the graph of 3° colocations above 500 mb, but there $\overline{S}$ ranges from 20 to 40 m/sec, so the mean horizontal shear would have to be from 10 to 20 m/sec over a distance of 333 km. (3° latitude). This does not seem to be unreasonable, and any remaining error (attributed to the sensors) should be tolerable. Unfortunately, the 50% value also shows up in 1° colocations; a shear of 10 to 20 m/sec over only 111 km seems rather large.

5.3 RMSVE of sensors colocated with other sensors of the same type: This type of colocation has the advantage of eliminating the effects of BIAS and the question of which of the two sensors is responsible for high RMS values. Other factors remain of course, but a direct comparison between sensors is more meaningful than those with RAOB as a common partner.

Since only Japanese satellites have a respectable number of colocations below 500 mb, no graph will be presented for that level. Above 500 mb (Fig. 11) aircraft are far worse than the others, which are nearly equal. ASDAR colocations are rather few (dying out completely at the end), accounting for the jumpiness of RMSVE values.

For RMSVE/$\overline{S}$ (Fig. 12), the sensors are nearly equal in winter. In summer aircraft is worse, ASDAR is better, and the three satellites are nearly equal half way in between. ASDAR values near the end should be taken with a large block of salt since there are fewer than 10 colocations per month.

It is interesting to note that the RMSVE values for these colocations are significantly lower than corresponding values for any sensor vs RAOB, despite the fact that these are single level sensors and cannot be interpolated to each other. Also, the RMSVE/$\overline{S}$ values for satellite vs. aircraft colocations are higher than for aircraft vs aircraft or satellite vs satellite. This pattern suggests the possibility of some intrinsic differences between sensors but there may be other factors involved which are more difficult to identify or isolate. One possibility is that vertical separation distances are smaller for same sensor colocations.

5.4 "Window box" patterns - It was mentioned earlier that the contribution of horizontal wind shear to the RMSVE of colocated sensors should vary directly with the distance of maximum allowable separation. For example, if the RMSVE for 1° colocations is 6 m/sec, the RMSVE for 2° colocations should be 12 m/sec, and for 3° colocations it should be 18 m/sec. This relationship assumes the absence of significant small scale features in the wind field.

A casual view of observed patterns shows that such a relationship almost never occurs. In many cases, there are not enough colocations to establish a meaningful pattern. The following discussion is therefore confined to the most common colocations such as aircraft-RAOB, aircraft-aircraft, and Japanese satellite vs RAOBS or other Japanese satellites. Sample RMSVE values given in Table 2 are 6 month averages over the last half of 1980 for 1 hr colocations above 500 mb.

The ratio of RMSVE (3°) to RMSVE (1°) should be about 3:1. The actual ratio ranges from 1:1 to 3:2. Same sensor colocations have better (higher) ratios than RAOB colocations. ASDARS are better than aircraft or satellites; the latter two are virtually equal. The RMS values for 2° colocations are more or less midway between the values for 1° and 3° colocations.

Small scale features in the wind field sensors may be a significant cause of such a large difference between theoretical and actual ratios. Uncertainty of actual horizontal positions of the sensors could also be responsible for these results, as well as temporal variations (1 hour can be equivalent to 1/2 degree latitude). In the case of ASDAR vs ASDAR, positions are supposed to be pretty precise; however, the temporal window was 3 hours. For the 1 hour window, a casual glance at ASDAR vs ASDAR suggests a ratio that may be as good as 2:1. Finally, the importance of vertical wind shear cannot be discounted; its contribution to the RMSVE may range from 4 to 10 m/sec. This appears to be a very large fraction of the values given in Table 2, and perhaps actual vertical separations between single level sensors are significantly less than for the samples described below.

5.5 A special "colocation" was made of the two adjacent radiosonde sounding levels immediately above and below the level of a colocated sensor. This would determine the contribution of vertical wind shear to the overall RMSVE, particularly for two single-level sensors. Since the horizontal and temporal separation is virtually zero and instrument characteristics are not a factor, almost all of the RMSVE is due to vertical wind shear. The results here were poor because adjacent radiosonde levels were seldom within 2000' of each other (the limit of vertical separation for single level sensors). Unfortunately, the actual vertical separation was not recorded. The low number of usable reports caused considerable jumpiness in the statistics, but the average RMSVE appears to be about 7 m/sec, and RMSVE/$\overline{S}$ averages about 20%.

6.0 JAPANESE SATELLITES: AN IN-DEPTH STUDY

6.1 Introduction: Fig. 5c showed a very interesting pattern of BIAS above 500 mb involving Japanese satellites, aircraft, and RAOBS. A very large seasonal fluctuation indicated that Japanese satellite winds were considerably slower than aircraft or RAOB winds during the northern hemisphere winter, while aircraft vs. RAOB colocations in the region covered by Japanese satellites showed little BIAS (aircraft winds tend to be slightly faster than RAOB winds in winter).

These winter winds were quite strong, particularly in satellite-aircraft colocations, but even the normalized value (BIAS/$\overline{S}$) was very high. Two explanations for this phenomenon are possible: 1) Japanese satellite cloud top altitudes are biased (in regions of strong vertical shear), or 2) gravity wave phenomena in the cloud tops mask the true wind speed. The regularity, magnitude, and persistence of the BIAS pattern seems to favor the first explanation as the primary cause.

Robert Hirano (unpublished report, 1981) has been working with limited cases in applying a "level of best fit" technique, in which he found that satellite cloud top measurements tend to average about 2 km too high. Frederick R. Mosher described cloud height assignment techniques, admitting that these height assignments were probably the largest source of error in cloud-tracked winds (p. 58, Systems & Techniques for Synoptic Wind Finding, Atmospheric Technology, Number 10, winter 1978-79, NCAR). This chapter describes some other ways of investigating the problem.

6.2 Data: A check of actual distribution of Japanese satellite-RAOB colocations revealed that many of them are concentrated over mainland China, particularly during the northern hemisphere winter when two-thirds of all the colocations are located there. A listing of RAOB-Japanese satellite BIAS for each 10° longitude-latitude "square" revealed large positive values (satellite winds slower) in the mid-latitude southern hemisphere winter. Finally, a time-series map of wind speed (average of Japanese satellite and RAOB) vs BIAS for the northern hemisphere was constructed (Fig. 13). This map covers all colocations (3°, 3 hr) at all levels.

Japanese winds are slowest with respect to RAOBS in regions of strong winds during the winter. They are nearly equal to radiosonde winds during the summer, regardless of wind speed, and are often somewhat faster. It is quite apparent that the strength of wind shear with height, rather than absolute wind speed, is the key factor in the Japanese satellite BIAS. A strong jet stream with strong vertical wind shear is usually present over mainland China in winter. Mosher (ibid) indicated that the emissivity of thin cirrus layers (such as found with a jet stream) is considerably less than unity, causing problems with height assignments.

In dense cirrus, such as are found with convective and tropical systems during the summer, emissivity is close to unity, permitting fairly accurate height assignments.

The uncorrected emmissivity of thin cirrus, making the cloud appear warmer than it is, would result in a cloud height assignment that is too low. However, Hirano indicated in his report that most often these assignments were too high. If this is true, the problem appears to be one of over correction.

An attempt was made to provide a profile of BIAS vs height; this proved unsatisfactory because most colocations were clustered in several narrow zones with no real continuity. Another attempt was made to correlate individual wind speed differences with actual vertical wind shear (Fig. 14). Since actual heights were not always available, wind shear had to be with respect to pressure. This problem was alleviated somewhat by plotting results for a single layer 50 mb thick. Horizontal wind shear also muddied the picture; the failure of Fig. 14 to show any correlation between wind speed differences and vertical wind shear could easily be attributed to these two factors. This was one of those tests where a definite correlation (in face of the obstacles) would have been significant but lack of a correlation would not.

6.3 <u>Conclusion and remarks</u>: There is evidence that cloud top height measurement errors are largely responsible for slow Japanese satellite winds; this evidence is strong but largely circumstantial. A single BIAS vs wind speed profile indicated that GOES-A and GOES-B exhibit the same behavior as the Japanese satellite, but there are too few colocations for an in-depth study. More uniform distribution of GOES colocations apparently prevented any marked BIAS pattern from showing up on the time series graph. An interesting footnote is that aircraft vs RAOB colocations, used as a control in BIAS vs height profiles, indicated that aircraft winds tend to be up to 6 m/sec faster than radiosonde winds in the region covered by Japanese satellites during the winter when winds were about 60 m/sec. Otherwise aircraft winds were little affected by wind speed or season.

7.0 SUMMARY AND CONCLUSIONS

7.1 The "window box" theory and the graph shown in Fig. 1 predict that RMSVE of colocated sensors varies directly with separation distance between them as long as that distance is significantly smaller than the scale of wind patterns.

7.2 Observed "window box" patterns rarely even approach theoretical patterns. There are five possible causes:

a) For single level colocations, vertical wind shear alone can cause an RMS of about 7 m/sec (above 500 mb) thus putting a lower limit on observed RMS values.

b) For satellite colocations with RAOB, apparent height misalignment combined with vertical wind shear can produce the same results described above.

c) Smaller scale wind features may be present often enough to influence the pattern. These may be more prevalent at lower altitudes.

d) Uncertainty of position (and horizontal separation) of sensors.

e) Temporal separation may have a small effect.

7.3 Observed RMSVE/$\overline{S}$ values appear to be reasonable for most 3° colocations, considering the amount of horizontal wind shear implied by actual winds and "window box" theory.

7.4 No direct evidence is available for judging the quality of radiosondes with respect to other sensors. There is some indirect evidence to indicate that radiosondes may be no better and no worse than the others: RMSVE/$\overline{S}$ values for aircraft vs. satellite colocations are approximately the same as the values for colocations involving radiosondes.

7.5 In colocations above 500 mb involving radiosondes, ASDARS have the lowest RMSVE, Japanese satellites the highest, and the rest pretty much in between. When RMSVE/$\overline{S}$ is used, ASDAR continues to have the lower values. Below 500 mb, ASDAR has the lowest values for either RMSVE or RMSVE/S, followed by the three satellites. Aircraft samples are too small to be significant.

7.6 In "same sensor" colocations above 500 mb, aircraft have significantly higher RMSVE and the rest are about the same. RMSVE/$\overline{S}$ values of "same sensor" colocations are probably the best indicators available of the relative quality of various sensors. These indicators show that there is little difference in winter while in summer ASDARS have lower values, aircraft have higher values, and the satellites are in between. Comparison below 500 mb is not possible due to lack of data.

7.7 In the limited data available, European satellites are rather poor with respect to the other sensors, particularly as measured by RMSVE/S.

7.8 Japanese satellite winds are much slower than aircraft or radiosonde winds in the northern hemisphere winter, particularly when winds are strong. In summer this BIAS is nearly independent of the wind speed and differences are small; satellite winds may be slightly faster than radiosonde winds. Most Japanese satellite colocations are over mainland China, suggesting that a combination of erroneous cloud top measurements and strong wind shear in a jet stream is responsible for the phenomenon.

Other attempts to verify this relationship have proved to be inconclusive but support can be found in work by other investigators. Wind speed vs BIAS profiles suggest that GOES-A and GOES-B behave in a similar manner but is less obvious because of the greater dispersion of colocations (fewer occuring in jet stream areas).

7.9 In a nutshell the following statements can be made about colocations (liberally prefixed by the words probably, perhaps, and maybe):

a) A certain consistency of results suggest that ASDARS are best, GOES-A and GOES-B are close behind, followed by aircraft. The limited EURSAT data indicates rather poor quality. The Japanese satellite reports did poorly because of the BIAS problem, but they would rival ASDAR if this problem were corrected

b) There is a faint hint that radiosondes may be in the same general category as the others sensors with respect to the quality of wind reports.

c) The ratio between the best and the worst sensors appears to be about 3:2. This ratio would exceed 2:1 if the wind shear effects were subtracted out. These wind shear effects appear to be about the same magnitude as apparent differences between sensors.

d) Satellites seem to have a problem with cloud-top (wind level) assignments. If this problem were rectified, satellites could be the best sensors available.

e) All sensors, with the possible exception of EURSAT, appear to be adequate. Japanese satellite data should be useable with even a rough empirical correction for BIAS (see fig. 13).

TABLE 1

POSSIBLE SOURCES OF DIFFERENCES BETWEEN WIND MEASUREMENTS BY VARIOUS COLOCATED SENSORS

A. Real (Meteorological) Differences

1. Horizontal Shear
2. Vertical Shear
3. Temporal Variation (Intrinsic & Advective)

B. Position Errors + Meteorological Differences

1. Horizontal Position Error by One or Both Sensors
2. Vertical Position Error by One or Both Sensors
3. Temporal Error (obs time) of One or Both Sensors

C. Scaling Errors

1. Excess Resolution + Small Scale Activity (thunderstorms, etc.)
2. Insufficient Resolution of One Sensor in Jet Stream

D. Instrument errors

1. Bias by One or Both Sensors
2. Calibration Problems - One or Both Sensors
3. Intrinsic RMS in Instrument Response (Accuracy)
4. Triangulation Errors (RAOB)

E. "Transmission" Errors (time, position, or wind vectors)

TABLE 2

RMSVE VALUES AS A FUNCTION OF SEPARATION DISTANCE

July-Dec 1980 Average for 1 Hr Colocations Above 500 mb

Colocation	Separation	RMSVE (m/sec)	Number (per month)
Aircraft vs RAOB	1°	12.9	1000
	2°	13.3	
	3°	14.2	
ASDAR vs RAOB	1°	7.2	100-300
	2°	8.4	
	3°	10.1	
Aircraft vs Aircraft	1°	10.5	>10000
	2°	11.8	
	3°	13.3	
ASDAR vs ASDAR	1°	5.1	100 (3 hrs)
	2°	6.2	
	3°	7.8	
Japanese Sat. vs Japanese Sat.	1°	6.0	3000
	2°	6.9	
	3°	7.8	

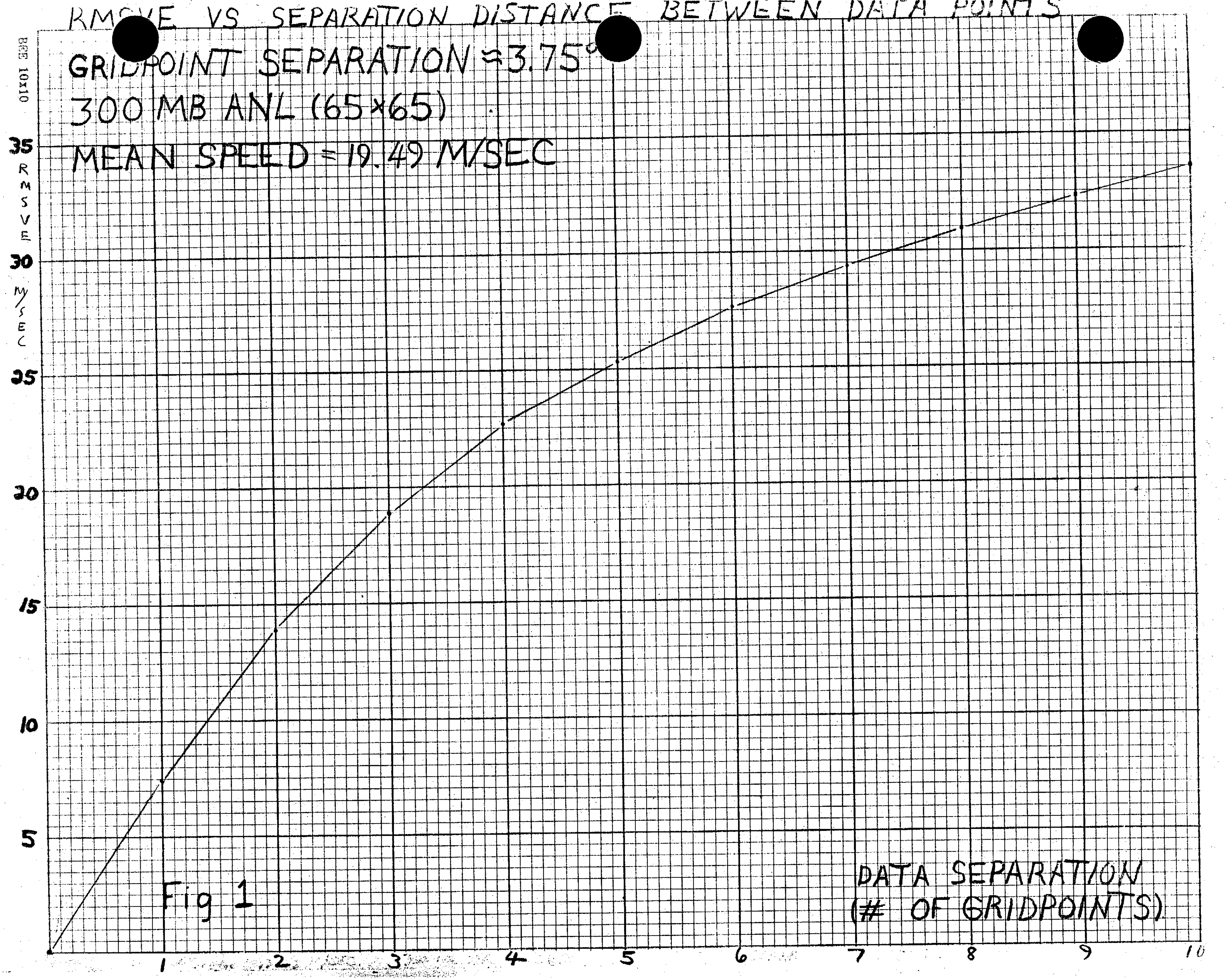

RMSVE VS SEPARATION DISTANCE BETWEEN DATA POINTS
GRIDPOINT SEPARATION ≈ 3.75°
300 MB ANL (65×65)
MEAN SPEED = 19.49 M/SEC
RMSVE M/SEC
35
30
25
20
15
10
5
DATA SEPARATION
(# OF GRIDPOINTS)
1
2
3
4
5
6
7
8
9
10

Fig 1

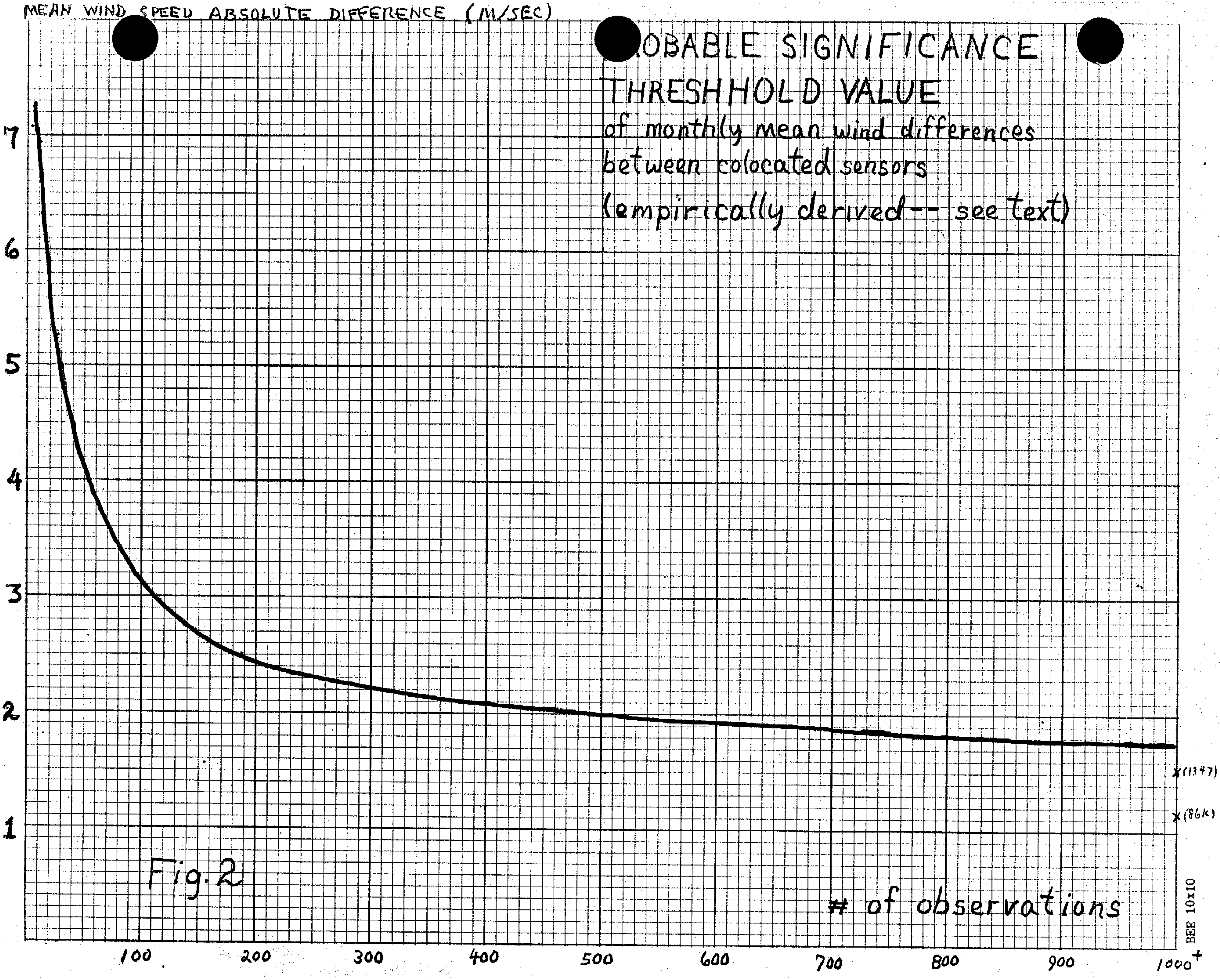

MEAN WIND SPEED ABSOLUTE DIFFERENCE (M/SEC)
PROBABLE SIGNIFICANCE
THRESHHOLD VALUE
of monthly mean wind differences
between colocated sensors
(empirically derived -- see text)
7
6
5
4
3
2
1
x (1347)
x (86K)
# of observations
100
200
300
400
500
600
700
800
900
1000+

Fig. 2

**** PROGRAM FREQ2 (C. VLCEK, 5 NOV. 1979): SUMMARY OF STATISTIC FROM 81040000 TO 81050000 ****

0-9 ABOVE 500 MB

NUMBER OF COLOCATIONS OF EACH TYPE WITHIN THE INDICATED SPACE-TIME WINDOW LISTED BELOW

DEG	HR	0	1	2	3	4	5	6	7	8	9
1	1	696	89	0	20	299	4	22	26	0	0
1	2	1405	160	43	26	300	10	39	43	0	0
1	3	2254	268	44	26	300	21	52	76	0	0
2	1	2261	289	3	76	1269	25	70	80	0	0
2	2	4822	566	218	116	1287	53	153	143	0	0
2	3	7483	924	219	116	1287	92	203	259	0	0
3	1	5448	549	5	159	2914	45	163	160	0	0
3	2	11659	1086	533	269	2952	111	25	301	0	0
3	3	18702	18 8	538	269	2952	196	445	511	0	0

0 = AIRCRAFT VS RAOB
1 = ASDAR VS RAOB
2 = GOES-A VS RAOB
3 = GOES-B VS RAOB
4 = J-SAT VS RAOB
5 = GOES-A VS AIRCRAFT
6 = GOES-B VS AIRCRAFT
7 = J-SAT VS AIRCRAFT

MEAN SPEED ERROR STATISTICS FOR EACH TYPE OF COLOCATION WITHIN THE INDICATED SPACE-TIME WINDOW LISTED BELOW

DEG	HR	0	1	2	3	4	5	6	7	8	9
1	1	0.97	0.82	0.0	2.42	-4.70	-0.90	-1.99	2.38	0.0	0.0
1	2	1.07	0.83	1.78	2.90	-4.73	1.33	-1.45	4.70	0.0	0.0
1	3	0.99	1.06	1.99	2.90	-4.73	3.60	-1.37	5.31	0.0	0.0
2	1	0.54	0.84	3.10	0.76	-4.93	0.59	-0.03	4.67	0.0	0.0
2	2	0.79	0.52	1.47	1.11	-4.88	-1.35	1.03	6.36	0.0	0.0
2	3	0.68	0.86	1.51	1.11	-4.88	-0.35	1.19	6.44	0.0	0.0
3	1	0.20	0.40	4.22	0.81	-4.93	-0.55	-0.44	6.76	0.0	0.0
3	2	0.36	0.43	0.94	1.10	-4.91	-1.50	0.48	7.22	0.0	0.0
3	3	0.35	0.74	0.97	1.10	-4.91	-0.78	0.81	6.58	0.0	0.0

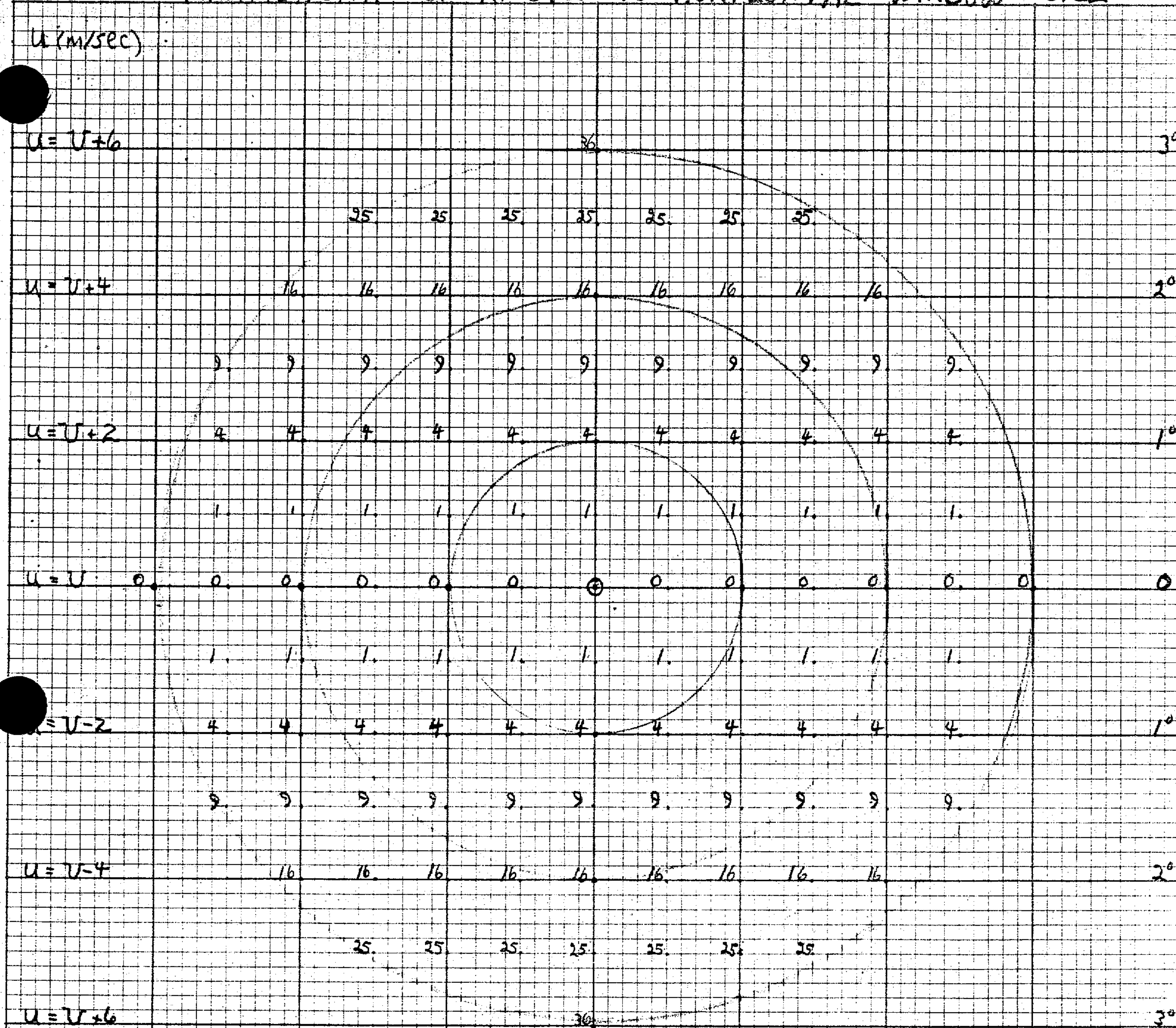
RMSVE STATISTICS FOR EACH TYPE OF COLOCATION WITHIN THE INDICATED SPACE-TIME WINDOW LISTED BELOW

DEG	HR	0	1	2	3	4	5	6	7	8	9
1	1	11.99	6.47	0.0	12.97	14.47	7.09	15.40	12.45	0.0	0.0
1	2	12.10	6.46	11.85	12.70	14.47	11.50	12.75	13.94	0.0	0.0
1	3	12.29	6.75	11.83	12.70	14.47	14.53	12.27	14.95	0.0	0.0
2	1	12.20	9.74	16.63	11.65	15.01	13.47	14.64	15.26	0.0	0.0
2	2	12.47	8.88	11.80	11.94	14.98	12.21	14.14	16.00	0.0	0.0
2	3	12.60	8.74	11.79	11.94	14.98	13.55	15.07	15.68	0.0	0.0
3	1	13.39	11.04	13.71	12.13	15.65	12.91	15.27	17.60	0.0	0.0
3	2	13.49	10.41	12.75	12.51	15.61	13.20	14.93	18.03	0.0	0.0
3	3	13.66	10.44	12.84	12.51	15.61	15.13	15.81	17.07	0.0	0.0

FIG. 3

DEG IS MAX HORIZONTAL SEPARATION IN WHOLE DEGREES LATITUDE AND HR IS MAX TIME SEPARATION IN WHOLE HOURS

RELATIONSHIP OF RMSVE TO HORIZONTAL "WINDOW" SIZE



number plotted is $(u-u_c)^2$, where u_c is u at center
v and $v-v_c$ are zero everywhere
$du/dx = 0$; du/dy = constant

$$RMSVE = \left[\left(\Sigma(u-u_c)^2\right) / N-1\right]^{1/2}$$

= 1 m/sec for 1° circle
= 2 m/sec for 2° circle
= 3 m/sec for 3° circle

Fig 4

BEE 10x10

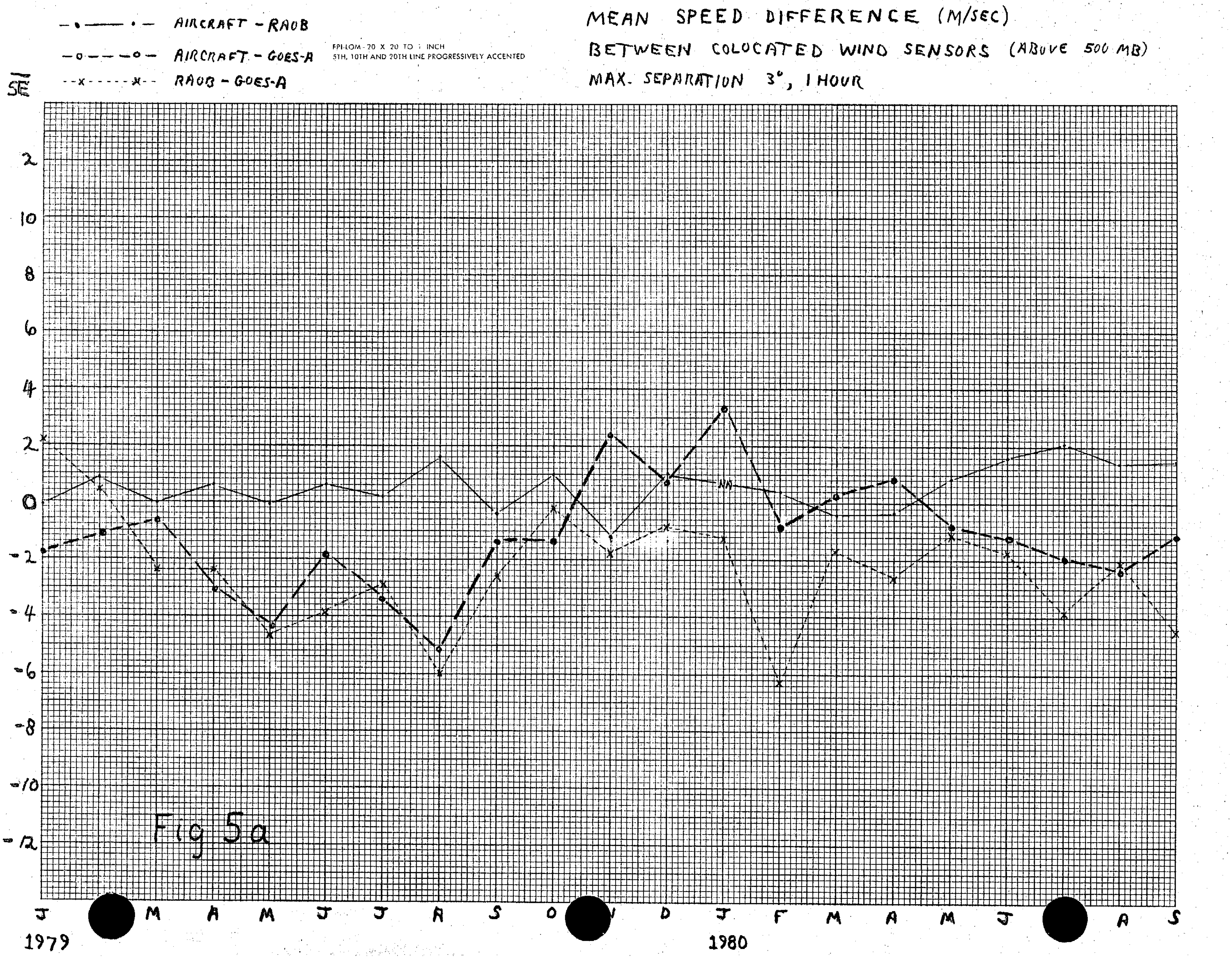
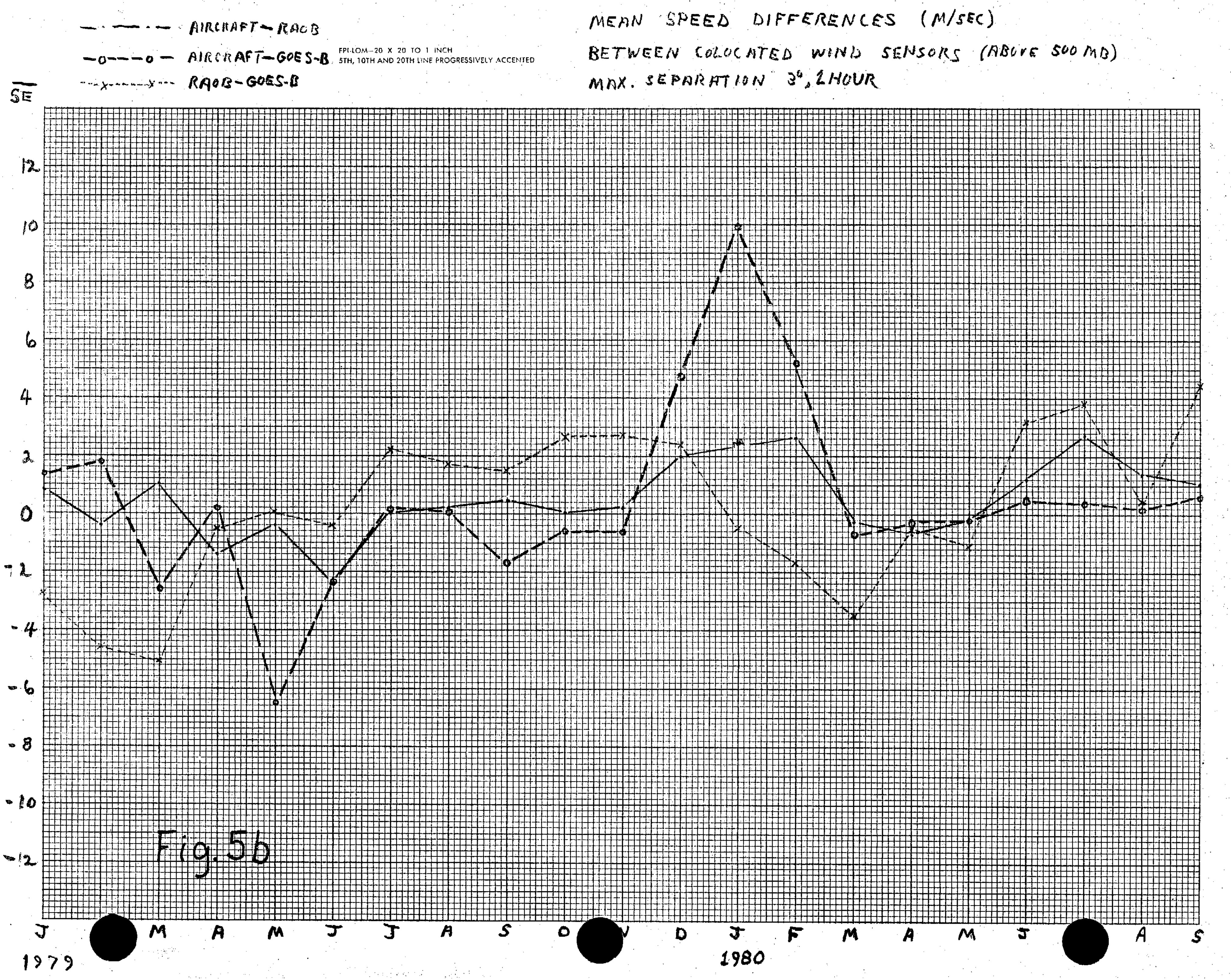

AIRCRAFT - RAOB
AIRCRAFT - GOES-A
RAOB - GOES-A
FPI-LOM - 20 X 20 TO 1 INCH
5TH, 10TH AND 20TH LINE PROGRESSIVELY ACCENTED
MEAN SPEED DIFFERENCE (M/SEC)
BETWEEN COLOCATED WIND SENSORS (ABOVE 500 MB)
MAX. SEPARATION 3°, 1 HOUR
SE
2
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
J
M
A
M
J
J
A
S
O
D
J
F
M
A
M
J
A
S
1979
1980

Fig 5a



AIRCRAFT – RAOB
AIRCRAFT – GOES-B
RAOB – GOES-B
FPI-LOM–20 X 20 TO 1 INCH
5TH, 10TH AND 20TH LINE PROGRESSIVELY ACCENTED
MEAN SPEED DIFFERENCES (M/SEC)
BETWEEN COLOCATED WIND SENSORS (ABOVE 500 MB)
MAX. SEPARATION 3°, 2 HOUR
$\overline{SE}$
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
J M A M J J A S O N D J F M A M J A S
1979
1980

Fig. 5b

MEAN SPEED DIFFERENCES (M/SEC)
BETWEEN COLOCATED WIND SENSORS (ABOVE 500 MB)
MAX. SEPARATION 3°, 1 HOUR

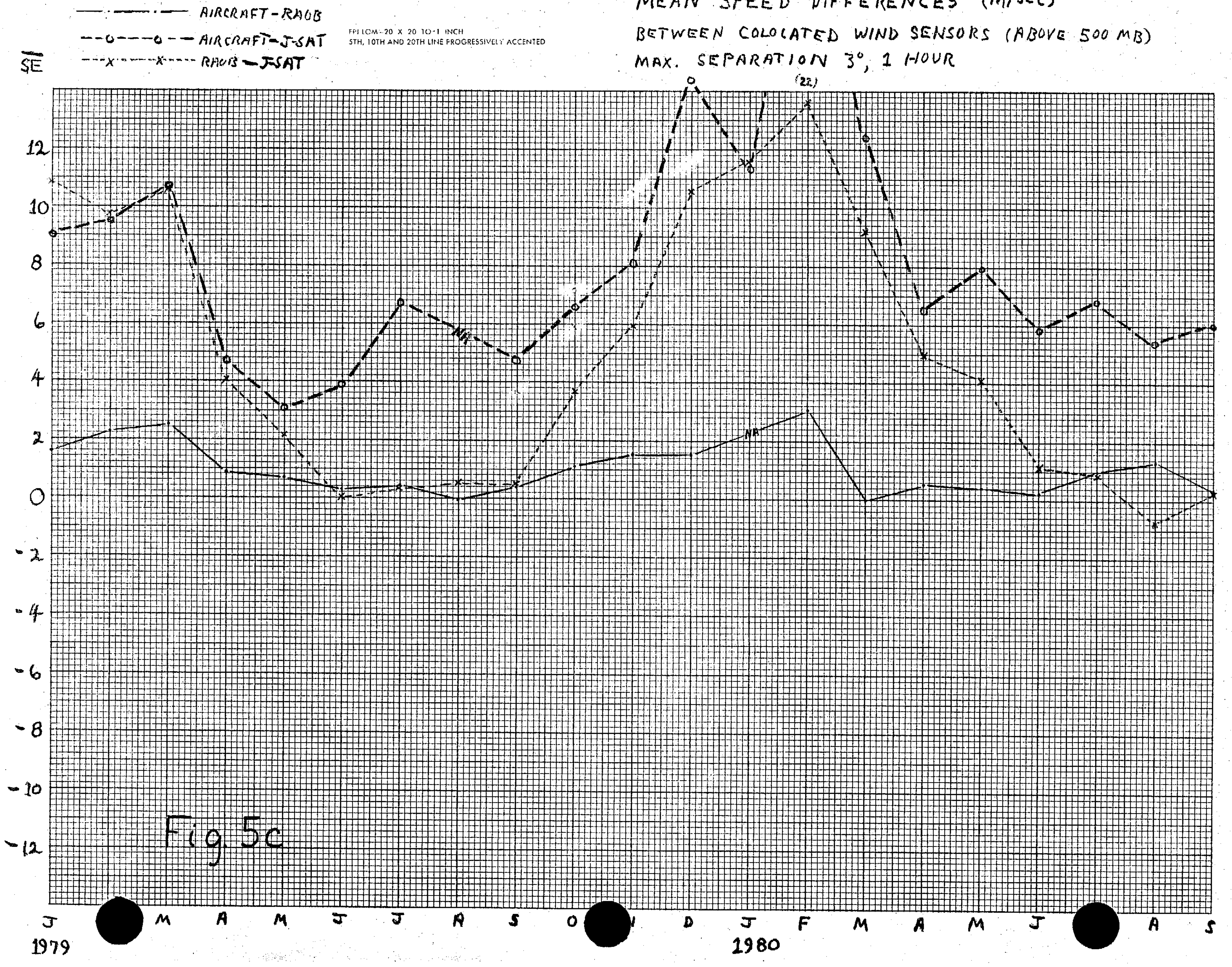


Fig. 5c

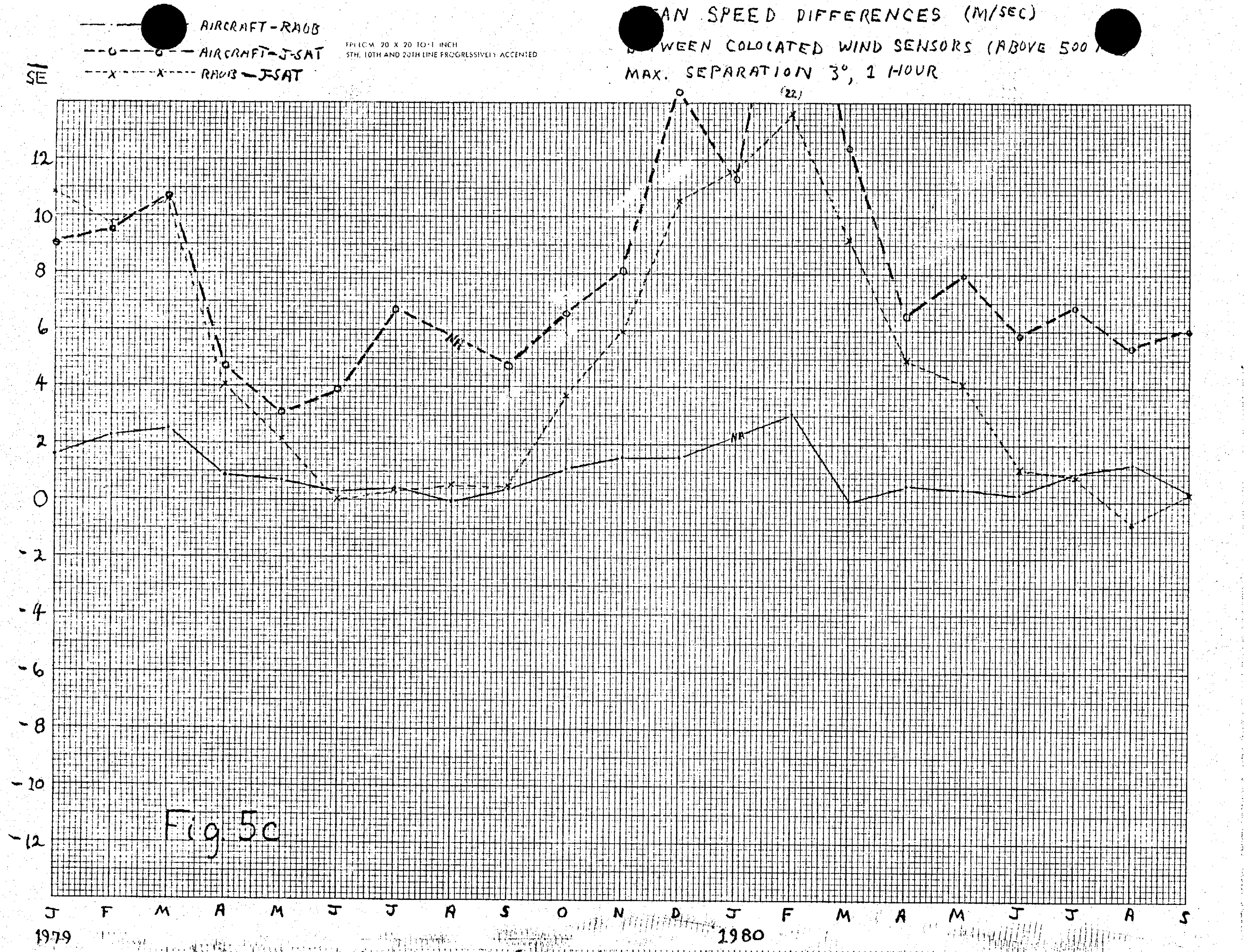

AN SPEED DIFFERENCES (M/SEC)
WEEN COLOCATED WIND SENSORS (ABOVE 500
MAX. SEPARATION 3°, 1 HOUR
AIRCRAFT-RAOB
AIRCRAFT-J-SAT
RAOB-J-SAT
$\overline{SE}$
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
(22)
NR
J F M A M J J A S O N D J F M A M J J A S
1979
1980

Fig. 5c

MEAN SPEED DIFFERENCE (M/SEC) ABOVE 500 MB
MAX. SEPARATION 3°, 1 HOUR

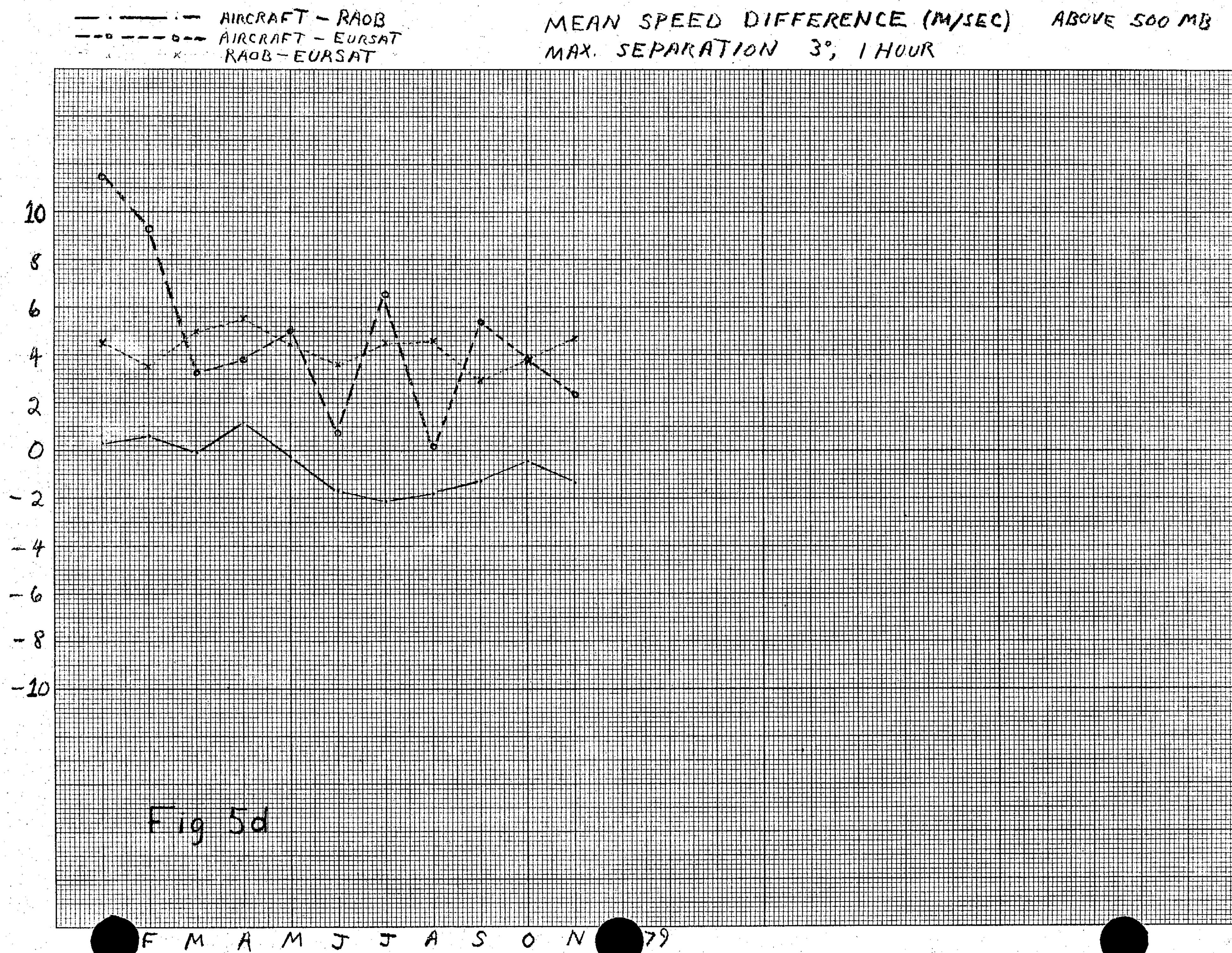


Fig 5d

RMSVE (M/SEC) of WIND SENSORS COLOCATED WITH RAOB ABOVE 500 MB (≤3°, ≤1 HOUR SEPARATION)

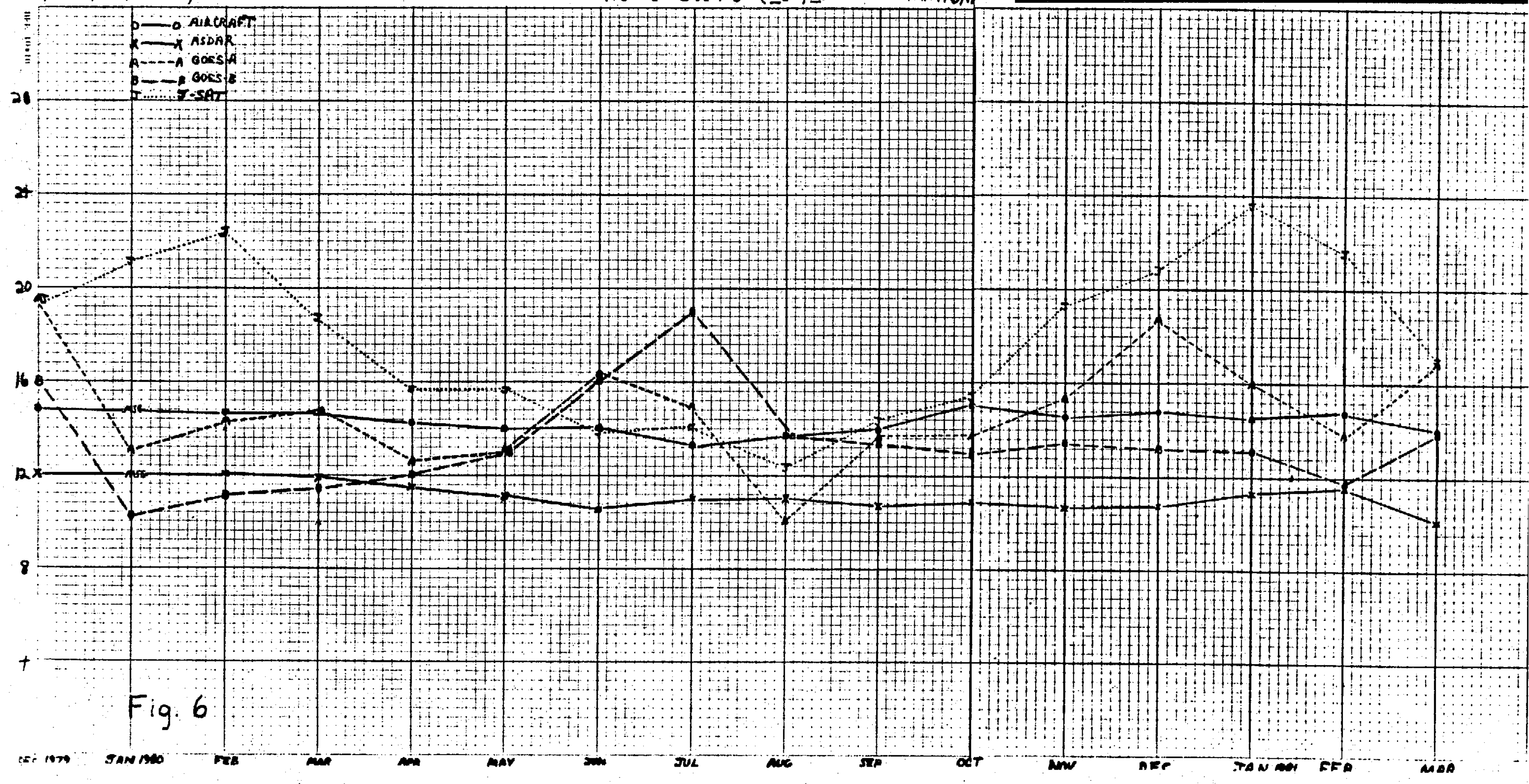


Fig. 6

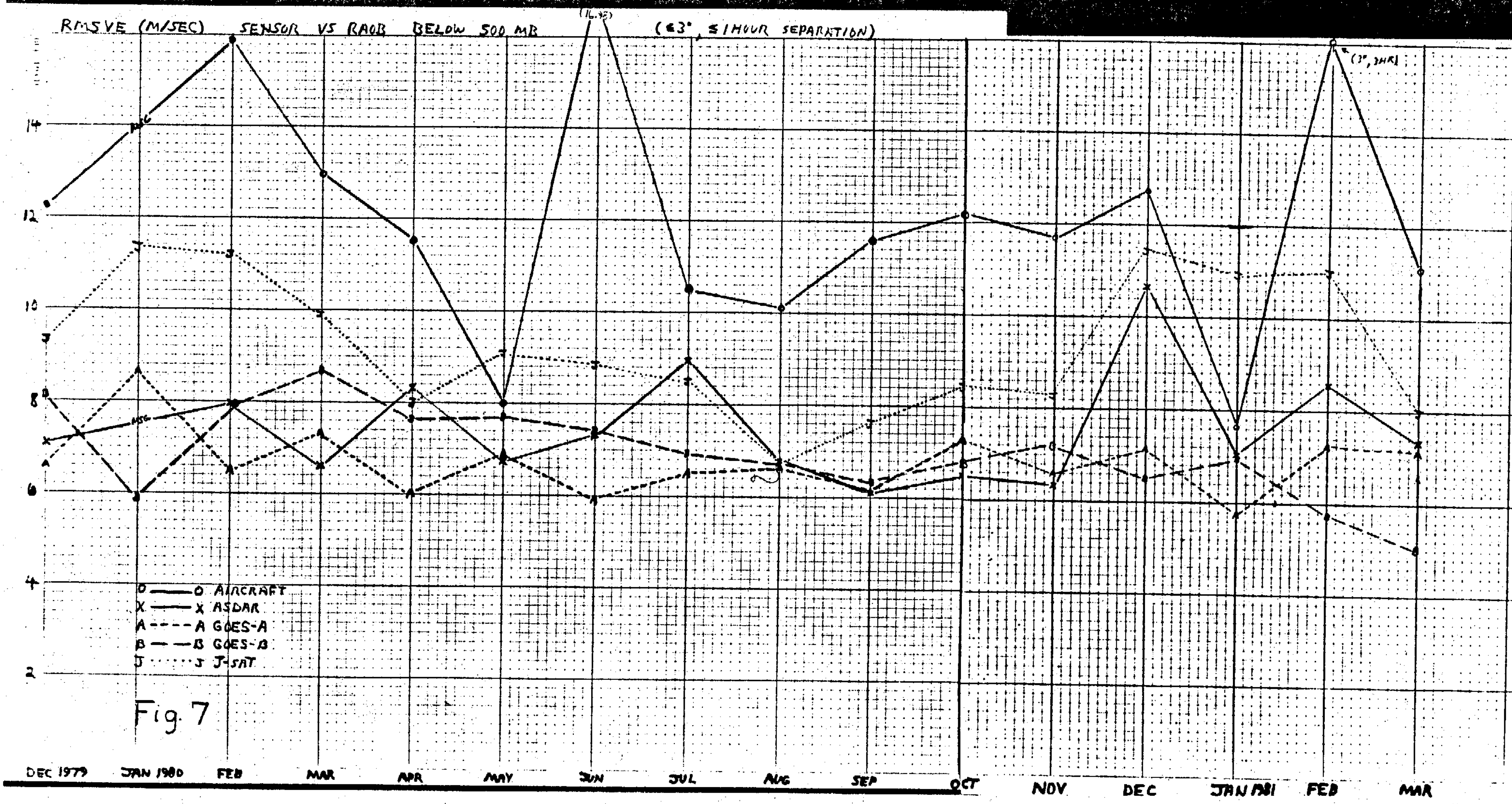

RMSVE (M/SEC) SENSOR VS RAOB BELOW 500 MB (≤3°, ≤1 HOUR SEPARATION)
(16.45)
(3°, 3HR)
14
12
10
8
6
4
2
O —— O AIRCRAFT
X —— X ASDAR
A - - - A GOES-A
B — — B GOES-B
J ····· J J-SAT
DEC 1979
JAN 1980
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN 1981
FEB
MAR

Fig. 7

RMSVE/$\bar{V}$ (%) SENSOR VS. RAOB ABOVE 500 MB (≤3°, ≤1 HOUR SEPARATION)

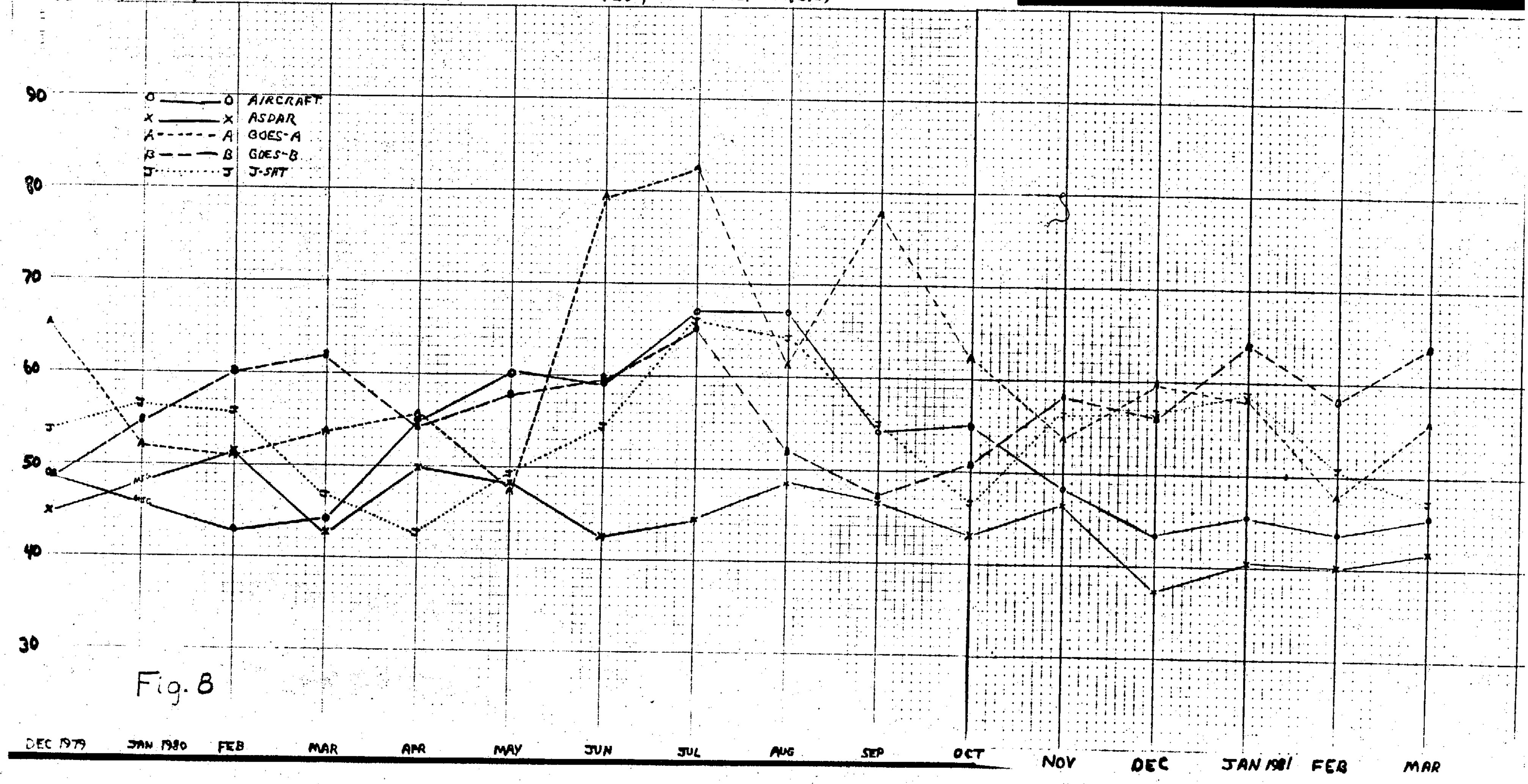


Fig. 8

[redacted]

RMSVE/S̄ (%) SENSOR VS RAOB BELOW 500 MB (≤ 3°, ≤ 1 HOUR SEPARATION)

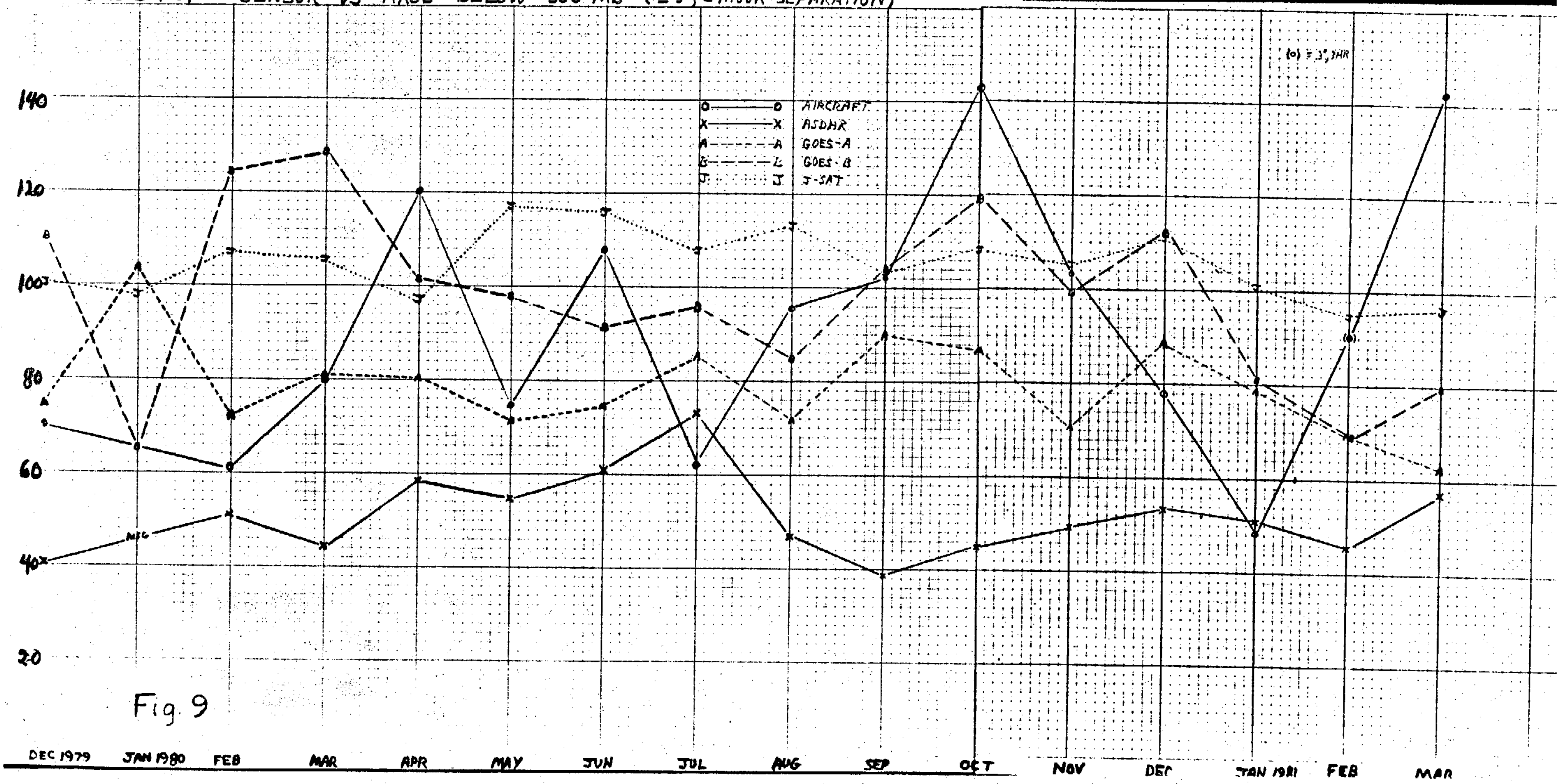


Fig. 9

RMSVE/$\bar{S}$ (%) SATELLITE VS AIRCRAFTS ABOVE 500 MB (≤3°, ≤1 HOUR SEPARATION)

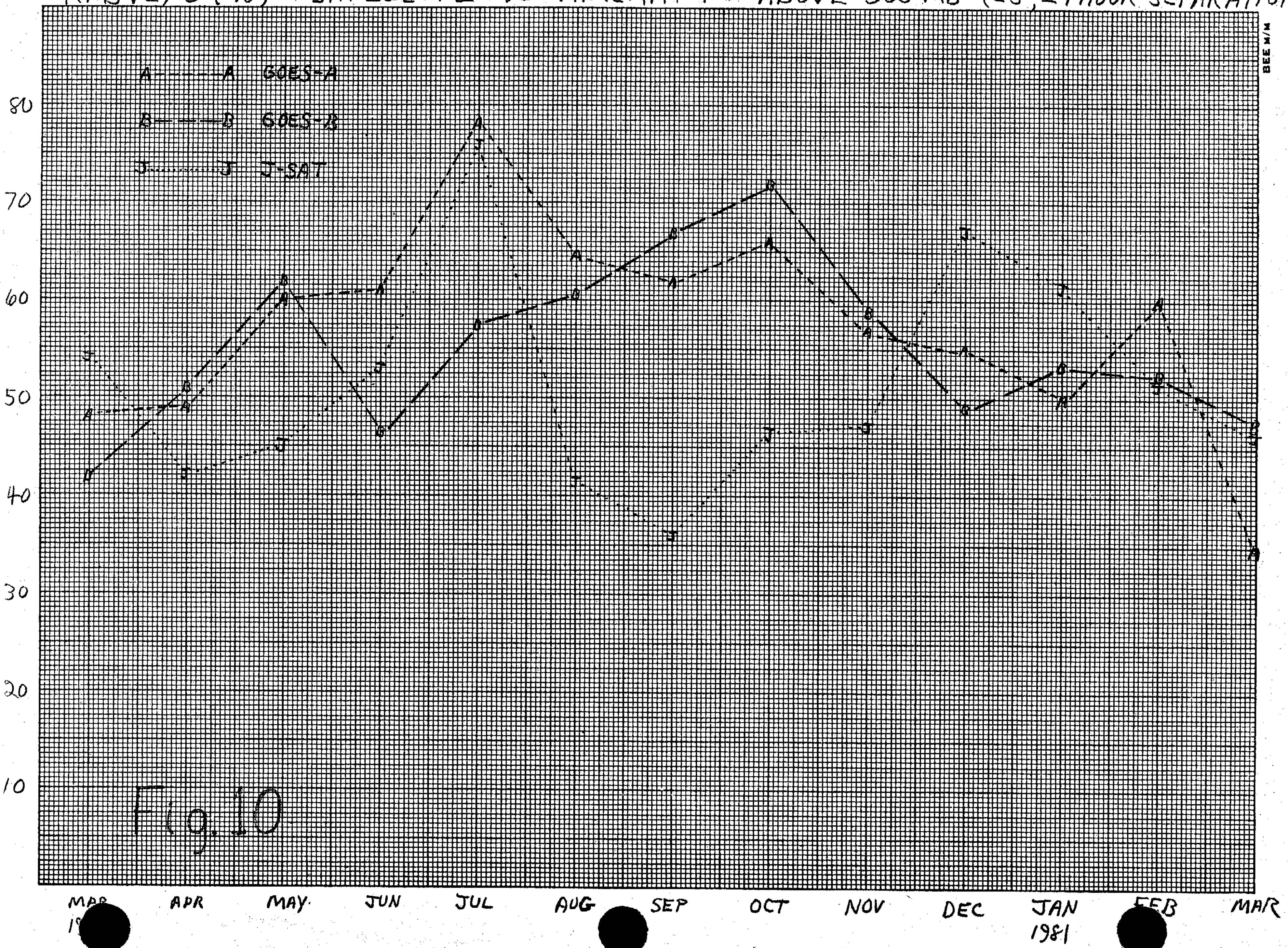


Fig. 10

RMSVE of "SAME SENSOR" COLOCATIONS ABOVE 500 MB (<3°, <1 HOUR SEPARATION)

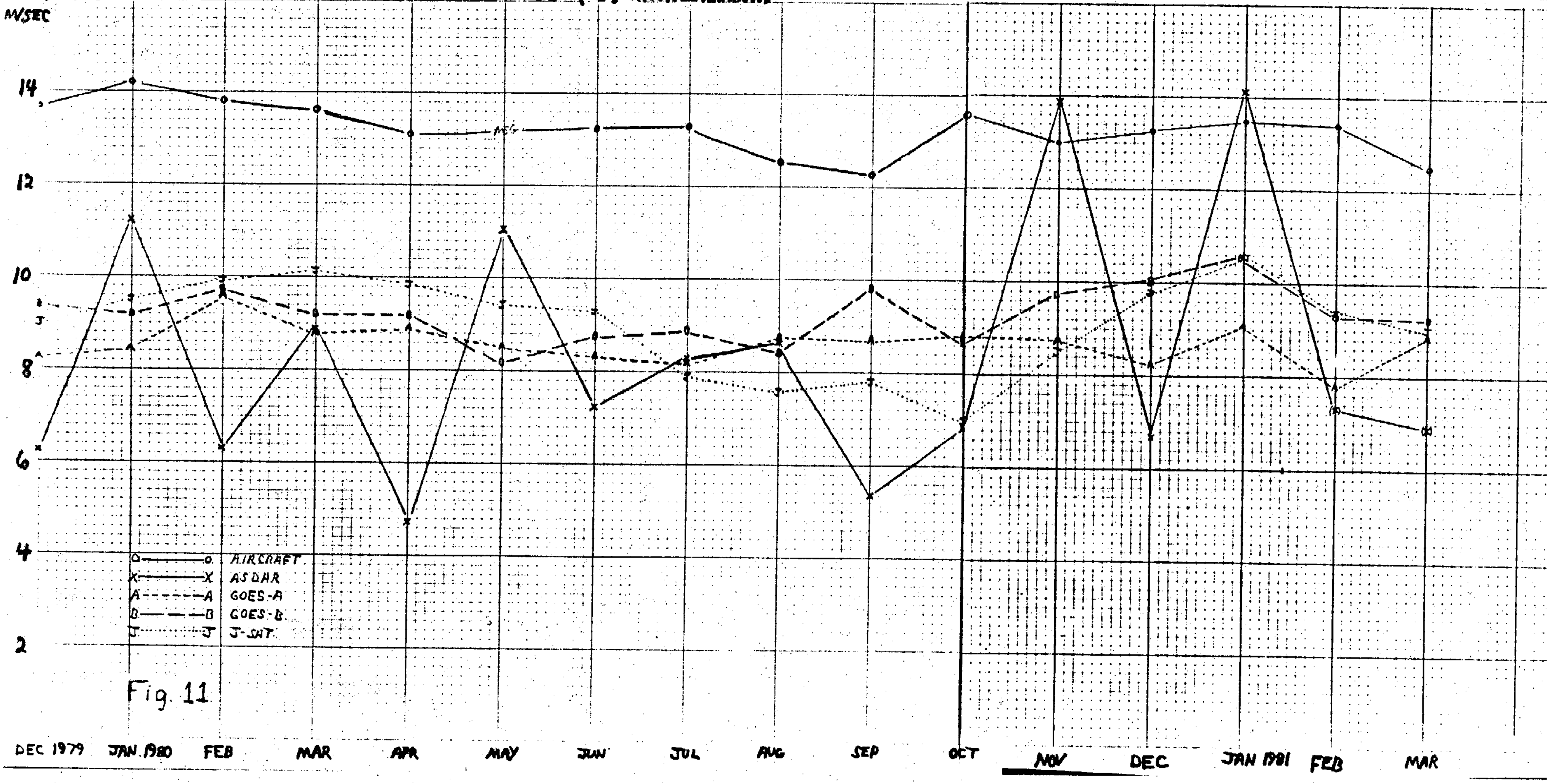


Fig. 11

[redacted]

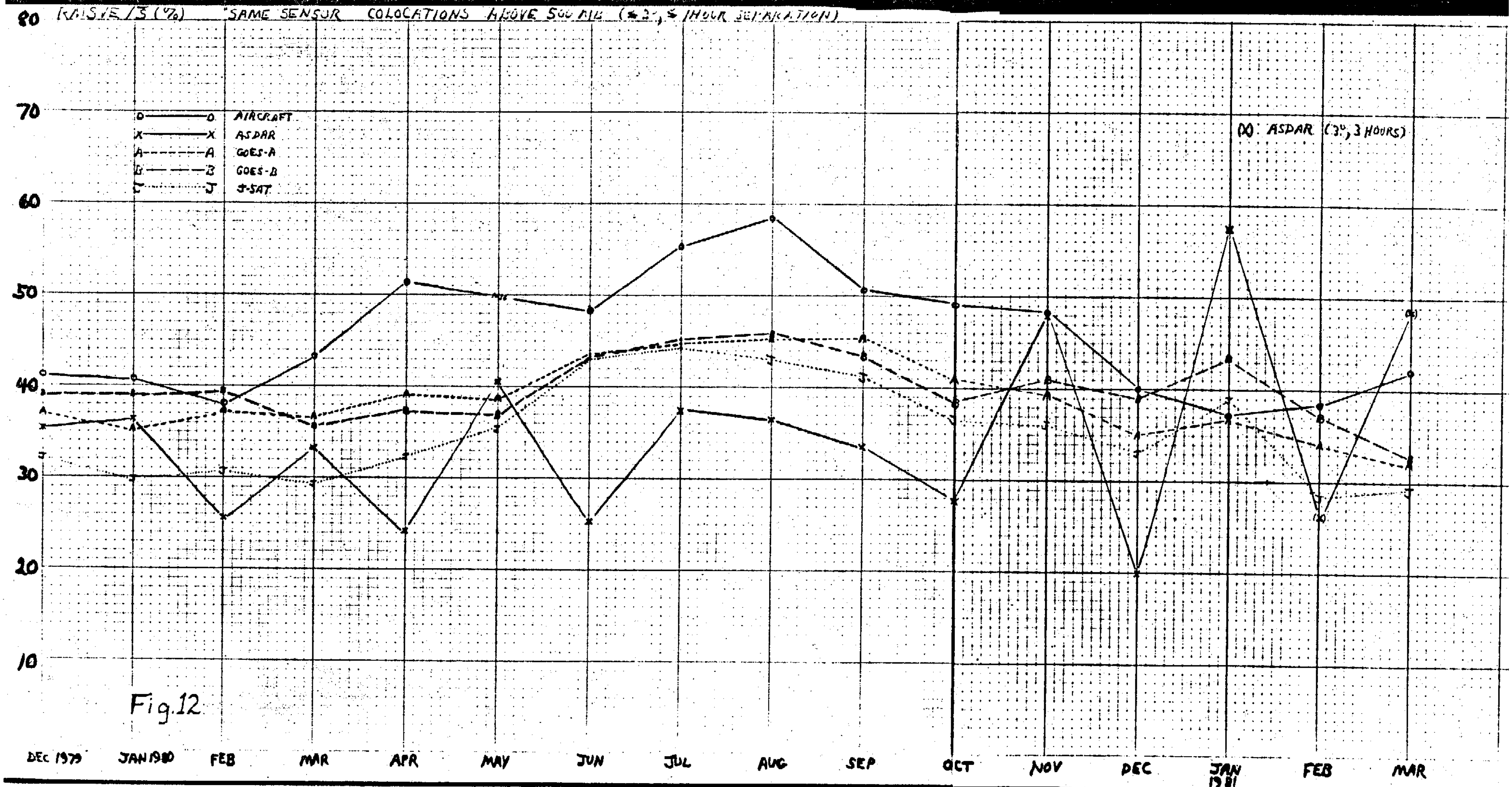


Fig.12

FPI-LOM-10 X 10 TO 1 INCH
10TH LINE HEAVY

RADIOSONDE - JAPANESE SATELLITE MEAN SPEED DIFFERENCE (M/SEC) (N. HEM.)

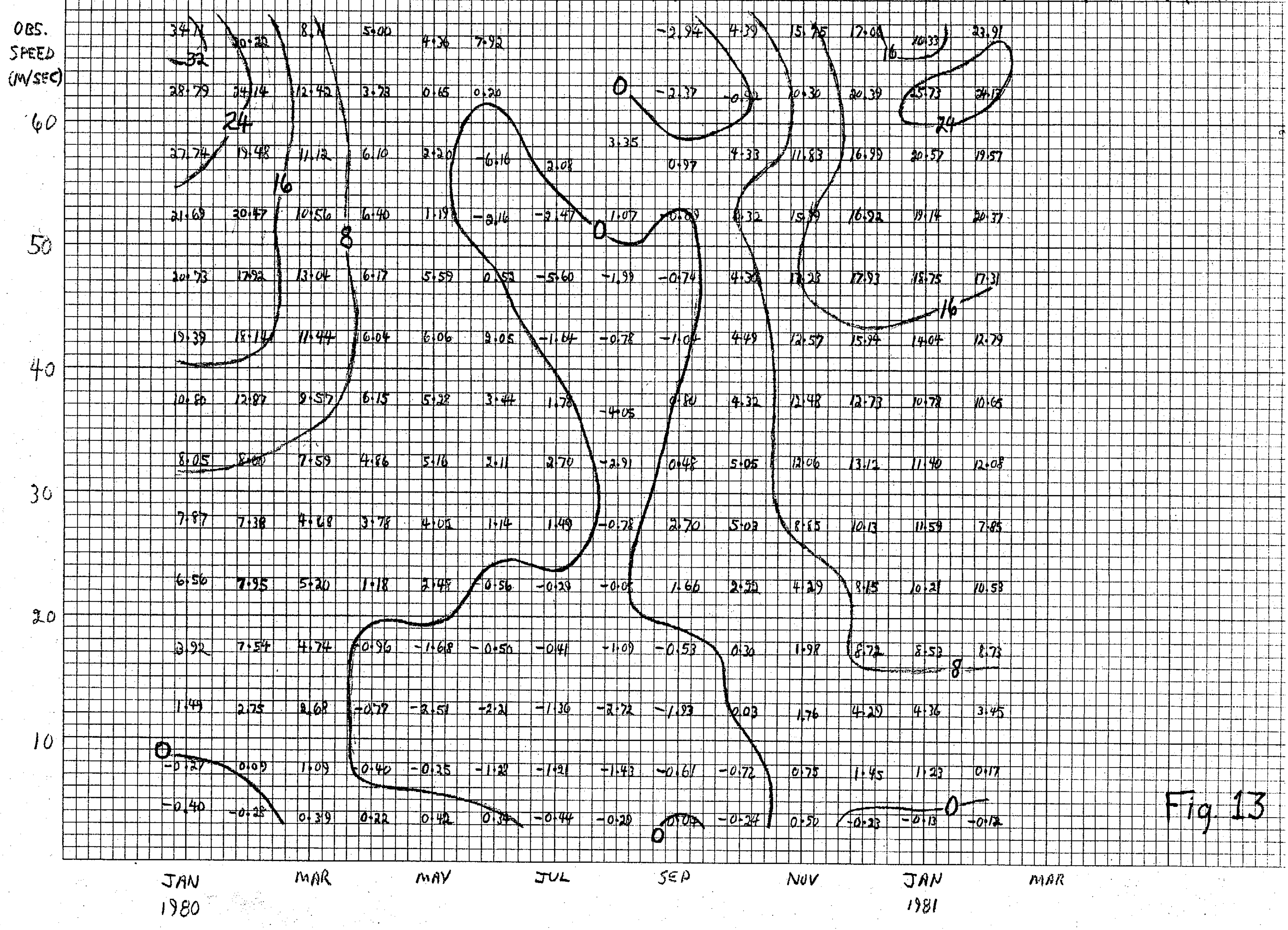


Fig. 13

SPEED ERROR IN M/SEC (ACROSS) VS VERTICAL WIND SHEAR IN CM/SEC/MB (DOWN): JAPANESE SATELLITE-RAOB COLOCATIONS **300 MB**

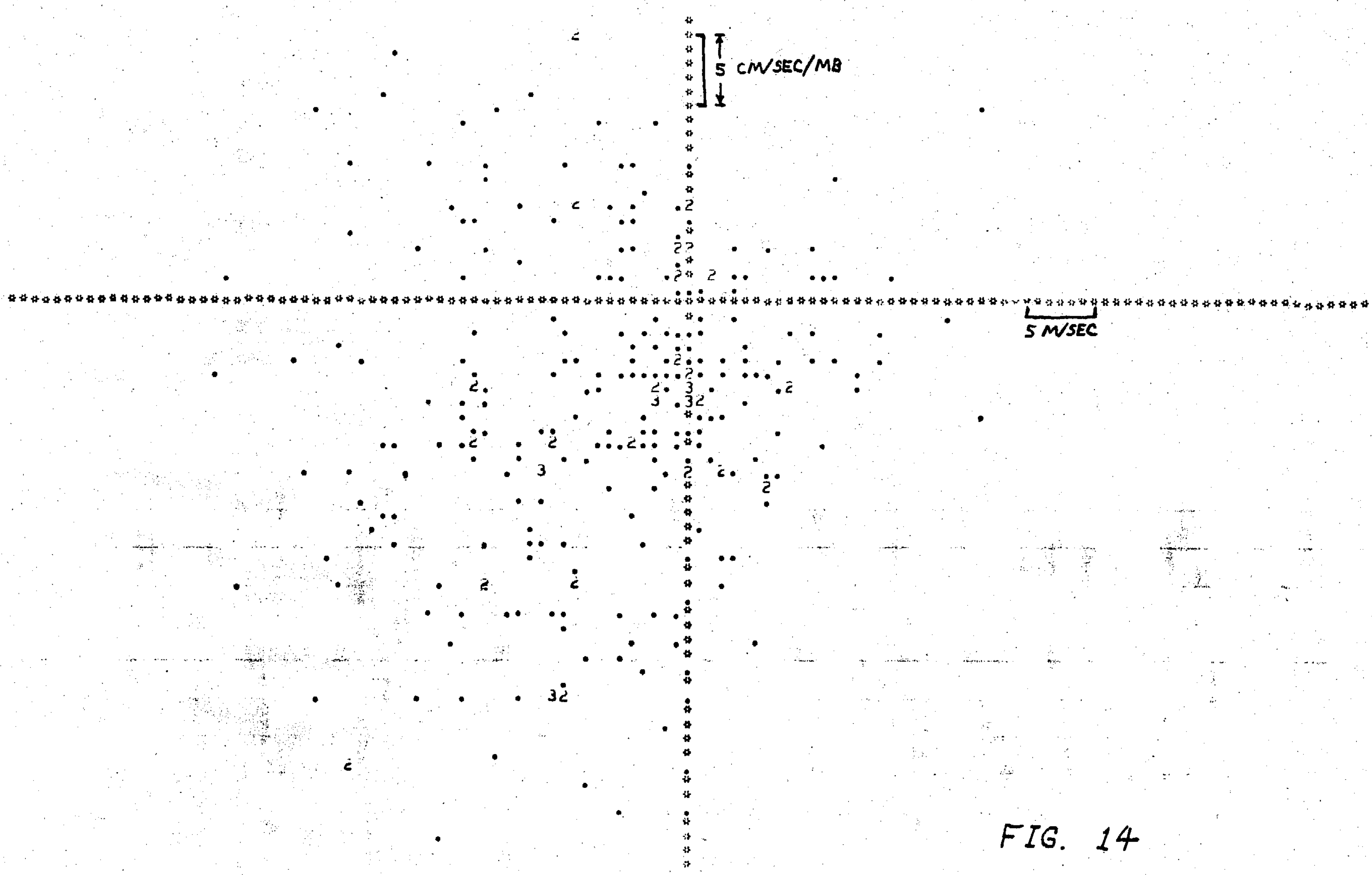


FIG. 14