Met.O.(APR) Turbulence and Diffusion Note No. 207

Validation Of Computed Power Station Plume Trajectories Using Aircraft Observations

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Note

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Summary

Aircraft measurements of SO_2 were made on seven separate occasions to test whether trajectory methods could be used to predict realistic concentrations for the UK composite plume and identify individual sources. There is a good comparison between computed and observed concentrations in southwesterly meteorological situations but the agreement is less marked in different and more complex conditions.

Introduction

This work is a sequel to aircraft experiments performed in the early 1980's when a tracer, sulphur hexafluoride, was released from Eggborough power station in Northern England and sampled and detected by on-board aircraft instrumentation (Crabtree 1982). The use of a tracer gave an unequivocal indication as to the sample's source.

Sulphur dioxide emissions vary greatly across the UK, the largest sources being the coal and oil burning power stations (Figures 1 and 2). In the aircraft experiments to be described no tracer was used, instead relative concentrations of SO_2 were measured with the aim of identifying individual signatures of large sources within Britain's composite plume. The results were used to verify trajectories calculated from numerical weather prediction model wind fields and assess their potentiality for predicting cross-boundary pollutant transport. The experiments comprised of flights made parallel to the UK coast at various distances and heights, in different meteorological conditions.

Instrumentation and Flight Pattern

Sulphur dioxide was measured by an on-board analyser which performs real time and continuous dry analysis of SO_2 using a Flame Photometric Detection technique. Sulphur containing molecules are converted to an S_2 species by a hydrogen flame and the hydrogen and hydroxyl radicals which are also produced by the flame react with S_2 to produce an activated S_2^*.

$$H. + H. + S_2 \rightarrow S_2^* + H_2 \quad (1)$$

$$OH. + H. + S_2 \rightarrow S_2^* + H_2O \quad (2)$$

The excited sulphur then reverts to a lower energy state emitting a broad band of light radiation with the maximum intensity at 394 nm., the intensity of the emission being directly proportional to a power slightly less than the square of the sulphur concentration. A photomultiplier tube produces an electrical current which is then converted to a voltage which is used as the instrument output. The output is recorded at a frequency of 1 Hz, the usual detection range being 0 to 100 parts per billion. All flights had to be made below ten thousand feet as the hydrogen flame is extinguished above this level.

A typical flight pattern made is shown in Figure 3. Transit was made to the North Sea below ten thousand feet and the box pattern flown with vertical profiles from five thousand feet to fifty feet at points A, B, C and D. The profile measurements included temperature and dewpoint and these were used to ascertain the likely boundary layer top in the locality. Runs 1 and 2 (A to B and C to D) were typically 150 km long and flown ideally two to three hundred feet below the inversion and at a level which was cloud-free. The aircraft speed during each transit was usually about 100 m/s.

SO_2 Integration Model

The Meteorological Office Atmospheric Processes Branch trajectory analysis (Maryon (1989)) used wind fields derived from the operational fine mesh model (since superseded by the Unified limited area model). The back trajectories could only be initialised at 00Z, 03Z, 06Z, 09Z, 12Z, 15Z, 18Z and 21Z; they were also initialised at prescribed pressure levels, 950 mb trajectories being used almost exclusively in this study.

A back trajectory was typically computed for a period of 36 hours with positions located at three hourly intervals. These positions were mapped onto an i, j co-ordinate array of SO_2 emission squares (Figure 4). To compute the concentration of SO_2 at point A for example, the contribution from each emission square coincident with the trajectory path has to be calculated and all the contributions summed:

Total Contribution $=\sum_{i,j} S_{i,j} T_{i,j}$

where $S_{i,j}$ is the emission rate of square i, j and $T_{i,j}$ is the time spent in square i, j.

The aircraft's position along each straight run was extracted at thirty second intervals from navigational data and back trajectories were computed from all these positions. The SO_2 concentrations at each point were then calculated to produce finally a cross-section of integrated concentrations. The boundary layer depth was ascertained from the aircraft profiles and each integrated concentration was divided by this depth to give a volume concentration. The relationship of 1 ppb of SO_2 equalling 2.7 * 10^{-9} kgm^{-3} (at 288K and 1013 mb.) was then used to calculate a mixing ratio. The measured and computed SO_2 values could then be compared directly.

The SO_2 integration model used a dataset of UK annual emissions of sulphur dioxide for 1987 supplied by the Warren Spring Laboratory. The data is arranged into 10 by 10 kilometre squares, the largest values being located at the major power stations. Figure 1 is a pictorial representation of this dataset.

Experiments In Westerly Conditions

Flight H918 28/7/89

There was a stable and dry south-westerly air-flow as shown by the synoptic chart in Figure 5. Such a situation was ideal for good plume formation and detection and a box pattern was flown as in Figure 3, two straight runs being made at an approximate height of 750 feet. Figure 6 is a diagram of the computed and measured SO_2 mixing ratios for runs 1 and 2. (All plotted runs in this paper have been arranged with south at the start and north at the end. This is why some of the timings have had to be reversed).

In run 1 (10:40 to 11:10 GMT) the measured trace is similar to that of the computed. It is probable that computed peak A matches measured peak 1, likewise B with 2, C with 3, D with 4, E with 5/6 and possibly peak F with 7. The sources of the computed peaks were inferred from the back trajectories' coincidence with high SO_2 emission grid squares and hence particular power stations. Peak A originated from Ratcliffe-On-Soar (distance 236 km.), B from Cottam (189 km.), C from West Burton (194 km.), D from Fiddler's Ferry (302 km.), E from the major Yorkshire power stations (196 km.) with F having no large emission sources, the trajectory running through Teeside.

The mixing ratios of the two traces are generally similar, E and 5 being notably good. The measured peaks are also closer together than the theoretical ones but by no consistent factor. It is possible that the actual winds were converging over Eastern England and the North Sea whereas this was not simulated by the fine mesh model. The lack of observations made it difficult to confirm this. Crabtree (1982) suggested the presence of a mesoscale eddy off the North York Moors in south-westerly winds and such a feature has been reproduced successfully by a high resolution version of the Met.Office mesoscale model. Such an eddy might explain some of the narrowing observed.

The physical displacements of matching peaks were calculated by using the aircraft navigational positions at the appropriate times. Peaks A and 1 were thirteen km apart, B and peak 2 seven km , C and 3 six km., D and 4 twenty-two km. whilst E and 5 were 23 km apart. If a computed peak was further north than a measured one, the sign of error is taken as positive, so that the above differences correspond to errors of $-3^0; -0.5^0; +2^0; +4^0$ and $+7^0$. These are well within the model trajectory errors detailed in Maryon and Heasman (1988).

Of further interest was peak width against downwind distance. The highest value peaks 5 and 6 which correlated with peak E were examined. Each of the two plumes was approximately 40 seconds wide which at an estimated aircraft speed of 100 m/s is a physical width of only 4 km. They were, however, evidently beginning to merge. Peak

E's source was from the high emitting Yorkshire power stations which was a downwind distance of approximately 200 km. Figure 7 is a plot of plume width against plume distance from source, collated from experimental data (Pasquill and Smith 1983). The diagram suggests that for 200 km overland the plume width should be about 60 km, whereas Crabtree's results over the North Sea (Figure 7) which should be more appropriate suggest a width of 15-20 km. The sampled plumes probably left their source at about 06Z in a stable boundary layer with little lateral diffusion. Thereafter the plumes reached the North Sea where with cooling from below and lower surface roughness, turbulence was further reduced.

Run 2 (C to D) was performed 100 km downwind of run 1 between 11:50 and 12:20 GMT. Peak 8 should be disregarded as the aircraft encountered smoke from a ship burning waste. The remaining measured trace appears to have resulted from the merging of peaks 1 to 6, with the Teeside peak (7) no longer present. Diffusive events of some kind have evidently taken place. The computed and measured traces do not compare well.

National Power later provided figures of power station loadings at 06Z 28/7/89. These confirmed that Drax was working at near full capacity, with Eggborough, West Burton and Thorpe Marsh working at slightly less. Unfortunately information for the Powergen stations of Fiddler's Ferry, Ferrybridge, Cottam and Ratcliffe-on-Soar was unavailable. Obtaining such verification remained a problem throughout this work.

Flight H967 12/1/90

This flight used a similar box pattern over the North Sea to the previous flight; however the situation was more complex as the sortie encountered a cold front moving south-eastwards (Figure 8). Figure 9 shows the computed and measured plots for the first run (11:55 to 12:55 GMT). Computed peak W originated from Cottam and Aberthaw, X from the Yorkshire power stations, Y from Fiddler's Ferry and Z from a relatively high emission square near Tyneside (actually at Blyth where a power station and large factory are located). Peaks 1,2 and 3 appear to match W, X and Y respectively, however no significant peak materialised to match Z. This was possibly due to precipitation on the cold front which removed the SO_2 before detection.

The measured peaks were again closer together than the back trajectory plot but by no consistent factor and there was also a northward displacement of the measured when compared with the computed. Using the navigational data as before the difference between peaks 1 and W was 96 km, peaks 2 and X 60 km and 3 and C 40 km. These represented large angular errors of -27.5^o, -17.66^o and -7.5^o. respectively. It is probable that the plumes were distorted near the front by ageostrophic flows with rather larger errors resulting.

The widths of peaks W, X and Y were calculated to be 35 km, 10 km and 10 km with approximate upwind source distances of 465km, 188 km and 296 km. Figure 7 would suggest that these are reasonable figures although the plumes were still relatively narrow.

The second run downwind produced a poor comparison between computed and measured plots as before in flight H918. The timing of run 2 (13:10 to 14:10 GMT) did however give the opportunity to test the sensitivity of the back trajectory plots with regard to the initial time used. The second plot in Figure 9 displays the computed SO_2 mixing ratios with trajectories initialised at 12Z and 15Z, the sets of peaks being annotated M+ to Q+ and M to Q respectively. The 15Z peaks are further south than their 12Z counterparts, for example O is calculated to be 29 km further south than O+ and as the source was the Yorkshire power stations this corresponds to an angular shift of 5-6 degrees. Also single peak M/N becomes the two peaks M+ and N+ which must have been due to the orientation of the trajectories in relation to the power stations concerned, namely West Burton, Aberthaw, Rugeley and Cottam.

Flight A025 31/7/90

There was a south-westerly flow over the British Isles with a small high over the southern North Sea which developed into a substantial anticyclone in the subsequent hours. It was a very warm day and by midday sea-breezes had already developed along the East Coast.

A box pattern was adopted as in the first two flights, the first run from A to B was made at 1700 feet above the surface (11:15 to 12:00 GMT) run C to D was made at the same height (12:40 to 13:30 GMT) and a third run was performed made part way from C to D at 2700 feet (13:30 to 13:40 GMT). High SO_2 levels were found in the first run, no SO_2 being detected in the second but by ascending to 2700 feet the sulphur dioxide plumes were rediscovered at lower concentrations. The back trajectory concentrations gave no meaningful comparison with measured values and this is attributed to the sea breezes along the East Coast. Such meso-scale processes are not simulated by the fine mesh model.

Flight A062 29/1/91

The weather situation was a light south to south-westerly air flow over the UK. The flight track was a box pattern with the first run made quite close to the East coast from the Wash to Aberdeen with a parallel track about 100 kilometres downwind. The first leg (11:55 to 13:10 GMT) gave a good comparison between the measured and computed plots (Figure 10). The calculated peaks whose sources were easily identifiable were A - Trent Valley, B - Yorkshire, C - Rugeley, D - Fiddler's Ferry and E an unlikely peak as theoretically the plume had travelled 600 km from Aberthaw. The measured plot follows the calculated trace quite well although again the peaks are more closely grouped and are lower in value. Peaks 1-3 were again narrow being 15, 13 and 17 km in width with upwind distances of approximately 170, 145 and 300 km respectively. The angular differences between peaks A/1; B/2 and C/3 were -3.5^o, 0 and $+1^o$.

Output working data was only available from the power stations of West Burton, Drax and Eggborough all of which were operating near to capacity on that day. The widths of all the sampled plumes were between 11 and 17 kilometres being again on the narrow side of expected values. Figure 10 shows that on this flight the second parallel run (13:40 to 15:10 GMT) ($\approx$ 100 km downwind of the first run) does give a rather better comparison than before. The measured trace does show a resemblance to the computed but with very much lower concentrations as expected since the trajectory model takes no account of lateral diffusion. The strong diffusion taking place between the flight runs is difficult to account for when contrasted with that which has taken place up to the first run; it may be attributable to mesoscale phenomena of some kind. It may be, however, that the aircraft missed important parts of the plume (e.g. sampling at the wrong level).

Experiments In Non-Westerly Conditions

Flight H993 30/3/90

The synoptic situation was an anticyclone off the South of Ireland giving a light north-easterly airflow over southern areas. The sortie (10:25 to 12:20 GMT) traversed along the South coast and then parallel to the north coasts of Devon and Cornwall. SO_2 was only detected along the Devon/ Cornwall coast and back trajectory analysis showed the origin to be the Aberthaw power station in South Wales. National Power later confirmed that at 6Z on that day Aberthaw was working at 90% capacity.

The trajectory model therefore correctly predicted the SO_2 plume which was followed along the coast. Analytical comparison between computed and measured SO_2 was however made difficult because the plane flew periodically in cloud where pollution levels were high relative to cloud-free air.

Flight A091 30/5/91

An anticyclone over Greenland gave an east to north-easterly airflow over the UK. The sortie flown is shown in Figure 11. Transit was made to point A and runs between A and B were made at heights of 750, 1500 and 2200 feet (between 10:45 and 13:30 GMT). The aircraft then flew to the Solway Firth , along the Cumbrian coast and through the eastern sector of the Irish Sea at a height of 1500 feet (13:50 to 14:15 GMT) before finally flying back to Farnborough. Profiles from 5000 feet to 50 feet were performed at A and B.

This was an unsuccessful flight as none of the runs gave sensible comparisons. The only plume to be sampled probably originated from emissions from the Morecambe Bay gas field which is not included in the SO_2 inventory. Back trajectory analysis predicted plumes from Fiddler's Ferry and Yorkshire power stations on the runs between A and B but these were never found. The Cumbrian coast leg was of little value as no SO_2 was detected and none predicted.

It is uncertain as to why no SO_2 originating from the major power stations was found. It was ascertained from National Power that the Yorkshire power stations were working that day, although no information was available concerning Fiddler's Ferry. Synoptic data indicated low cloud and drizzle over Northern England which may have removed some sulphur dioxide near source. The winds over Yorkshire were more northerly than expected which may have transported the plumes south of the sortie runs. If the Fiddler's Ferry station was operating (as is likely) then any plume would have crossed the Welsh mountains. These are generally 1500 to 3000 feet high and may have dispersed any SO_2 sufficiently to make it difficult to detect.

Flight A117 4/9/91

An anticyclone was present over Northern Britain with a ridge extending southwards producing north to north-easterly winds over Northern England and east to south-easterly winds over the Midlands and Wales. The flight pattern was similar to the previous flight with the only runs made between A and B (Figure 11). The straight runs were performed between 10:30 and 13:20 GMT at heights of 1000, 2500 and 3200 feet, but as previously this was an unsuccessful flight. At 1000 feet one measured peak was found, the origin of which was uncertain. The trajectory model however calculated two peaks the first originating from Rugeley and Ratcliffe stations with the second originating from the Trent stations and Fiddler's Ferry. In the other runs little or no SO_2 was detected although trajectories suggested that there should have been. The weather situation was similar to that for flight A091 and the points raised are appropriate here.

Conclusions

1. It appears possible to use a trajectory model to identify sources for peaks in an observed plume, particularly when the meteorology is relatively straightforward. SO_2 plumes from the major power stations were usually detectable in south-westerly flows but not in north-easterly flows where the influence of the Pennines and the Welsh Mountains appeared to make detection very difficult.
2. There were positioning errors depending on the particular weather situation and indeed the comparisons became increasingly erroneous as the situation became more complex. The plumes were characteristically very narrow in the south-westerly flows, and unless the aircraft failed to intercept denser parts of the plume, there appeared to be an increased diffusion further out over the North Sea. These effects are difficult to account for on the available evidence. Zones of convergence or mesoscale effects are possible explanations.
3. It appears possible to estimate realistic SO_2 mixing ratios using the simple trajectory model.
4. The results are moderately encouraging as regards using a NWP model to predict cross-boundary pollutant transports in west to south-westerly weather types.

Acknowledgments

The author would like to thank the staff of Met.Research Flight, Farnborough, for their assistance in the aircraft experiments. Thanks are also due to the Warren Springs Laboratory for the use of their SO_2 emission data. Finally, special mention should be made of P. Anwyl of National Power Tech. who kindly lent his expertise in the operation of their SO_2 detector.

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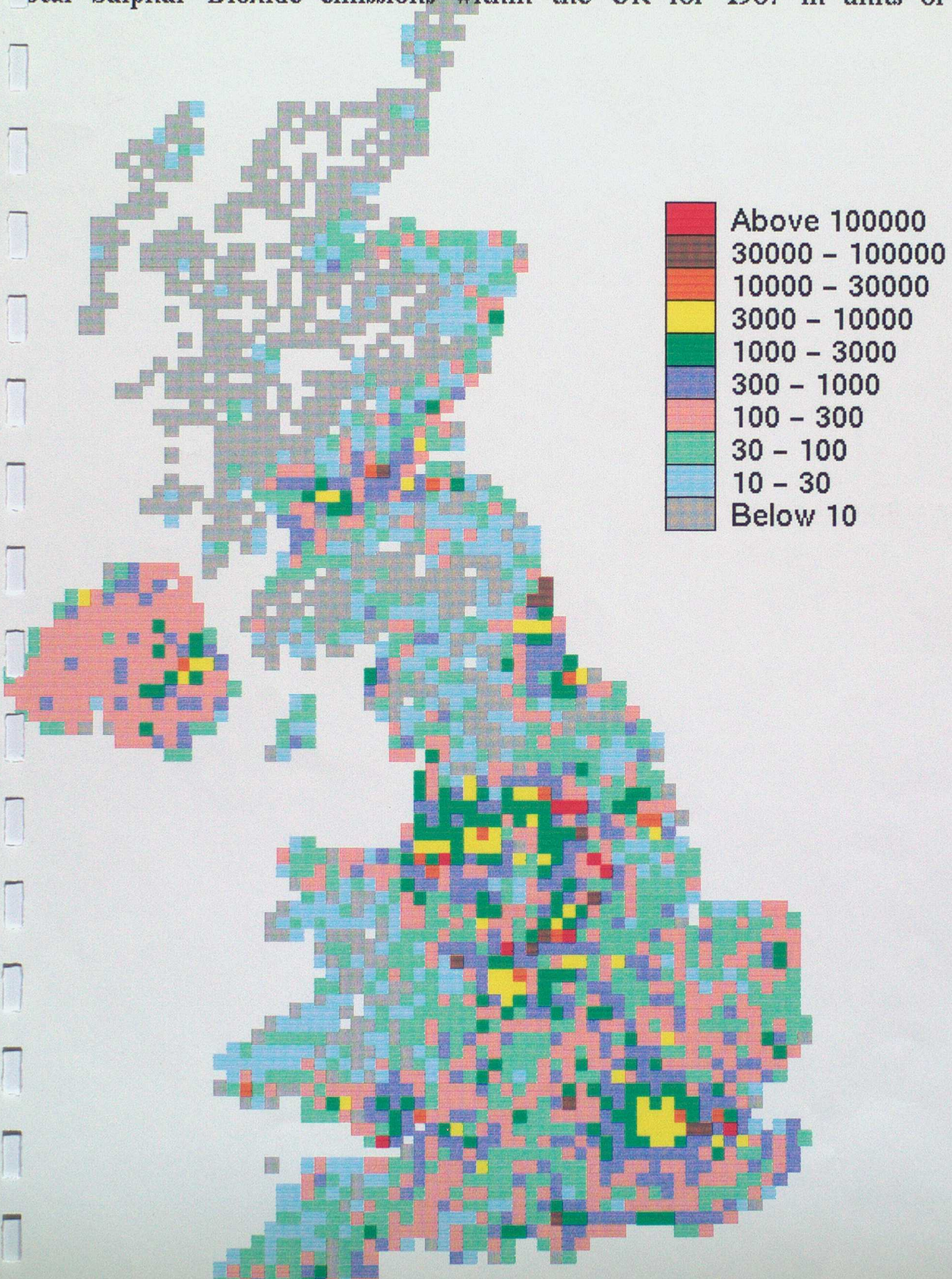
Maryon R.H. and Heasman C.C. 1988: The accuracy of plume trajectories forecast using the UK Meteorological Office operational forecasting models and their sensitivity to calculation scheme. *Atmospheric Environment*, **22-2**, 259-272.

Pasquill F. and Smith F.B. 1983: Atmospheric Diffusion *Ellis Horwood Publishers.*

Figure 1
Total Sulphur Dioxide emissions within the UK for 1987 in units of metric tonnes.



(Warren Spring Laboratory, 1989, priv.Comm.)

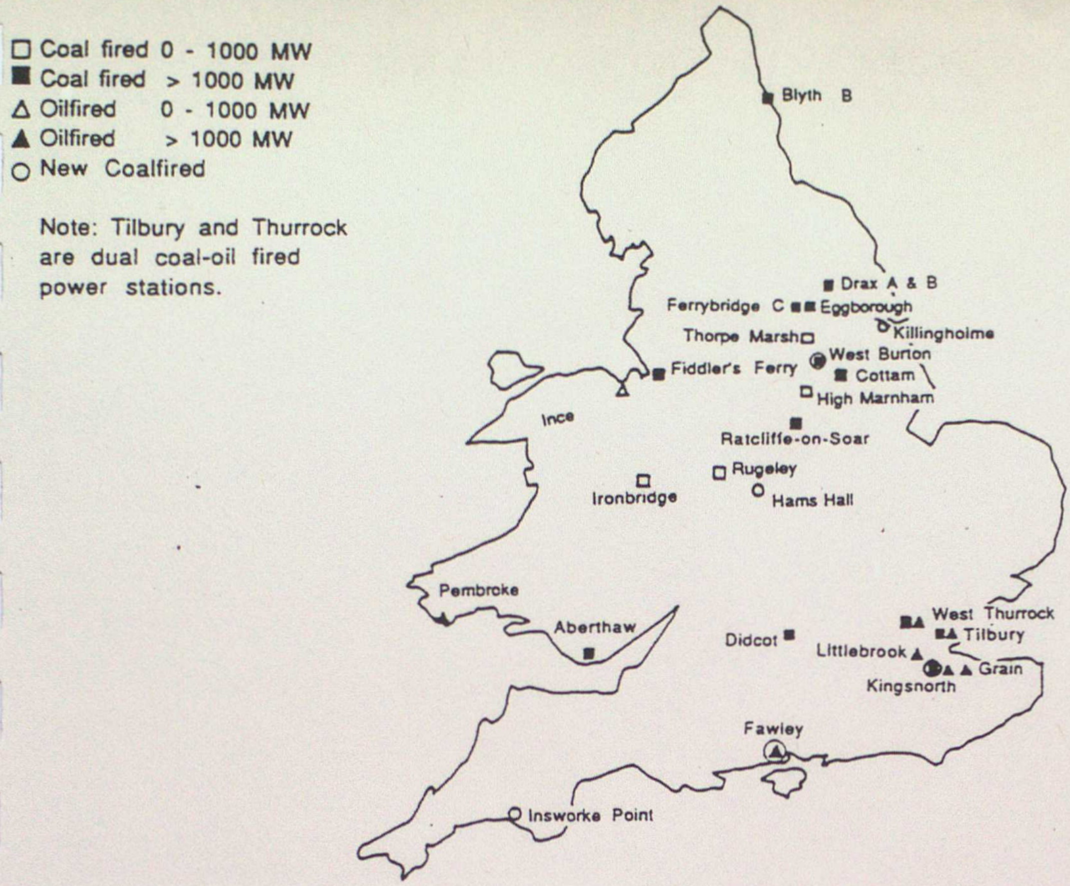


Figure 2 Location of Major Fossil Fuelled Power Stations in England and Wales (Extracted from Acid Deposition. Sources, Effects and Controls Edited by J.W.S. Longhurst (1989))

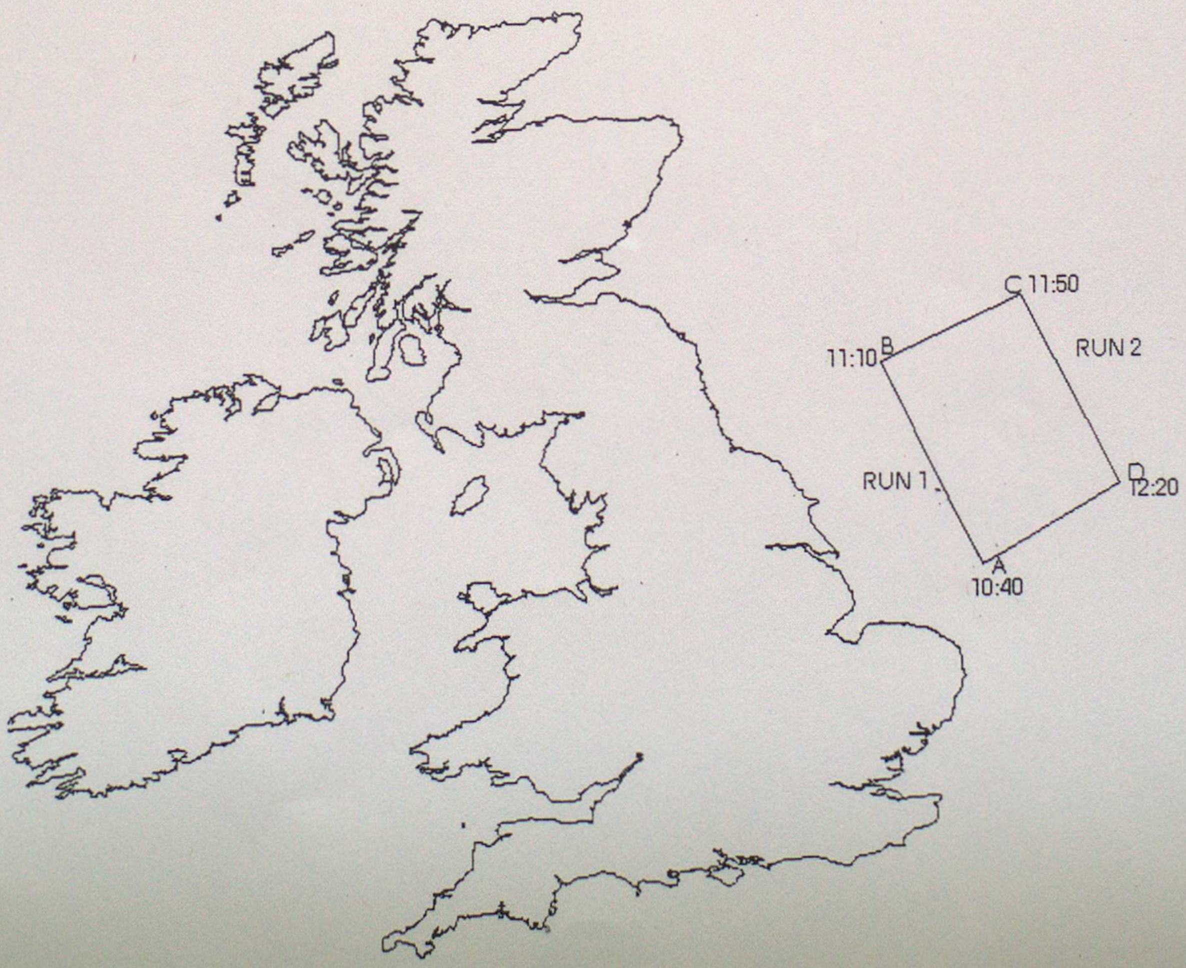


Figure 3 Flight Pattern Made On July 28th 1989

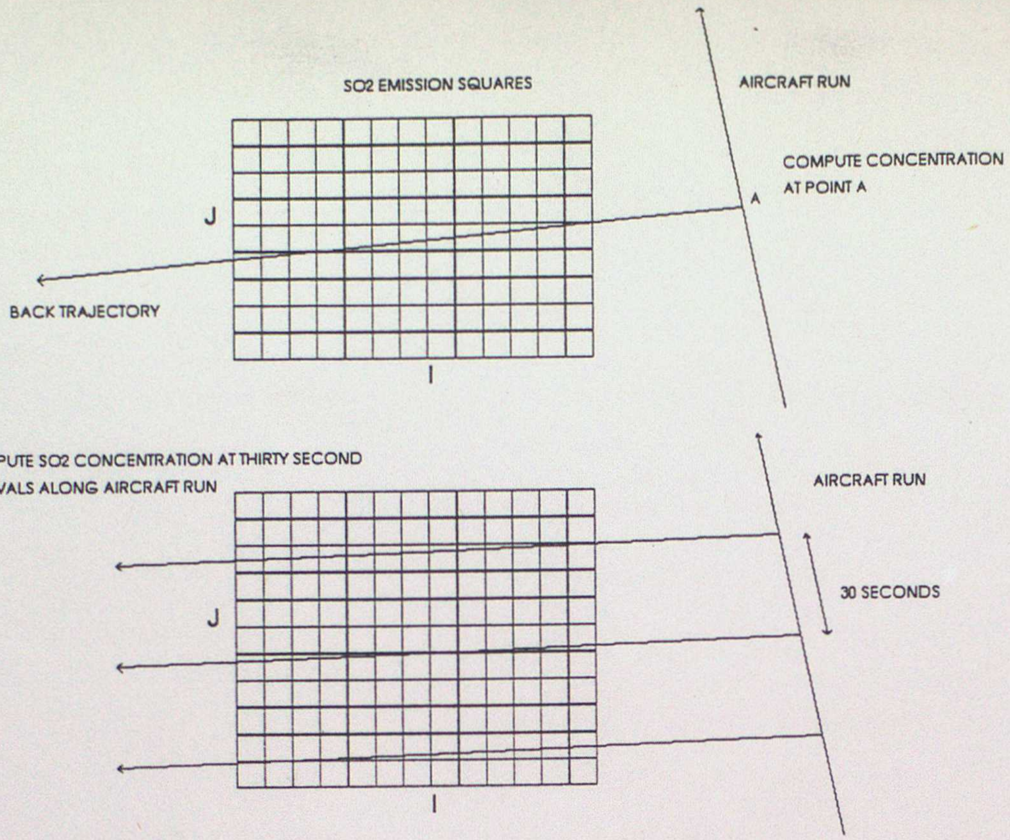


Figure 4

Figure 5
Synoptic Chart at 12Z 28/7/89 (From London Weather Summary)

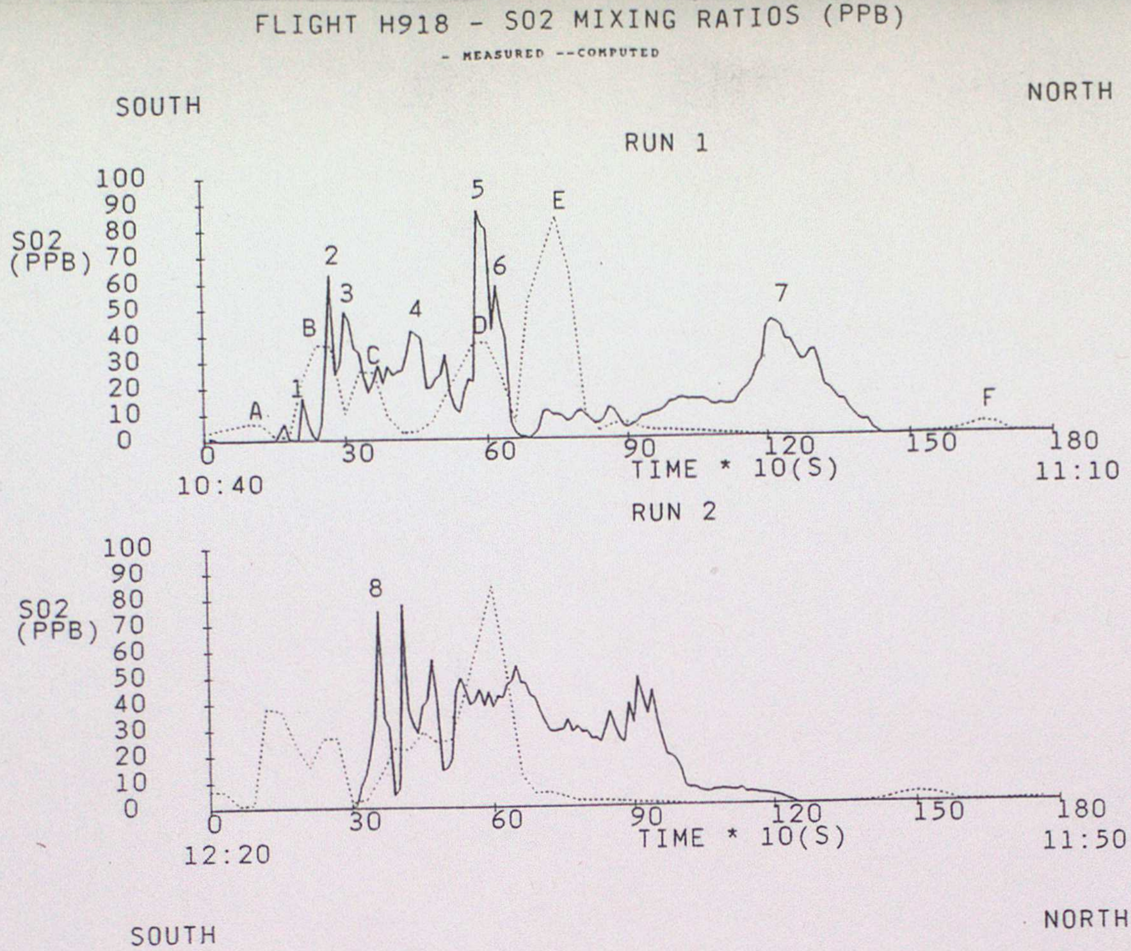
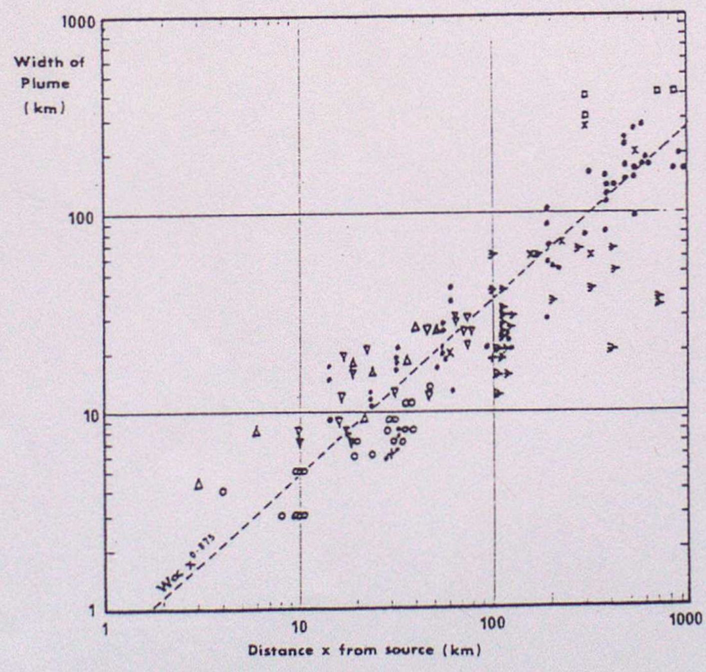


Figure 6 Flight H918 - Plots Of SO_2 Mixing Ratios



Data on the width of plumes as a function of distance from the source. × Richardson and Proctor (1925); ∇ Porton data (Pasquill, 1974); + Gifford (see Slade, 1968); □ Classified project (see Slade, 1968); △ Braham *et al.* (1952); ○ Smith and Heffernan (1956); ● Mt. Isa data (Bigg *et al.*, 1978; Carras and Williams, 1981); ⋗ Crabtree (1982): data collected over the sea.

Figure 7
Plot of Plume Width v Downwind Distance
(Atmospheric Diffusion - Pasquill and Smith (1983))

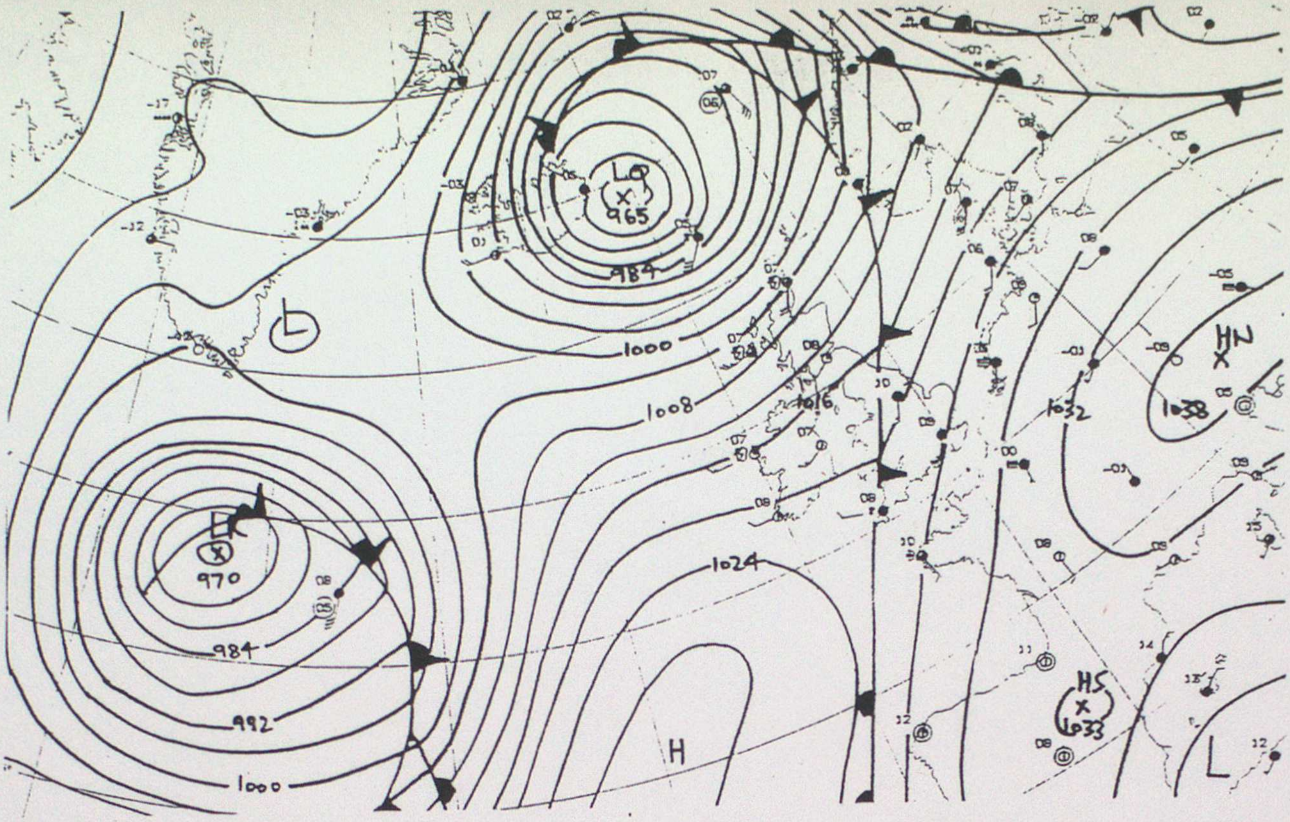


Figure 8 Synoptic Chart At 12Z 12/1/90

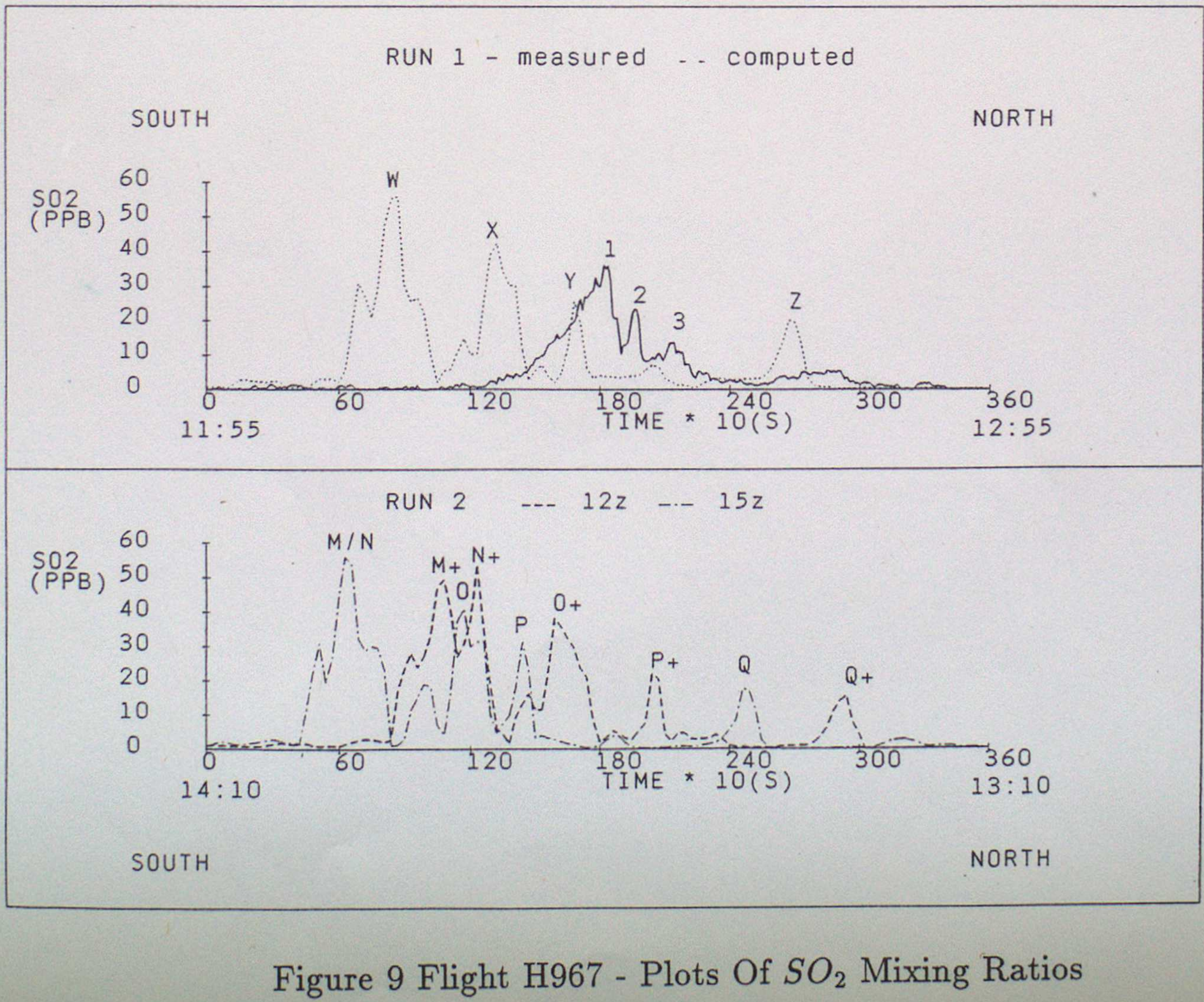


Figure 9 Flight H967 - Plots Of SO_2 Mixing Ratios

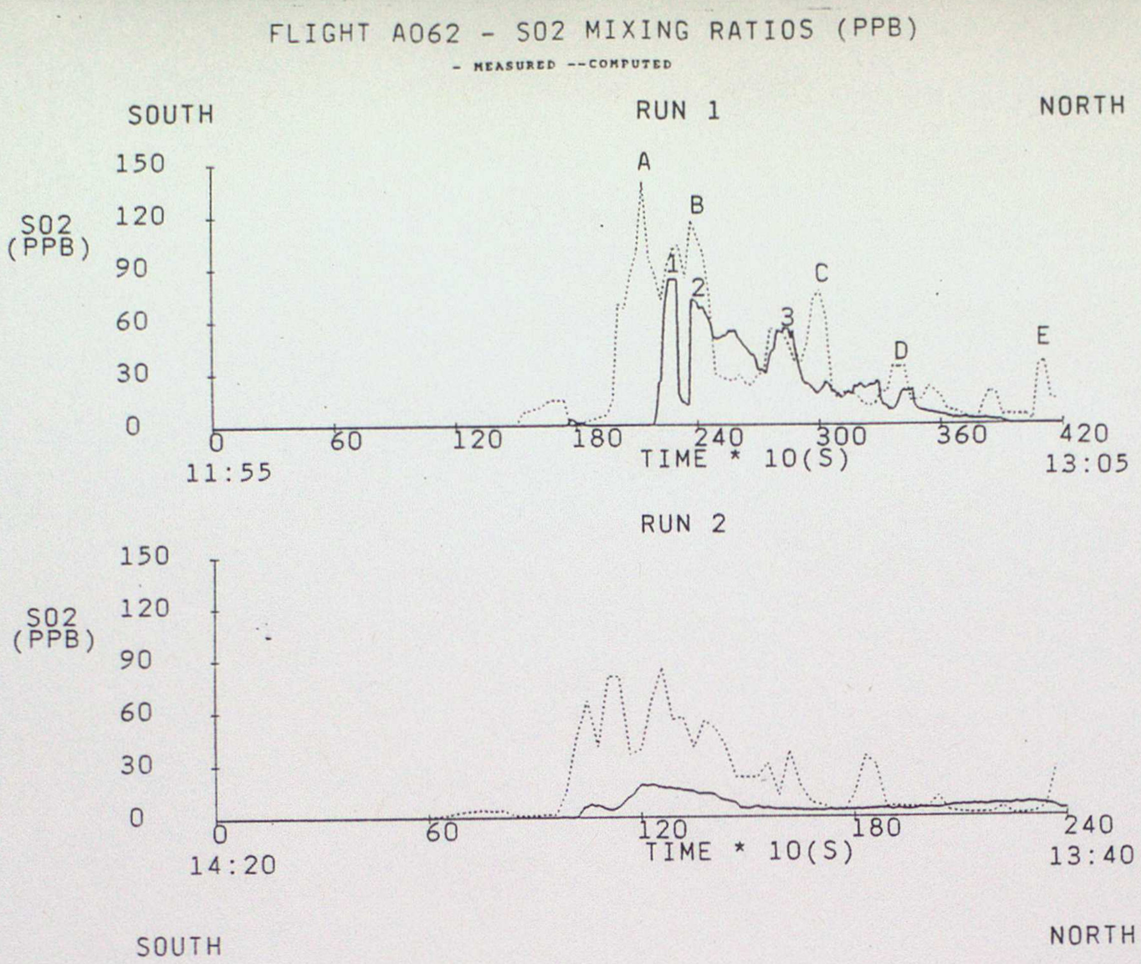


Figure 10 Flight A062 - Plots Of SO_2 Mixing Ratios

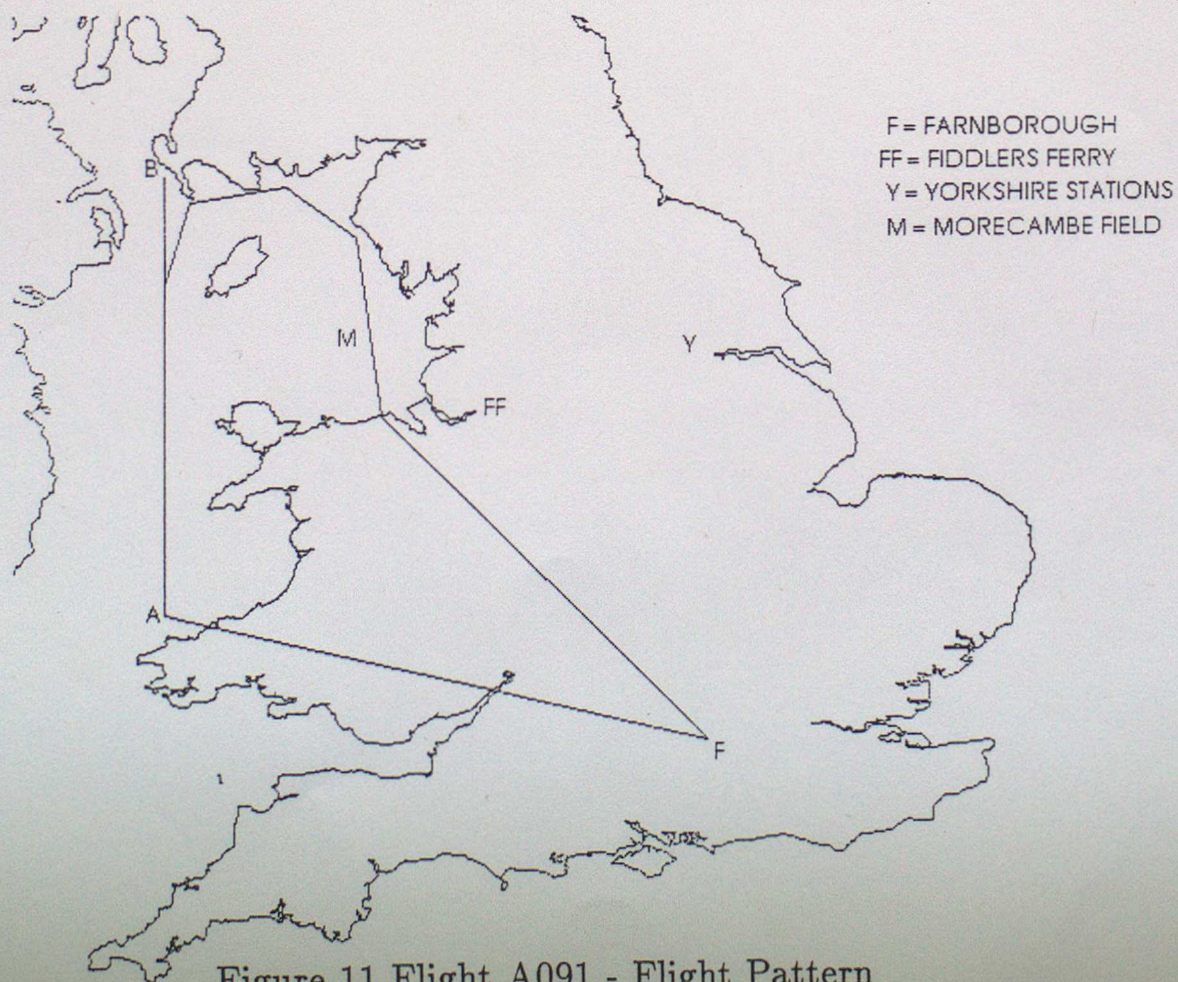


Figure 11 Flight A091 - Flight Pattern