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# Accuracy of Remotely Sensed $SO_2$ Mass Emission Rates

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# ACCURACY OF REMOTELY SENSED $SO_2$ MASS EMISSION RATES

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## ABSTRACT

Remote sensing data of single-track power plant emissions and local wind speed have been analyzed to determined $SO_2$ mass flux for comparison with EPA referenced methods. Four days of $SO_2$ data were gathered from a moving platform by three upward-viewing remote sensors -- two ultraviolet absorption spectrometers and an infrared gas filter spectrometer. Wind velocity data were gathered by a laser-doppler velocimeter (LDV); supplemental data were obtained from a tethered balloon (telemetered) and pilot balloons (optical theodolite). The data matrix ($SO_2$, X-Y position, wind velocity for 120 traverses) was computer processed; the end result was the $SO_2$ mass flux derived from the remote sensing data. Comparisons were made between these $SO_2$ fluxes (averages for 20 minutes and 60 minutes) and those derived from in-stack measurements. The results of the comparisons show the relative accuracy of the remote sensing technique for quantifying $SO_2$ mass emission rates. The analysis shows that as averaging time increases from 20 minutes to 12 hours the difference between the remotely measured $SO_2$ mass flux and the stack sampling $SO_2$ mass flux decreases from about ±35% to ±10%. In general, no single wind measuring system produced superior results over the other two. The LDV and COSPEC, however, produced the best agreement with Method 6 (+6%) when the plume was transported near the LDV instrument.

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ACKNOWLEDGEMENTS

The data processing was performed by Michael Peache and Jean-Jacques Garbarz; the analysis and report writing were done by Mr. Peache, Dr. William Vaughan, and Roger Sperling, Project Manager; Joan Geary, Suzanne Klimsza, Daisy Chan, and Evelyn More prepared the report. All are EMI employees.

The guidance of Dr. William Herget, the EPA Project Officer, throughout the project is gratefully acknowledged.

## SECTION 1

## INTRODUCTION

### BACKGROUND

Environmental Measurements, Inc. (EMI) collected air quality data with three remote sensing spectrometers at a southwestern U.S. coal-fired power plant using a moving instrument platform and an automated data acquisition system. The instruments were:

- COSPEC III
- COSPEC II
- Gas-Filter Correlation Spectrometer

The measurements were made over a five-day period, 2-6 August, 1976, to gather upward-looking $SO_2$ data to be used to evaluate the relative accuracy of the instruments for determining mass emissions rates remotely.

Concurrent wind measurements were made with three systems:

- Laser Doppler Velocimeter (LDV), Lockheed Missles and Spacecraft Corporation[4]
- Tethersonde (TS), Intera, Inc.[5]
- Pilot balloons (PB), EMI.[1]

Simultaneous in-stack reference method testing of $SO_2$ concentrations EPA (Method 6) and gas velocity EPA (Method 2) were made by Entropy Environmentalists, Inc.[3]

The data collected from the moving laboratory have been reported in tabular and plotted formats.[1] These listings provided the spatial $SO_2$ data needed to combine with the wind velocity profile data for calculating $SO_2$ mass emission rates.

### PURPOSE

All of the field data have been synthesized into a three-by-four $SO_2$ mass flux matrix: mass emission rates from *three* remote sensing spectrometers for *four* sets of wind measurements. These remotely quantified $SO_2$ fluxes were compared with reference method in-stack measurements to determine the:

- Relative accuracy of the remote sensing method as compared to the reference method, and
- Improvements, if any, in remote sensing accuracy using more accurate measuring equipment.

# SECTION 2

# SUMMARY

## EQUIPMENT

The data analyzed in this report were gathered by three remote sensing spectrometers and three different wind measuring systems.

### Spectrometers

Two of the spectrometers were Barringer Research Ltd. correlation spectrometers: COSPEC III (serial number 6061) and COSPEC II (serial number 5922) were provided by EMI and U.S. EPA/RTP, respectively. The third instrument was a government-provided gas-filter correlation spectrometer built by Science Applications, Inc. All three instruments were installed in an EMI Air Quality Moving Laboratory in the upward-viewing mode.

### Wind Measurements

Three different wind measuring systems were used to determine wind velocities at the altitude of the stack emissions:

- The van-mounted Laser Doppler Velocimeter (LDV) system was located 800 meters northwest of the stack. From this location it collected and analyzed horizontal and vertical remote wind velocity data at altitudes from 30 meters to 800 meters above ground level (AGL). The data were recorded on strip charts and on magnetic tape for later analysis.

- A tethered balloon system located 100 meters from the LDV site was used to measure wind velocity from ground level to a height of 600 meters. The data were recorded on strip charts for later analysis.

- Pilot balloons were released from the tethersonde site; the data were analyzed to determine wind velocity up to 1000 meters AGL.

All data have been reported separately by the individual contractors.[1,3,4,5]

MEASUREMENTS

The equipment provided the following sets of measurements:

- 120 traverses with the moving laboratory
- 13 hours of vertical wind profile data from the LDV
- 20 hours of vertical wind profile data from the tethersonde
- 20 pilot balloon measurements of winds aloft

Figure 1 illustrates the field measurement activities, and Figure 2 shows the traverse routes used by the moving laboratory and the sites of the meteorlogical systems.

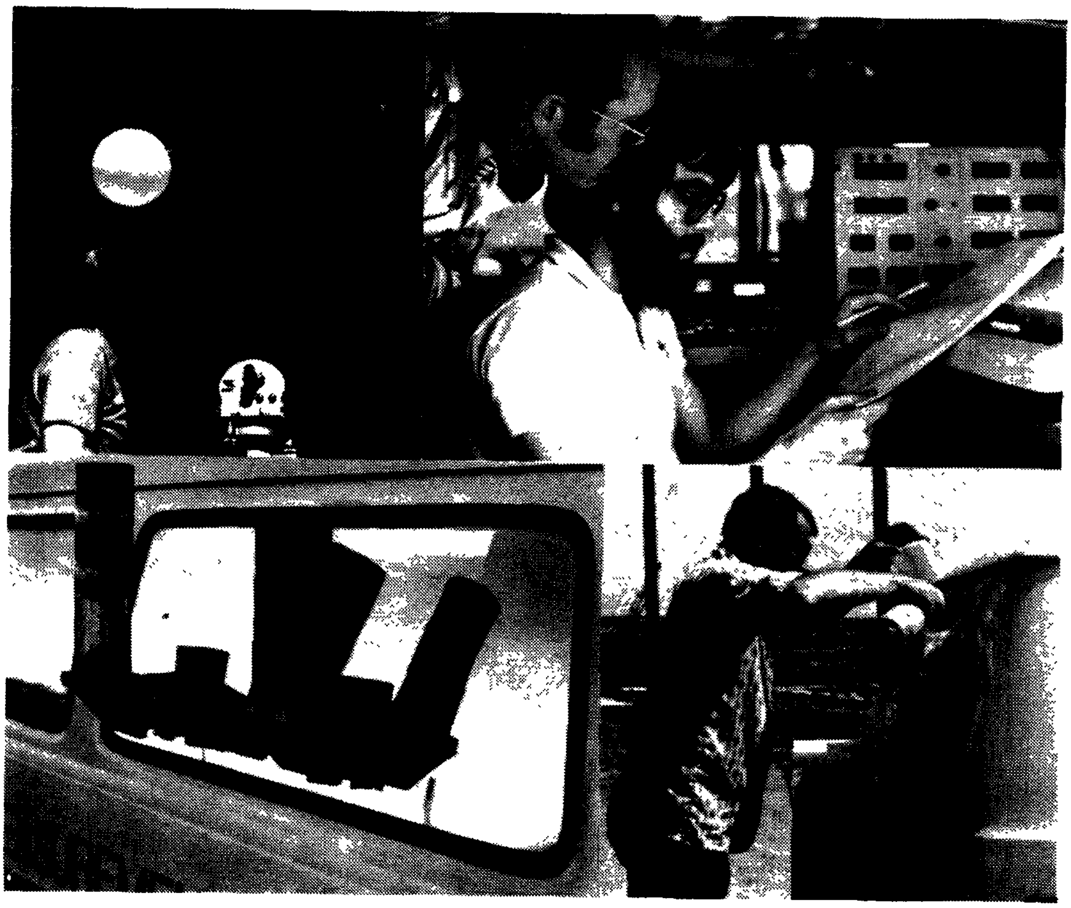

Figure 1. Field activities (clockwise from lower right): Adding liquid nitrogen to GFC Spectrometer; pair of upward-looking COSPEC remote sensors; observing flight of pibal toward tethered balloon; checking MAP listing of van position and spectrometer $SO_2$ data.

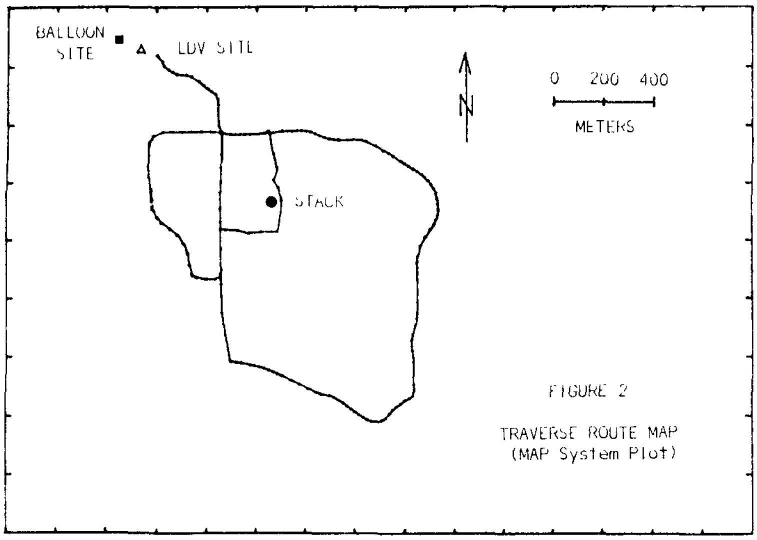


Figure 2. Traverse route map

## DATA PROCESSING

All the field data prepared by EMI and other contractors were reviewed and integrated into a single data matrix.

### Remote Sensor Data

The $SO_2$ optical depth data for the three spectrometers were edited, and appropriate calibration factors were applied to convert the millivolt reading to part-per-million-meters $SO_2$ (ppmM $SO_2$). The X-Y coordinates of the moving laboratory were also edited to establish the same coordinates system for all 120 traverses. The final coordinates and $SO_2$ optical depth data were stored into a computer for the computation of $SO_2$ mass emission rates.

### Wind Data

The LDV system wind data were reviewed; discrepancies were noted between the tabular listings and the plotted results. It was determined that the data had been hand-processed and could contain a systematic error of +10% (the difference between hand-processed *peak* values and machine-processed *average* values). A second processing by computer was requested. This computer processing resulted in a new set of LDV wind velocity numbers. Rather than to present both sets of numbers, it was decided to present only the revised LDV values. The original data (LDV) were computer-processed to form an LDV' set, which was used as delivered.

## RESULTS

The processed data were used to calculate $SO_2$ mass emission rates yielding a three-by-four matrix: $SO_2$ mass emission rates from *three* remote sensing spectrometers for *four* sets of wind measurements. The in-stack measurements of $SO_2$ mass flux were converted to common units of metric tons per day $SO_2$ (MT/D $SO_2$) for comparison with the remote sensing data.

## COMPARISON of RESULTS

To compare the remote sensor results with the in-stack results all data were averaged over the same time periods. The remote sensor $SO_2$ fluxes were averaged over 20-minute periods during which the in-stack data were collected; 60-minute averages were also determined. The 20-minute averages were within about ±35% of the reference data, whereas the 60-minute averages were within ±20%. Extending the averaging time to 7-to-12 hours further narrows the difference to ±10%, showing clearly that the relative accuracy of the remote sensing method is dependent on the averaging time or, more precisely, the number of profiles used in an average. There was no significantly superior wind measuring system, considering the time-averaged comparison of results. The pibal-derived $SO_2$ fluxes, however, were closer to the reference method than were either the LDV' or the tethersonde results for 20-minute averaged data.

## SECTION 3

## CONCLUSIONS and RECOMMENDATIONS

### CONCLUSIONS

The following conclusions can be drawn from the first-order analysis presented in Section 6 of this report regarding the relative accuracy of the remote sensor flux calculations:

#### $SO_2$ Flux Accuracy

The relative accuracy of the $SO_2$ mass flux calculations using remote sensor and wind speed data is dependent on the averaging time or number of profiles. The approximate differences relative to reference methods are:

- ±35% for 20-minute averages or 2-to-5 traverses
- ±20% for 60-minute averages or 4-to-13 traverses
- ±10% for 7-to-12 hour averages or 25-to-75 traverses

These results are consistent with previous studies. Single measurements of a plume profile can have greater than ±50% error because under most dispersion conditions the actual plume cross-section is non-uniform, and several measurements (traverses are required to provide a representative average profile. The greater the number of traverses, the lower the expected error until the minimum difference (±10% in the case of these data) is approached.*

#### Wind Measurement Accuracy

The relative accuracy of the three sets of wind speed data, as shown in the individual sets of $SO_2$ mass flux calculations, can be assessed as follows:

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*Millán M. Millán, in his research for Atmospheric Environmental Service of Canada, notes that their average for 18 to 22 profiles/hour at ≈1.5 km downwind is about ±15-17% different, which agrees reasonably well with this data.

LDV' --

The reprocessed LDV' data corrected the positive bias of the original LDV data. Overall, the LDV' average mass flow (78.9MT/D) was 17% greater than the average Method 6 determination (67.4MT/D). However, selecting data associated with SE winds that brought the plume over the LDV site and using only the Method 6 results for the same time frame, the LDV' results with COSPEC III are only 6% higher than the average for Method 6 (70.1 vs 66.2).

TS --

The tethersonde data had a negative bias producing fluxes over the long term within -10% of the reference method.

PB --

The pibal data produced the best results (<±5% in the long term), but the number of 20-minute averages was smaller than the other two methods.

It appears that the LDV system may be the most accurate of the systems tested, provided that it is used near the plume to measure the wind field near or in the plume. This finding from the subset of SE winds implies that a mobile remote wind monitoring system would be desirable for remote sensor plume studies.

## RECOMMENDATIONS

The following recommendations are offered to assist in advancing the state-of-the-art of remote sensing emissions monitoring:

### Further Analysis

Further analysis of the body of data in this report could lead to:

- Interpretation of the relative accuracy of remote sensor $SO_2$ mass fluxes expressed in terms of error intervals and confidence limits.
- Comparison of these data (1976) with previous similar data (1975) to determine how to optimize remote $SO_2$ mass flux measurements.
- Identification of measurement protocols that should be followed to minimize the error in the flux calculation and conditions that should be avoided that degrade the measurement technique.
- Selection of the most suitable wind velocity measurement system to accompany remote sensor measurements used for emission rate calculations.

Further Testing

With or without further analysis, further field testing could lead to:

- Confirmation of measurement conditions that tend to optimize the flux calculation.
- Verification of the most suitable wind velocity measurement system for remote sensor field work, such as a mobile remote wind sensing system to operate in conjunction with a remote sensor team.

## SECTION 4

## DATA PROCESSING

The first step in processing the remote sensor and supporting data was to prepare an activity summary relating all sets of measurements in time. Figure 3 shows the times for every field measurement.

Each set of data was reviewed for the four measurement days to determine its suitability for further analysis. The three sets of wind data were reviewed independently; the three spectrometer data sets were individually prepared for merging with the wind data to calculate $SO_2$ mass flux. For each of the 414 flux calculations a plume profile was drawn to aid in the analysis.

### WIND SPEED DATA

Before wind speed figures could be selected from the various data sets for the individual *times* of the remote sensor traverses, the individual *altitudes* first had to be selected. This was done by calculating plume rise and vertical dispersion; the appropriate wind speeds within the plume were then taken from the vertical wind profiles.

#### Plume Height

The extensive wind information could not increase the accuracy of the flux calculations unless the height of the plume was known. If the wind speed varied considerably with altitude, it was imperative to know the height of the plume because the flux calculation results are directly proportional to the wind speed. A 20% error in wind speed causes a 20% error in the flux calculation.

To obtain an approximate plume height (since no direct measurements were made) the existing wind information was used in conjunction with the Briggs plume rise formula. (Though its agreement with a wide range of plumes is established[6], its use during unstable conditions such as those of these tests is not so well established.)

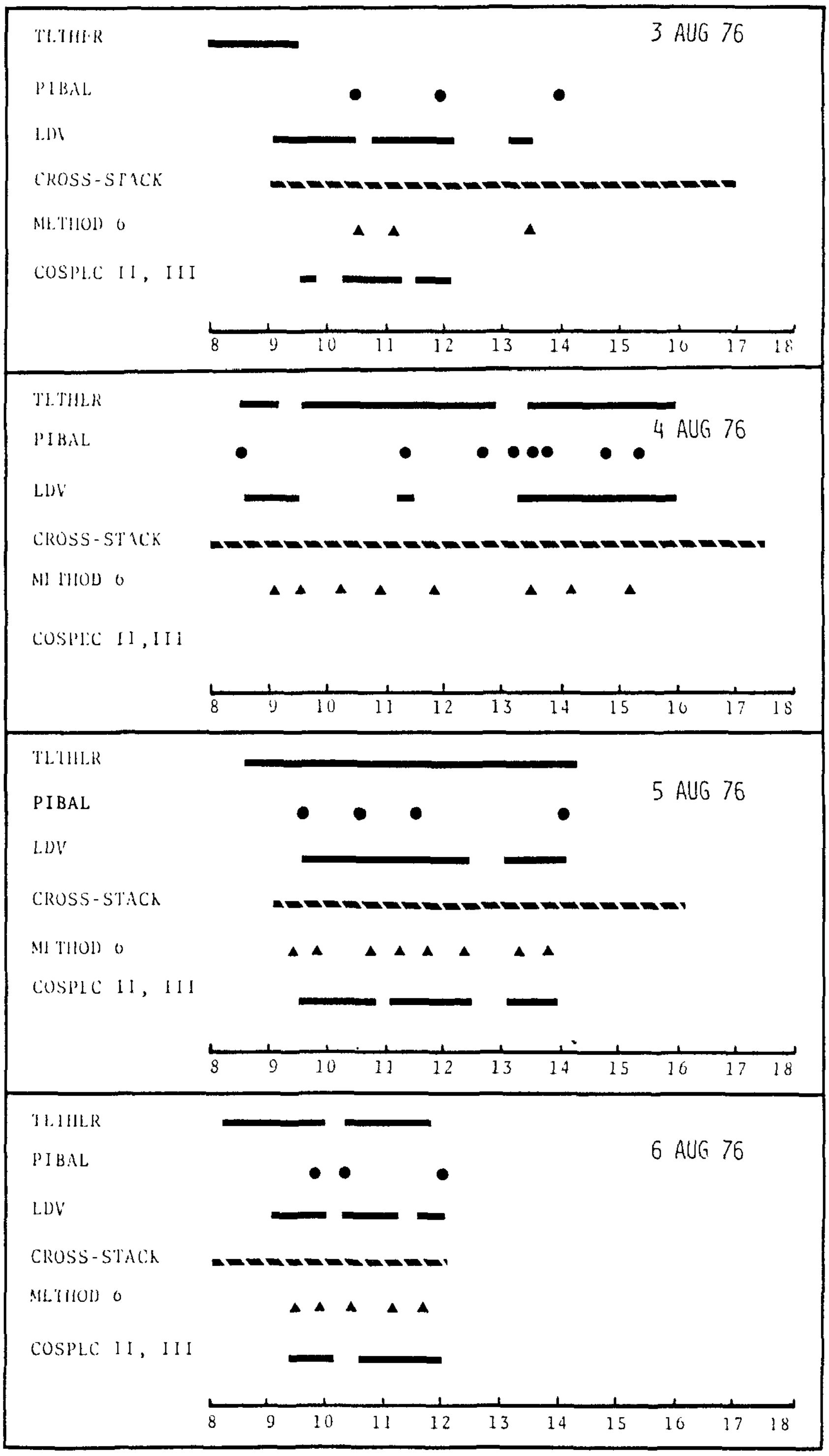


Figure 3. Activity Summary.

$$\Delta h = 2.0 \; F^{1/3} \; \chi^{2/3} \; \upsilon$$

where

$$F = \frac{g \; \Delta T \; V_s \; d^2}{4 \; T_s}$$

$\Delta h$ = height of plume axis above the top of the stack at given distance downwind (plume rise)
$g$ = acceleration due to gravity
$\Delta T$ = $T_s - T$
$T$ = absolute temperature of ambient atmosphere
$T_s$ = absolute temperature of stack gas
$V_s$ = stack gas velocity at stack top
$d$ = diameter of stack opening
$\chi$ = downwind distance
$\upsilon$ = wind speed

The average stack gas velocity and temperature as measured by Entropy Environmentalists Inc. were used because of a relatively small variation in these values during the test period. Likewise, the average ambient temperature was used because the 14°K variation would have caused only a ± 1% variation in the calculated plume height. To determine the downwind distance of each traverse, a computer program was used to find the point of maximum concentration and then calculate the distance of that point from the power plant stack. Finally, as an initial wind speed input, the wind speed at stack height, as determined by the Laser Doppler Velocimeter or the Tethersonde, was input and the plume rise was calculated.

The plume rise when added to stack height gave plume height. The wind speed at this height was then compared with the speed at stack height. If the two speeds varied considerably, the plume rise calculation was repeated using the wind speed at the calculated plume height and the wind speeds were again compared. It must be remembered that the accuracy of the plume rise calculations is probably within a factor of two, so that the results were not expected to converge on an exact figure for plume rise, but were used to determine the general region in which the plume was likely to be moving at the time it was sensed by the COSPEC and GFC. These height determinations were then used to choose the appropriate wind speeds from the wind profiles.

A second set of calculations was made to determine the probable vertical dispersion of the measured plume. To generalize the process Stability Class B was assumed for all four measurement days; this is based on the conditions of strong insolation and wind speeds greater than 3 meters per second. According to Gifford (Ref.6,p. 259) $\sigma_z$ is on the order of 20-to-30 meters at 200-to-300 meters downwind of the stack. These assumptions were all reasonable for the typical plume measurement made with the moving laboratory. Hence a $6\sigma$ vertical plume dispersion of ±75 meters, centered on the plume height calculated previously, was used for selecting wind speeds. For example, if the calculated plume height was 200 meters, wind speed data from 125 to 275 meters altitude above ground level would be selected for that traverse.

Each set of wind data was studied in turn, starting with the LDV data.

<u>LDV</u>

The laser Doppler Velocimeter wind speed data were originally presented tabularly for vertical sweeps to 80 meters altitude and for temporal measurements made at fixed altitudes for periods of 30 seconds. Selected data were also plotted with time. Comparison of the tabular and plotted velocity data revealed some discrepancies -- differences of up to 30%.

Rather than completely discarding the original data, both sets were retained for the purpose of Table 1 and identified as follows:

- LDV - original hand-processed results decreased by 10% to approximate the averages produced by computer processing.
- LDV' - new computer-reprocessed results. (For 3 August LDV' could not be computed because the full set of necessary data was either not available or not adequate for this calculation.)

From the LDV' data wind speeds within the plume (plume height ±75 meters) were selected that were coincident with the traverse time recorded by the moving laboratory. Where two or three values were available, they were averaged; in many cases only one value existed.

All wind speeds are summarized in Table 1. If there were no data at the proper altitude the nearest-altitude wind speed was selected and coded "*a*". Also, if there were no data within the time limits the nearest-time wind speed was selected and coded "*b*". (See Section 5 for further discussion of these Error Codes.)

<u>Tethersonde</u>

The same criteria were applied to the tethersonde data, and the best wind speed values were chosen and tabulated. (See Table 1.) Over half of the tethersonde measurements were made at altitudes lower than the caculated plume; they are coded "*a*". None were out of tolerance with respect to time.

### Pibal

The twenty pilot balloon measurements were treated similarly. However, the selected pibal wind (all of which were in tolerance for altitude) were purposely applied to adjacent time intervals to simulate the situation often necessitated by extrapolating infrequent pibal measurements. They are coded "*b*" in Table 1.

### Wind Summary

The selected wind data presented in Table 1 are also plotted in Figure 4. These daily plots show the differences between the four sets of velocities. It is important to note:

- The differences between the LDV and LDV' wind data are significant; the LDV results tend to be higher by as much as 30%, so they were not used for final computation.
- The tethersonde data tend to be low, principally because the balloon was often tethered at altitudes below plume heights determined after the field project.
- The pibal data show general agreement with other results.

## REMOTE SENSOR DATA

The remote sensor $SO_2$ optical depth data required further processing prior to merging with the wind data (in the flux calculations). The COSPEC and GFC were treated in a consistent fashion.

### COSPEC

When making mass flux calculations using COSPEC (or GFC) measurements, it is imperative to accurately determine a zero reference (background) level, which is subtracted from the COSPEC (or GFC) values, thereby leaving only a signal due to the $SO_2$ of the measured plume. In working with digital results (which are averages over 20 meters, as provided by the MAP System), it is difficult to spot a background value such as might be done by drawing a baseline on a chart record output; therefore, a different technique was used.

Most traverses under the plume were made so that there were five to ten 20-meter averages on either side of the plume that were measurements of background levels. Each traverse was evaluated, and an average of five readings in the background region on either side of the plume was calculated to provide an average background. If the average background on one side was more than six

## TABLE 1. WIND SPEED SUMMARY

| TRAV-ERSE NO. | TIME (MDT) | STACK DIST. (M) | PLUME HEIGHT (M) | LDV TIME (MDT) | LDV HEIGHT (M) | LDV SPEED (M/S) | LDV' TIME (MDT) | LDV' HEIGHT (M) | LDV' SPEED (M/S) | TETHERSONDE TIME (MDT) | TETHERSONDE HEIGHT (M) | TETHERSONDE SPEED (M/S) | PIBAL TIME (MDT) | PIBAL HEIGHT (M) | PIBAL SPEED (M/S) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 AUG 76 | | | | | | | | | | | | | | |
| 1 | 0929-0933 | 214 | 171 | 0929-0933 | 150-200 | 10.7 | | | | 0925 | 234 | 6.3 | | | |
| 2 | 0936-0941 | 213 | 174 | 0939-0941 | 182 | 9.6 | | | | | | | | | |
| 3 | 1020-1024 | 204 | 183 | 1020-1024 | 121 | 8.4 | | | | | | | | | |
| 4 | 1026-1029 | 213 | 193 | 1026-1029 | 121 | 7.7 | | | | | | | 1031 | 97-202 | 7.7 |
| 5 | 1032-1035 | 214 | 189 | 1030 | 121 | 8.0 | | | | | | | 1031 | 97-202 | 7.7 |
| 6 | 1047-1049 | 241 | 187 | 1047-1049 | 121 | 7.8 | | | | | | | | | |
| 7 | 1057-1102 | 279 | 185 | 1057-1102 | 121 | 7.5 | | | | | | | | | |
| 8 | 1103-1108 | 288 | 208 | 1103-1108 | 121 | 7.6 | | | | | | | | | |
| 9 | 1109-1112 | 285 | 231 | 1109-1112 | 121 | 6.2 | | | | | | | | | |
| 10 | 1139-1142 | 526 | 289 | 1145 | 300 | 8.6 | | | | | | | | | |
| 11 | 1143-1146 | 288 | 235 | 1145-1146 | 200-300 | 8.5 | | | | | | | | | |
| 12 | 1147-1150 | 285 | 215 | 1149 | 150-200 | 8.6 | | | | | | | | | |
| 13 | 1157-1159 | 238 | 210 | 1204 b | 200 | 11.9 | | | | | | | | | |
| 14 | 1159-1204 | 278 | 218 | 1204 | 200 | 11.9 | | | | | | | 1201 | 97-202 | 5.0 |
| | 4 AUG 76 | | | | | | | | | | | | | | |
| 15 | 0856-0901 | 201 | 210 | 0856-0900 | 150-200 | 5.9 | | | | 0856-0900 | 203 | 5.4 | | | |
| 16 | 0904-0908 | 220 | 206 | 0904-0908 | 150-200 | 6.8 | | | | 0904-0908 | 234 | 5.5 | | | |
| 17 | 0908-0913 | 207 | 204 | 0908-0912 | 150-200 | 5.4 | | | | 0908-0909 | 234 | 5.3 | | | |
| 18 | 0913-0916 | 210 | 208 | 0916 | 150-200 | 6.1 | | | | | | | | | |
| 19 | 0917-0920 | 213 | 213 | 0920 | 150-200 | 5.8 | | | | | | | | | |
| 20 | 0925-0929 | 213 | 210 | 0928 | 150-200 | 6.0 | | | | | | | | | |
| 21 | 0931-0934 | 217 | 227 | 0932-0933 | 150-300 | 5.7 | | | | | | | | | |
| 22 | 0935-0938 | 220 | 211 | 0932 | 150-200 | 5.7 | | | | 0938 | 20a | 6.2 | | | |
| 23 | 0938-0942 | 210 | 208 | 0932 | 150-200 | 5.7 | | | | 0942 | 112 | 5.4 | | | |
| 24 | 0954-0959 | 226 | 212 | | | | | | | 0954-0959 | 142 | 4.4 | | | |
| 25 | 1001-1003 | 216 | 220 | | | | | | | 1001-1003 | 173 | 4.2 | | | |
| 26 | 1007-1010 | 532 | 300 | | | | | | | 1007-1010 | 173 | 3.6 | | | |
| 27 | 1011-1015 | 502 | 292 | | | | | | | 1011-1015 | 165 | 3.1 | | | |
| 28 | 1016-1022 | 415 | 272 | | | | | | | 1016-1022 | 153 | 3.6 | | | |
| 29 | 1022-1027 | 455 | 282 | | | | | | | 1022-1027 | 163 | 3.8 | | | |
| 30 | 1029-1034 | 539 | 325 | | | | | | | 1029-1034 | 142 | 3.8 | | | |
| 31 | 1034-1038 | 550 | 328 | | | | | | | 1034-1038 | 152 | 3.1 | | | |
| 32 | 1038-1042 | 518 | 319 | | | | | | | 1038-1042 | 142 | 3.0 | | | |
| 33 | 1047-1051 | 511 | 317 | | | | | | | 1047-1051 | 142 | 4.0 | | | |
| 34 | 1052-1055 | 481 | 310 | | | | | | | 1052-1055 | 142 | 4.0 | | | |
| 35 | 1055-1059 | 543 | 325 | | | | | | | 1055-1059 | 142 | 3.7 | | | |
| 36 | 1138-1141 | 257 | 229 | 1123-1124 | 150-300 | 5.9 | | | | 1138-1141 | 142 | 3.1 | | | |
| 37 | 1141-1146 | 245 | 225 | 1123-1124 | 150-300 | 5.9 | | | | 1141-1146 | 142 | 3.0 | | | |
| 38 | 1149-1154 | 308 | 241 | 1149-1154 | 142 | 4.3 | | | | 1149-1154 | 142 | 2.5 | | | |
| 39 | 1158-1204 | 277 | 234 | 1158-1204 | 142 | 4.6 | | | | 1158-1204 | 112 | 3.5 | | | |
| 40 | 1247-1251 | 280 | 235 | | | | | | | 1247-1251 | 81 | 2.9 | | | |
| 41 | 1257-1304 | 260 | 229 | | | | | | | 1257 | 81 | 3.4 | | | |

(continued)

## TABLE 1 (continued)

| TRAVERSE NO. | TIME (MDT) | STACK DIST. (M) | PLUME HEIGHT (M) | LDV TIME (MDT) | LDV HEIGHT (M) | LDV SPEED (M/S) | LDV' TIME (MDT) | LDV' HEIGHT (M) | LDV' SPEED (M/S) | TETHERSONDE TIME (MDT) | TETHERSONDE HEIGHT (M) | TETHERSONDE SPEED (M/S) | PIBAL TIME (MDT) | PIBAL HEIGHT (M) | PIBAL SPEED (M/S) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42 | 1305-1310 | 245 | 225 | | | | | | | | | | 1311 | 97-202 | 5.5 |
| 43 | 1316-1321 | 262 | 210 | | 150 | 4.9 | 1320 | 150-200 | 6.1 | | | | | | |
| 44 | 1321-1328 | 232 | 253 | 1327 | 150 | 4.9 | 1327 | 150 | 4.8 | 1325-1328 | 96 | 1.8 | | | |
| 45 | 1330-1336 | 259 | 208 | 1327-1325 | 150 | 6.2 | 1331-1335 | 150-200 | 4.5 | 1330-1336 | 81 | 3.5 | 1331 | 97-202 | 3.2 |
| 46 | 1338-1341 | 280 | 229 | 1339-1340 | 150-300 | 6.1 | 1338-1339 | 150-300 | 6.4 | 1338-1341 | 81 | 2.8 | | | |
| 47 | 1342-1347 | 295 | 222 | 1345-1346 | 150-300 | 6.5 | 1342-1347 | 150-300 | 4.7 | 1342-1347 | 96 | 3.8 | | | |
| 48 | 1348-1354 | 253 | 208 | 1349-1350 | 150-300 | 6.9 | 1349-1350 | 150-200 | 6.0 | 1348-1354 | 112 | 2.1 | 1351 | 97-202 | 5.4 |
| 49 | 1444-1448 | 276 | 250 | 1445-1446 | 200-300 | 5.2 | 1444 | 200-300 | 3.6 | 1444-1448 | 66 | 1.4 | | | |
| 50 | 1449-1452 | 285 | 262 | 1449-1450 | 200-300 | 5.0 | 1451 | 200-300 | 4.2 | 1449-1452 | 51 | 4.1 | 1451 | 97-306 | 3.3 |
| 51 | 1452-1456 | 312 | 264 | 1453-1454 | 200-300 | 4.3 | 1455 | 200-300 | 5.3 | 1452-1456 | 51 | 3.8 | | | |
| 52 | 1456-1501 | 259 | 234 | 1457-1458 | 200-300 | 5.8 | 1459 | 200 | 5.5 | 1456-1501 | 81 | 2.5 | | | |
| 53 | 1501-1506 | 296 | 222 | 1501-1506 | 150-300 | 7.1 | 1502-1507 | 150-300 | 5.7 | 1501-1505 | 81 | 3.2 | | | |
| 54 | 1506-1512 | 281 | 234 | 1509-1510 | 200-300 | 7.1 | 1506-1510 | 200-300 | 7.1 | | | | | | |
| 55 | 1533-1538 | 444 | 251 | 1533-1538 | 200-300 | 6.7 | 1532-1537 | 200-300 | 4.7 | | | | | | |
| 56 | 1538-1543 | 392 | 236 | 1538-1542 | 200-300 | 6.6 | 1540 | 200-300 | 4.3 | | | | | | |
| | 5 AUG 76 | | | | | | | | | | | | | | |
| 57 | 0924-0930 | 202 | 230 | 0926-0930 | 200-300 | 5.1 | 0927-0928 | 200-300 | 4.4 | 0924-0930 | 234 | 5.2 | | | |
| 58 | 0932-0937 | 227 | 236 | 0934-0935 | 200-300 | 5.2 | 0931-0935 | 200-300 | 4.2 | 0932-0937 | 234 | 4.7 | 0936 | 97-306 | 4.4 |
| 59 | 0937-0941 | 206 | 235 | 0938-0939 | 200-300 | 4.3 | 0938-0939 | 200-300 | 3.9 | 0937-0941 | 234 | 5.0 | | | |
| 60 | 0941-0948 | 222 | 239 | 0942-0943 | 200-300 | 4.3 | 0942-0946 | 200-300 | 3.9 | 0941-0948 | 234 | 4.5 | | | |
| 61 | 0948-0952 | 201 | 243 | 0950-0951 | 200-300 | 4.6 | 0950 | 200-300 | 3.8 | 0948-0952 | 234 | 4.0 | | | |
| 62 | 0952-0957 | 214 | 226 | 0954-0955 | 150-300 | 5.2 | 0953-0954 | 150-300 | 4.9 | 0952-0957 | 234 | 4.1 | | | |
| 63 | 1000-1004 | 205 | 237 | 1003-1004 | 200-300 | 3.7 | 0959 | 303 | 3.8 | 1000-1004 | 234 | 3.4 | | | |
| 64 | 1004-1008 | 214 | 227 | 1006-1007 | 150-300 | 3.9 | | 1000 | | 1004-1008 | 234 | 3.7 | | | |
| 65 | 1008-1013 | 202 | 245 | 1010-1011 | 200-300 | 3.8 | | 1000 | | 1008-1013 | 234 | 3.4 | | | |
| 66 | 1013-1018 | 479 | 340 | 1015 | 300-400 | 3.4 | | 1000 | | 1013-1018 | 224 | 3.5 | | | |
| 67 | 1019-1023 | 504 | 320 | 1019-1023 | 300 | 4.3 | | 1000 | | 1019-1023 | 173 | 3.8 | | | |
| 68 | 1036-1039 | 204 | 229 | 1036-1037 | 150-300 | 5.3 | 1037-1038 | 150-300 | 4.9 | 1031-1039 | 173 | 3.9 | 1036 | 97-306 | 2.3 |
| 69 | 1040-1044 | 233 | 239 | 1040-1041 | 200-300 | 5.5 | 1041 | 200-300 | 5.2 | 1040-1044 | 173 | 3.5 | | | |
| 70 | 1100-1108 | 219 | 237 | 1105 | 200-300 | 4.5 | 1100-1108 | 200-300 | 4.5 | 1100-1108 | 173 | 3.8 | | | |
| 71 | 1116-1120 | 217 | 225 | 1116-1120 | 150-300 | 5.4 | 1118-1119 | 150-300 | 4.1 | 1116-1120 | 173 | 4.0 | | | |
| 72 | 1121-1126 | 221 | 240 | 1120-1126 | 200-300 | 4.4 | 1122-1126 | 200-300 | 3.4 | 1121-1126 | 173 | 1.2 | | | |
| 73 | 1126-1132 | 417 | 305 | 1129 | 300 | 3.6 | 1127 | 400 | 3.1 | 1126-1132 | 155 | 3.2 | 1131 | 202-306 | 2.3 |
| 74 | 1132-1138 | 477 | 328 | 1129 | 300-400 | 4.2 | | | | 1132-1138 | 112 | 3.0 | | | |
| 75 | 1138-1143 | 540 | 345 | 1129 | 300-400 | 4.2 | | | | 1138-1143 | 112 | 3.5 | | | |
| 76 | 1150-1155 | 247 | 255 | | | | | | | 1150-1155 | 112 | 2.5 | | | |
| 77 | 1156-1201 | 310 | 277 | | | | | | | 1156-1201 | 112 | 1.7 | | | |
| 78 | 1211-1216 | 426 | 343 | 1217 | 300-400 | 3.8 | 1217-1218 | 300-400 | 2.9 | 1211-1216 | 112 | 2.8 | | | |
| 79 | 1216-1221 | 500 | 344 | 1217-1221 | 300-400 | 4.4 | 1217-1222 | 300-400 | 3.5 | 1216-1221 | 112 | 3.5 | | | |
| 80 | 1221-1227 | 539 | 325 | 1221-1225 | 300-400 | 4.6 | 1221-1225 | 300-400 | 4.0 | 1221-1227 | 112 | 2.7 | | | |
| 81 | 1308-1310 | 259 | 253 | 1310-1311 | 200-300 | 5.4 | 1311 | 200 | 3.7 | 1308-1310 | 81a | 3.6 | | | |
| 82 | 1310-1313 | 256 | 255 | 1310-1311 | 200-300 | 5.4 | 1311 | 200 | 3.7 | 1311-1313 | 81a | 2.3 | | | |
| 83 | 1314-1318 | 319 | 288 | 1315 | 300 | 4.0 | 1318 | 200 | 3.5 | 1314-1318 | 81a | 2.1 | | | |
| 84 | 1319-1323 | 267 | 239 | 1319-1323 | 200-300 | 5.0 | 1323 | 300 | 6.6 | 1319-1323 | 81a | 2.4 | | | |
| 85 | 1328-1331 | 265 | 250 | 1330-1331 | 200-300 | 4.2 | 1330 | 200 | 5.4 | 1328-1331 | 81a | 3.8 | | | |
| 86 | 1331-1334 | 259 | 245 | 1331-1334 | 200-300 | 4.6 | | | | 1331-1334 | 81a | 3.4 | | | |

(continued)

# TABLE 1 (continued)

| TRAV-ERSE NO. | TIME (MDT) | STACK DIST. (M) | PLUME HEIGHT (M) | LDV TIME (MDT) | LDV HEIGHT (M) | LDV SPEED (M/S) | LDV' TIME (MDT) | LDV' HEIGHT (M) | LDV' SPEED (M/S) | TETHERSONDE TIME (MDT) | TETHERSONDE HEIGHT (M) | TETHERSONDE SPEED (M/S) | PIBAL TIME (MDT) | PIBAL HEIGHT (M) | PIBAL SPEED (M/S) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 87 | 1345-1350 | 293 | 265 | 1352-1353 b | 200-300 | 5.9 | | | | 1345-1350 | 81 a | 3.2 | | | |
| 88 | 1351-1354 | 304 | 253 | 1352-1353 | 200-300 | 5.9 | | | | 1351-1354 | 81 a | 2.9 | 1401 | 97-306 | 2.4 |
| 89 | 2032-2035 | 248 | 437 | 2034-2035 | 400-500 | 2.0 | | | | 2033-2035 | 142 | 1.7 | | | |
| 90 | 2035-2038 | 210 | 430 | 2038 | 400-500 | 1.9 | | | | 2035-2038 | 142 | 1.8 | | | |
| 91 | 2041-2047 | 50 | 240 | 2041-2046 | 200-300 | 1.9 | | | | 2041-2047 | 173 | 1.8 | | | |
| 92 | 2048-2056 | 52 | 243 | 2049-2054 | 200-300 | 1.8 | | | | 2048-2056 | 173 | 1.8 | | | |
| 93 | 2056-2103 | 36 | 208 | 2057-2101 | 150-200 | 1.9 | | | | 2056-2103 | 173 | 1.8 | | | |
| | 6 AUG 76 | | | | | | | | | | | | | | |
| 94 | 0918-0923 | 201 | 250 | 0919-0923 | 200-300 | 3.9 | 0919-0923 | 200 | 3.4 | 0918-0923 | 295 | 3.6 | | | |
| 95 | 0931-0934 | 207 | 213 | 0934 | 150-200 | 5.5 | 0930-0934 | 150-200 | 4.2 | 0931-0934 | 264 | 3.4 | | | |
| 96 | 0934-0937 | 221 | 232 | 0935 | 200-300 | 5.2 | 0934-0935 | 200-300 | 3.6 | 0934-0937 | 264 | 4.1 | | | |
| 97 | 0937-0941 | 208 | 223 | 0938-0939 | 150-300 | 4.2 | 0938 | 150-300 | 4.5 | 0937-0941 | 264 | 3.9 | | | |
| 98 | 0941-0944 | 206 | 218 | 0942 | 150-200 | 5.1 | 0941-0942 | 150-200 | 4.1 | 0941-0944 | 264 | 4.0 | | | |
| 99 | 0944-0947 | 214 | 208 | 0942-0949 | 150-200 | 6.1 | 0945-0946 | 150-200 | 4.3 | 0944-0947 | 264 | 4.5 | | | |
| 100 | 0947-0951 | 211 | 207 | 0949 | 150-200 | 7.2 | 0949 | 150-200 | 4.2 | 0947-0951 | 264 | 5.0 | 0951 | 97-202 | 5.7 |
| 101 | 0951-0954 | 208 | 203 | 0953 | 150-200 | 7.0 | 0953 | 150-200 | 5.8 | 0951-0954 | 264 | 5.5 | | | |
| 102 | 0957-1001 | 496 | 273 | 0957-1001 | 200-300 | 6.0 | 0957-1001 | 200-300 | 5.6 | 0957-1000 | 264 | 5.7 | | | |
| 103 | 1005-1008 | 1061 | 374 | 1001 | 200-300 | 6.1 | 1005 | 300-400 | 5.8 | | | | | | |
| 104 | 1033-1038 | 236 | 203 | 1035 | 150-200 | 6.0 | 1034-1035 | 150-200 | 5.1 | 1003-1038 | 173 | 5.9 | | | |
| 105 | 1039-1043 | 532 | 267 | 1039-1043 | 200-300 | 7.0 | 1039-1043 | 200-300 | 6.0 | 1039-1043 | 173 | 5.8 | | | |
| 106 | 1043-1045 | 205 | 198 | 1042 | 150-200 | 7.3 | 1042-1046 | 150-200 | 6.0 | 1043-1045 | 173 | 5.8 | | | |
| 107 | 1046-1050 | 407 | 268 | 1049-1050 | 200-300 | 5.5 | 1046-1050 | 200-300 | 5.2 | 1046-1050 | 173 | 5.5 | | | |
| 108 | 1053-1056 | 209 | 211 | 1053 | 150-200 | 5.4 | 1053-1054 | 150-200 | 5.1 | 1053-1056 | 173 | 5.0 | | | |
| 109 | 1057-1102 | 527 | 279 | 1057-1102 | 200-300 | 6.1 | 1058-1102 | 200-300 | 5.5 | 1057-1102 | 173 | 5.5 | | | |
| 110 | 1103-1105 | 207 | 213 | 1105 | 150-200 | 5.8 | 1105 | 150-200 | 4.6 | 1103-1105 | 173 | 4.5 | | | |
| 111 | 1105-1110 | 548 | 303 | 1106-1110 | 300 | 6.3 | 1105-1110 | 200-300 | 5.8 | 1105-1110 | 173 | 4.9 | | | |
| 112 | 1112-1115 | 221 | 220 | 1113 | 150-200 | 5.6 | 1113 | 150-200 | 5.7 | 1112-1115 | 173 | 5.1 | | | |
| 113 | 1115-1120 | 505 | 291 | 1118 | 300 | 6.4 | 1117-1121 | 300 | 6.3 | 1115-1120 | 173 | 5.3 | | | |
| 114 | 1120-1126 | 437 | 263 | 1121-1126 | 200-300 | 5.5 | 1121-1124 | 200-300 | 5.9 | 1120-1126 | 173 | 5.4 | | | |
| 115 | 1126-1129 | 230 | 212 | 1127 | 150-200 | 5.7 | 1128 | 150-200 | 6.1 | 1126-1129 | 173 | 5.2 | | | |
| 116 | 1130-1135 | 549 | 286 | 1132 | 300 | 6.1 | 1132-1133 | 200-300 | 5.1 | 1130-1135 | 173 | 5.1 | | | |
| 117 | 1135-1139 | 271 | 226 | 1135-1136 | 150-300 | 5.5 | 1135-1139 | 150-200 | 5.3 | 1135-1139 | 173 | 5.2 | | | |
| 118 | 1143-1147 | 237 | 212 | 1143-1147 | 250-300 | 6.2 | 1143-1147 | 150-200 | 5.7 | 1143-1147 | 173 | 5.4 | | | |
| 119 | 1147-1151 | 234 | 212 | 1146-1150 | 150-200 | 6.4 | 1147-1151 | 150-200 | 7.0 | 1147 | 173 | 5.6 | | | |
| 120 | 1151-1156 | 288 | 226 | 1151 | 150-200 | 7.0 | 1151-1155 | 150-300 | 6.8 | | | | 1205 | 97-306 | 7.2 |

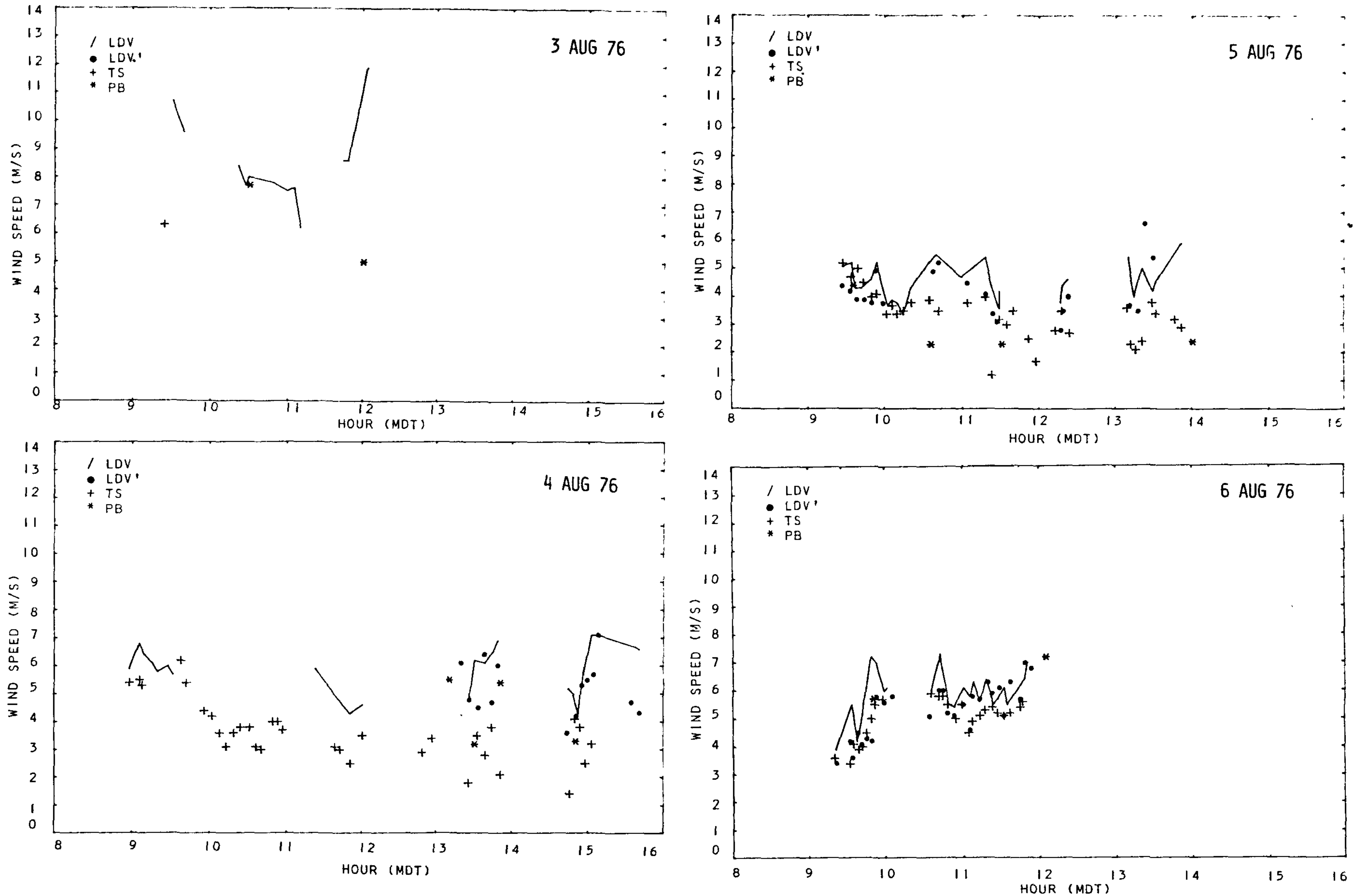


Figure 4. Wind Speed by Day

millivolts different from the other side, the traverse was considered to be invalid due to an incomplete traverse of the plume or another sampling problem. This background value was then subtracted from each 20-meter average for the traverse. When the resulting values were negative (due to instrument noise), the result was considered zero.

The next step was to multiply the adjusted millivolt readings by the calibration factor. This factor was determined from a calibration curve that was made up of data from all calibrations made during the test period. The calibration factor is time-dependent because the COSPEC's response varies markedly with the sun angle. This variation was considered to be consistent during the week of field work; therefore, the same time-dependent calibration curve was used each day.

Because of the non-linear response above 600 ppmM of the particular COSPEC used in this study*, an additional step was required to prepare the COSPEC data for flux calculations. Extensive tests were made in 1975 of the linearity of the two COSPECs used in this study. From the information gathered in these tests a curve was constructed to estimate readings for values about 600 ppmM $SO_2$. Values from the curve were then used in a polynominal regression to determine a conversion formula to obtain true ppmM values for those readings over 600 pppM. When this was completed, the COSPEC results were ready to be used for flux calculations.

GFC

The Gas Filter Correlation instrument data had not been previously processed because the sensitivity (ppmM $SO_2$/mv) was not available.[1] Using a calibration curve provided by the Project Officer[6] for 5 August 1976 (judged the most suitable data to be processed), the sensitivities were found to be:

- 5.88 ppmM $SO_2$/mv (day)
- 6.58 ppmM $SO_2$/mv (night)

Following the same procedure used with the COSPEC the zero reference level was determined for the millivolt readings for each of 33 GFC plume profiles. This was more difficult for the GFC because the profiles were less distinct than the typical COSPEC profile. In addition there was greater drift from one edge of the plume to the other, necessitating the subtraction

*Note added in review: It is now possible to execute special fine tuning to eliminate this high concentration nonlinearity for COSPEC II and III.

of sloped zero-reference lines. (No non-linearity correction was required.) The next step was to apply the sensitivities to yield the ppmM $SO_2$ optical depth values for processing into mass emission rates.

## $SO_2$ Mass Flux

The mass emission rates were calculated from the three remote sensor $SO_2$ optical depths, the four sets of wind velocities, and the geography (X-Y coordinates) provided by the MAP System. The procedure, described in detail elsewhere[2], is summarized below.

The $SO_2$ Mass Flux is calculated by the formula:

$$SO_2 \text{ FLUX} = \Sigma\,(C \times \sin\alpha \times l \times \upsilon \times F)$$

(summation of individual segments of traverse)

where C = COSPEC optical depth reading in ppmM (average value during one segment)

$l$ = length of road segment

$\alpha$ = angle between road segment and wind direction

$\upsilon$ = wind speed

F = conversion factor used to obtain MT/D $SO_2$.

As the COSPEC passes under the plume, it measures the total burden of $SO_2$ which is output by the MAP System as an average value each 20 meters along the road. To obtain the flux of gas across any segment the optical depth in ppmM is multiplied by the length of the segment to obtain the total gas above the segment. This value is multiplied by the sine of the angle between the wind direction and the road segment to account for the fact that the road may not be perpendicular to the flow of the gas. Finally, multiplying by the wind speed and a conversion factor to convert to metric tons per day (MT/D) gives the final result. The sum of these calculations over one traverse gives a value for total mass flux. The sine $\alpha$ term equals unity if the X-Y values are projected onto a line perpendicular to the wind direction. This step effectively shortens the segment length in proportion to the line of the wind/road angle and allows for calculation of the center of mass and movements about the center of mass.

Because the direction of the wind can vary dramatically during a short time, the wind direction was derived from the center of mass of each traverse rather than as measured by one of the wind sensors. This value gives the best estimate of true plume direction but does not account for possible wind shear.[7]

## Flux Calculations

Once the necessary calibration and nonlinearity factors had been applied to the data and the appropriate wind speed had been chosen, the data were ready for the actual flux computer calculations. The following outlines the methodology of the flux calculation program. Once the data to be used were loaded into the computer memory, the center of mass of the COSPEC data was calculated.

Because the gas flowing across the surface perpendicular to the wind direction is of interest, the X-Y points of the traverse are projected onto the line perpendicular to the stack-traverse midpoint segment, using the assumption that the wind is blowing parallel to the stack/midpoint vector. An example of the computer printout for the flux calculation is shown in Figure 5.

EPA SPECTROMETER EVALUATION: SO2 MASS FLUX AND STATISTICS CALCULATIONS

DATE: 4 AUGUST 76 TRAVERSE # 16

TIME: 904- 905 MDT WIND SPEED: 6.8 MPS

INSTRUMENT: 1

| SEGMENT # | W.P ANGLE | SEG LENGTH | SO2 PPMM | AREA PPMM2 | FLUX MT/DAY | SUM MT. DAY | |
|---|---|---|---|---|---|---|---|
| 120 | 103 | 37 | 3 | 113 | 0.2 | 0.2 | 0.13 |
| 121 | 103 | 20 | 1 | 132 | 0.0 | 0.2 | 0.03 |
| 122 | 103 | 19 | 3 | 191 | 0.1 | 0.3 | 0.09 |
| 123 | 103 | 21 | 3 | 256 | 0.1 | 0.4 | 0.10 |
| 124 | 103 | 20 | 0 | 256 | 0.0 | 9.4 | 0.00 |
| 125 | 103 | 19 | 0 | 256 | 0.0 | 0.4 | 0.00 |
| 126 | 103 | 21 | 12 | 497 | 0.4 | 0.8 | 0.38 |
| 127 | 103 | 20 | 41 | 1314 | 1.3 | 2.1 | 1.28 |
| 128 | 103 | 19 | 247 | 5377 | 7.3 | 9.3 | 7.29 |
| 129 | 103 | 20 | 361 | 13126 | 11.2 | 20.5 | 11.16 |
| 130 | 101 | 20 | 525 | 24649 | 18.3 | 38.9 | 18.30 |
| 131 | 101 | 21 | 123 | 27428 | 4.0 | 42.9 | 4.03 |
| 132 | 103 | 19 | 6 | 27543 | 0.2 | 43.0 | 0.19 |
| 133 | 101 | 20 | 9 | 27714 | 0.3 | 43.3 | 0.27 |
| 134 | 101 | 21 | 9 | 27897 | 0.3 | 43.6 | 0.29 |
| 135 | 101 | 20 | 1 | 27918 | 0.0 | 43.6 | 0.03 |
| 136 | 103 | 20 | [illegible] | 27979 | 0.1 | 43.7 | 0.10 |
| [illegible] | 103 | 19 | 0 | [illegible] | 0.0 | 43.7 | 0.00 |
| [illegible] | 101 | 21 | [illegible] | [illegible] | 0.2 | 43.9 | 0.24 |
| [illegible] | 100 | 16 | 0 | [illegible] | 0.0 | 43.9 | 0.00 |

SO2 MASS FLUX 43.9[illegible] METRIC TONS DAY
[illegible] KILOGRAMS HOUR

CENTER OF MASS COORDINATE: [illegible]565.0798 4075692.848

PT. NEAREST C OF M: 129 722565.3210 4075694.19

[illegible]MENT: [illegible]
ANGLE TO PT NEAREST C OF M: -13.[illegible]
ANGLE TO INITIAL PT: -12.[illegible]

Figure 5. Typical flux calculation printout

## Plume Profiles

At the time each flux calculation was made, an individual plume profile was plotted. Figure 6 shows eight representative plume profiles. The traverse route is shown as a straight or curved line, and the projection line is drawn normal to the plume axis (not shown, but the stack is indicated by a dot). The plume profile is plotted "away" from the stack, parallel to the wind flow. These plume profiles were useful as an editing tool and played a major part in the analysis of the flux results.

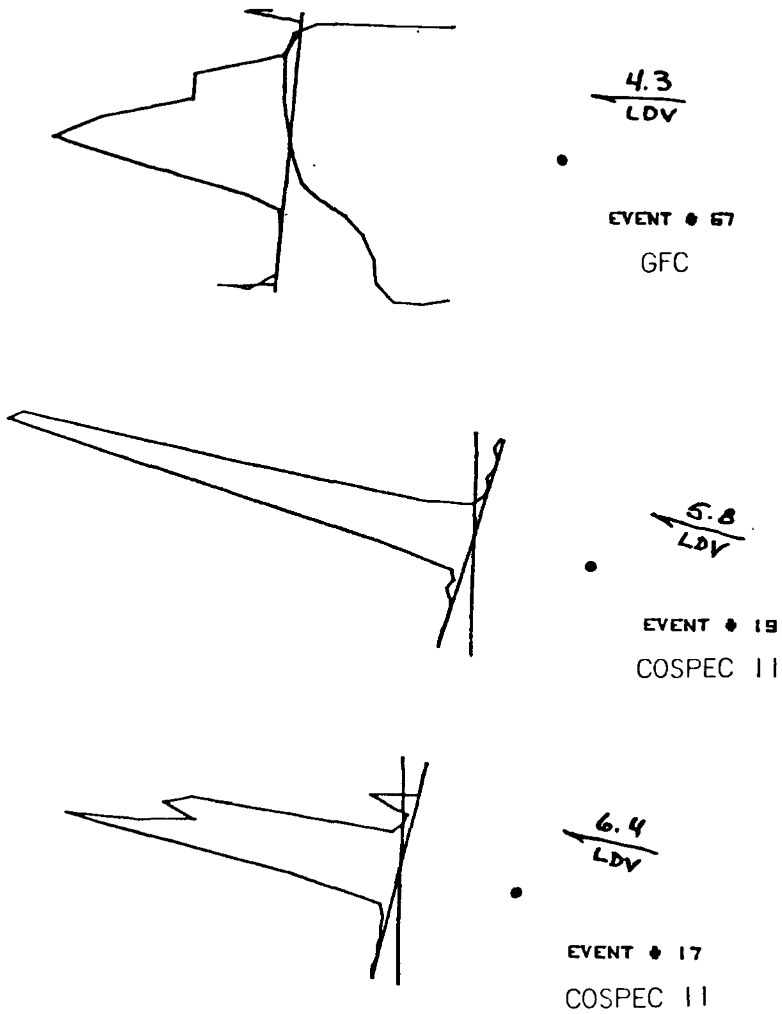


Figure 6. Typical plume profiles
(continued)

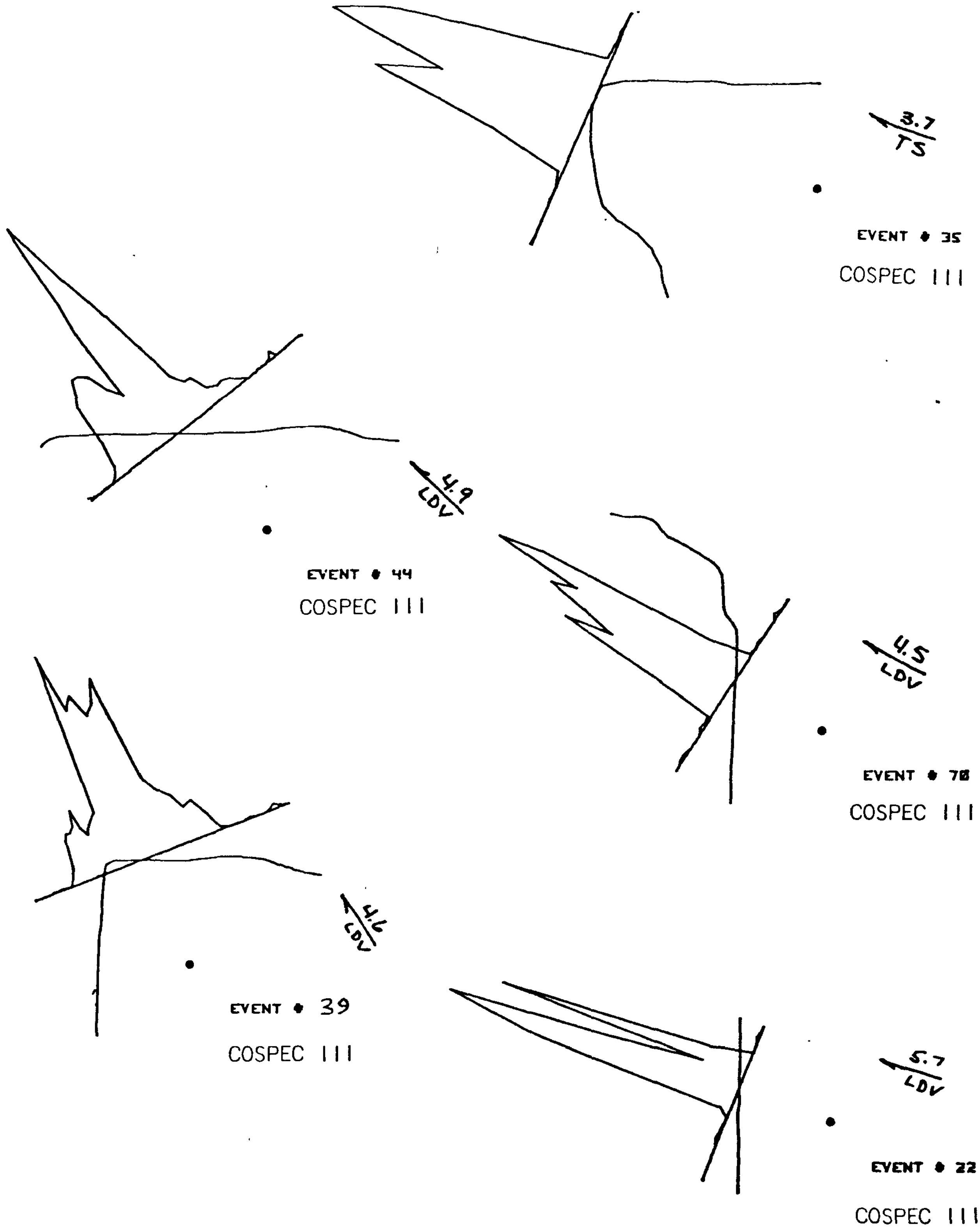


Figure 6. (continued)

## SECTION 5

## RESULTS

### REMOTE SENSORS

A total of 308 flux calculations were made from the three instrument/four wind system data matrix. The results for each instrument are presented in the following graphs and tables for the four measurement days.

### COSPEC III

The 176 $SO_2$ fluxes for the COSPEC III are presented in Figure 7 and Table 2. The averages and standard deviations for all values are summarized below:

| DATA SETS | $SO_2$ MASS FLUX MEAN (MT/D) | σ (% of MEAN) |
|---|---|---|
| COSPEC III/LDV' | 78.9 | 40.9 |
| COSPEC III/TS | 64.9 | 37.0 |
| COSPEC III/PB | 68.4 | 38.9 |

The plots (Figure 7) show the individual results as connected lines (except dots appear where more than 30 minutes passed between traverses). The horizontal line represents the mean for each set of results.

The tabulations (Table 2) give the day, time, traverse number, stack distance in meters, plume width (the approximate 6σ width of the projected plume profile (in meters), the wind speed in meters per second, and the three columns of fluxes where wind data were available (MT/D $SO_2$). The coding (a, b, c, d, e) is discussed under Analysis of Results.

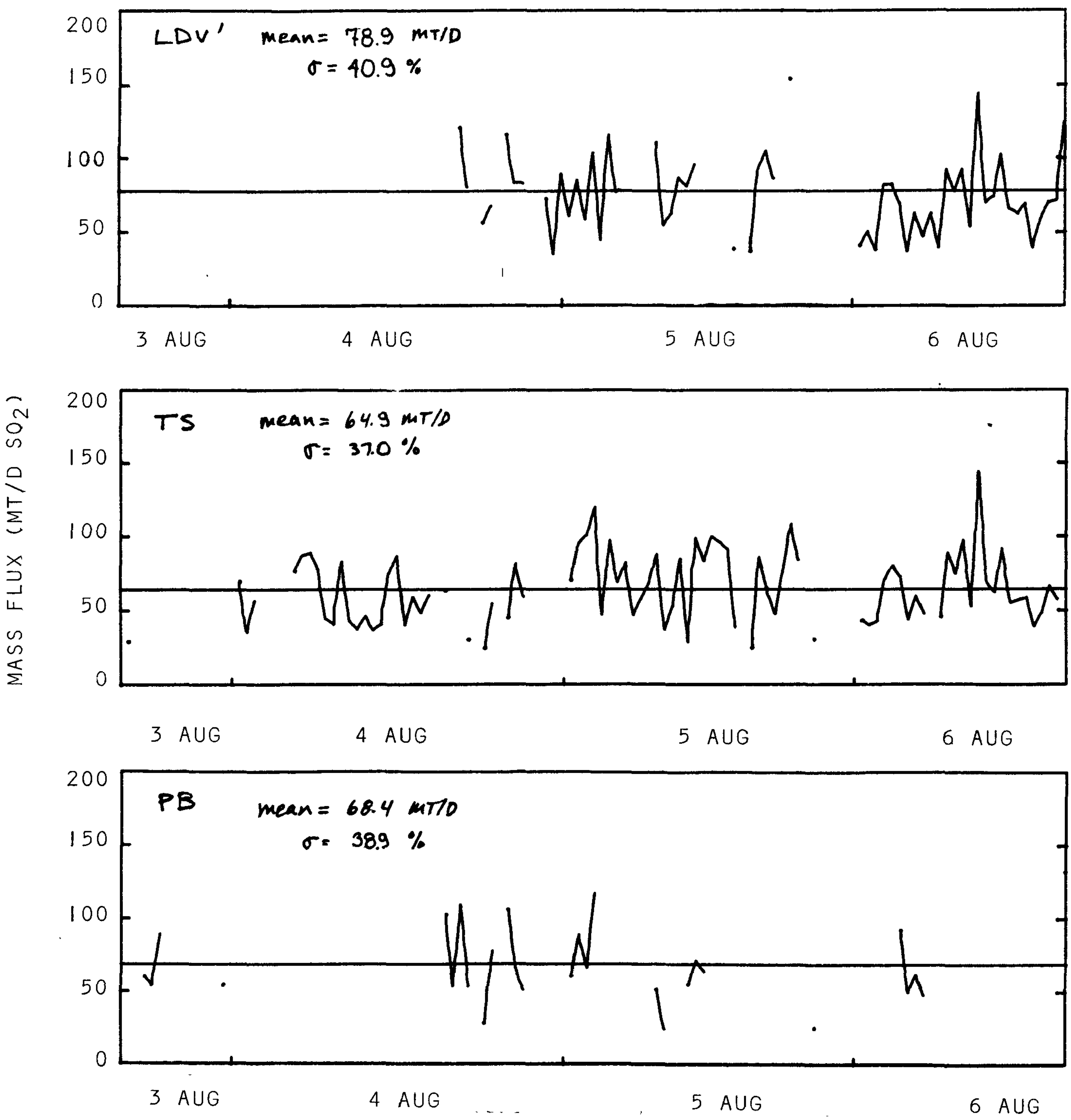


Figure 7. COSPEC III $SO_2$ Mass Flux Results

TABLE 2. $SO_2$ MASS FLUX RESULTS - COSPEC III

| DATE AUG 1976 | TIME (MDT) | TRAV-ERSE NO. | STACK DIST. (M) | PLUME WIDTH (M) | WIND SPEED (M/S) | $SO_2$ MASS FLUX (MT/D) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | LDV' | TS | PB |
| 3 | 0929-0933 | 1 | 225 | 150 | 10.7 | | 29.0 | |
| | 0936-0941 | 2 | 225 | 150 | 9.6 | | | |
| | 1020-1024 | 3 | 200 | 175 | 8.4 | | | 60.1b |
| | 1026-1029 | 4 | 225 | 150 | 7.7 | | | 54.1b |
| | 1032-1035 | 5 | 225 | 175 | 8.0 | | | 89.3b |
| | 1047-1049 | 6 | 250 | 125 | 7.8 | | | |
| | 1057-1102 | 7 | 275e | 300c | 7.5 | | | |
| | 1103-1108 | 8 | 300e | 150 | 7.6 | | | |
| | 1109-1112 | 9 | 275e | 175c | 6.2 | | | |
| | 1143-1146 | 11 | 275e | 225 | 8.5 | | | |
| | 1147-1150 | 12 | 300e | 250 | 8.6 | | | |
| | 1157-1159 | 13 | 250 | 250 | 11.9 | | | 54.5b |
| 4 | 0856-0901 | 15 | 200 | 200 | 5.9 | | 69.4 | |
| | 0904-0908 | 16 | 225 | 175 | 6.8 | | 35.5 | |
| | 0908-0913 | 17 | 225 | 175 | 6.4 | | 56.5 | |
| | 0913-0916 | 18 | 225 | 175 | 6.1 | | | |
| | 0917-0920 | 19 | 225 | 200 | 5.8 | | | |
| | 0925-0929 | 20 | 225 | 150 | 6.0 | | | |
| | 0931-0934 | 21 | 225 | 175 | 5.7 | | | |
| | 0935-0938 | 22 | 225 | 175 | 5.7 | | 76.7a | |
| | 0938-0942 | 23 | 225 | 175 | 5.7 | | 87.4a | |
| | 0954-0959 | 24 | 250 | 225 | 4.4 | | 89.2 | |
| | 1000-1003 | 25 | 225 | 175 | 4.2 | | 78.6 | |
| | 1007-1010 | 26 | 575 | 325c | 3.6 | | 44.4a | |
| | 1011-1015 | 27 | 575e | 350c | 3.1 | | 41.0a | |
| | 1016-1022 | 28 | 550e | 350c | 3.6 | | 82.7a | |
| | 1022-1027 | 29 | 525e | 350c | 3.8 | | 43.0a | |
| | 1029-1034 | 30 | 550e | 350c | 3.8 | | 37.3a | |
| | 1034-1038 | 31 | 575e | 375c | 3.1 | | 46.0a | |
| | 1038-1042 | 32 | 550e | 300c | 3.0 | | 36.8a | |
| | 1047-1051 | 33 | 550e | 325 | 4.0 | | 40.7a | |
| | 1052-1055 | 34 | 550e | 350c | 4.0 | | 75.4a | |
| | 1055-1059 | 35 | 575e | 325c | 3.7 | | 86.7a | |
| | 1138-1141 | 36 | 275 | 225c | 5.9 | | 40.5a | |
| | 1141-1146 | 37 | 225e | 300 | 5.9 | | 58.9a | |
| | 1149-1154 | 38 | 300e | 275 | 4.3 | | 48.8a | |
| | 1158-1204 | 39 | 275e | 400 | 4.6 | | 60.3a | |
| | 1247-1251 | 40 | 250 | d450 | 2.9 | | 108.2a | |
| | 1257-1304 | 41 | 275 | 325 | 3.4 | | 63.6a | 102.9b |
| | 1305-1310 | 42 | 250 | 150 | 5.5 | | | 53.9b |
| | 1316-1321 | 43 | 250 | 275 | 4.9 | 121.0 | | 109.1b |
| | 1321-1328 | 44 | 300 | 400 | 4.9 | 80.7a | 30.3a | 53.8b |

(continued)

TABLE 2. (continued)

| DATE AUG 1976 | TIME (MDT) | TRAV-ERSE NO. | STACK DIST. (M) | PLUME WIDTH (M) | WIND SPEED (M/S) | SO₂ MASS FLUX (MT/D) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | LDV' | TS | PB |
| 4 | 1330-1336 | 45 | 250 | d450 | 6.2 | 77.2 | 60.0 a | 54.9 |
| | 1338-1341 | 46 | 275 | 200 | 6.1 | 56.3 | 24.6 a | 28.2 b |
| | 1342-1347 | 47 | 325 | 300 | 6.5 | 67.7 | 54.7 a | 77.8 b |
| | 1444-1448 | 49 | 275 | 275 | 5.2 | 116.0 | 45.0 a | 106.0 b |
| | 1449-1452 | 50 | 275 | 225 | 5.0 | 83.3 | 81.3 a | 65.5 |
| | 1452-1456 | 51 | 300 | 300 | 4.3 | 82.5 | 59.1 a | 51.3 |
| | 1456-1501 | 52 | 275 | d425 | 5.8 | 137.1 | 62.3 a | 82.3 b |
| | 1506-1512 | 54 | 250 e | 250 | 7.1 | 72.5 | | |
| | 1533-1538 | 55 | 475 | 250 c | 6.7 | 35.2 | | |
| | 1538-1543 | 56 | 475 | 400 c | 6.6 | 89.6 | | |
| 5 | 0924-0930 | 57 | 225 | 200 | 5.1 | 60.9 | 70.2 | 60.9 b |
| | 0932-0937 | 58 | 225 | 200 | 5.2 | 85.0 | 95.2 | 89.1 |
| | 0937-0941 | 59 | 225 | 200 | 4.3 | 58.7 | 101.2 | 66.2 |
| | 0941-0948 | 60 | 225 | 200 | 4.3 | 103.8 | 119.7 | 117.1 b |
| | 0948-0952 | 61 | 225 | 175 | 4.6 | 44.8 | 47.1 | |
| | 0952-0957 | 62 | 225 | 200 | 5.2 | 116.0 | 97.1 | |
| | 1000-1004 | 63 | 225 | 200 | 3.7 | 77.1 | 69.0 | |
| | 1004-1008 | 64 | 225 | 200 | 3.9 | | 81.9 | |
| | 1008-1013 | 65 | 225 | 175 | 3.8 | | 47.2 | |
| | 1013-1018 | 66 | 575 e | 350 c | 3.4 | | 57.7 a | |
| | 1019-1023 | 67 | 550 e | 300 | 4.3 | | 68.1 a | |
| | 1036-1039 | 68 | 225 | 275 | 5.3 | 110.5 | 87.9 | 51.8 |
| | 1040-1044 | 69 | 250 | 275 | 5.5 | 54.7 | 36.8 | 24.2 b |
| | 1100-1108 | 70 | 250 | 200 | 4.5 | 62.7 | 52.9 | |
| | 1116-1120 | 71 | 225 | 225 | 5.4 | 87.0 | 84.9 | |
| | 1121-1126 | 72 | 225 e | 275 | 4.4 | 81.3 | 28.7 | 55.0 b |
| | 1126-1132 | 73 | 500 e | 450 c | 3.6 | 95.7 a | 98.8 a | 71.0 |
| | 1132-1138 | 74 | 475 e | 450 c | 4.2 | | 83.6 a | 64.1 |
| | 1138-1143 | 75 | 575 e | 475 | 4.2 | | 99.9 a | |
| | 1150-1155 | 76 | 450 e | 700 c | 2.5 | | 96.1 a | |
| | 1156-1201 | 77 | 300 e | 750 | 1.7 | | 91.5 a | |
| | 1211-1216 | 78 | 575 e | 450 c | 3.8 | 39.0 b | 39.0 a | |
| | 1221-1227 | 80 | 575 e | 475 c | 4.6 | 36.8 | 24.8 a | |
| | 1308-1310 | 81 | 250 | 425 | 5.4 | 92.0 b | 89.5 a | |
| | 1310-1313 | 82 | 250 | 375 | 5.4 | 104.9 | 65.2 a | |
| | 1314-1318 | 83 | 300 | 425 | 4.0 | 86.7 a | 47.9 a | |
| | 1319-1323 | 84 | 275 | 650 | 5.0 | 208.1 | 75.7 a | |
| | 1328-1331 | 85 | 275 | 500 | 4.2 | 154.3 | 108.6 a | |
| | 1331-1334 | 86 | 275 | 375 | 4.6 | | 84.2 a | |
| | 1351-1354 | 88 | 325 | 450 | 5.9 | | 30.6 a | 25.3 b |
| 6 | 0918-0923 | 94 | 200 | 175 | 3.9 | 40.7 | 43.1 | |

(continued)

TABLE 2. (continued)

| DATE AUG 1976 | TIME (MDT) | TRAV-ERSE NO. | STACK DIST. (M) | PLUME WIDTH (M) | WIND SPEED (M/S) | $SO_2$ MASS FLUX (MT/D) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | LDV' | TS | PB |
| 6 | 0931-0934 | 95 | 225 | 200 | 5.5 | 50.1 | 40.4 | |
| | 0934-0937 | 96 | 250 | 150 | 5.2 | 37.9 | 43.2 | |
| | 0937-0941 | 97 | 225 | 200 | 4.2 | 82.2 | 71.2 | |
| | 0941-0944 | 98 | 225 | 250 | 5.1 | 82.2 | 80.2 | |
| | 0944-0947 | 99 | 225 | 175 | 6.1 | 69.7 | 72.9 | 92.4b |
| | 0947-0951 | 100 | 225 | 150 | 7.2 | 36.8 | 43.8 | 49.9b |
| | 0951-0954 | 101 | 225 | 150 | 7.0 | 62.6 | 59.4 | 61.6 |
| | 0957-1001 | 102 | 550 | 275 | 6.0 | 47.0 | 47.9 | 47.9b |
| | 1005-1008 | 103 | 1125 | 225 | 6.1 | 62.6 | | |
| | 1033-1038 | 104 | 225 | 150 | 6.0 | 39.4 | 45.6 | |
| | 1039-1043 | 105 | 550e | 275 | 7.0 | 92.0 | 89.0 | |
| | 1043-1045 | 106 | 225 | 250 | 7.3 | 77.5 | 74.9 | |
| | 1046-1050 | 107 | 425 | 275 | 5.5 | 91.9 | 97.2a | |
| | 1053-1056 | 108 | 225 | 175 | 5.4 | 53.9 | 52.8 | |
| | 1057-1102 | 109 | 550 | 300 | 6.1 | 144.2 | 144.2a | |
| | 1103-1105 | 110 | 250 | 200 | 5.8 | 70.0 | 68.5 | |
| | 1105-1110 | 111 | 575e | 250 | 6.3 | 73.7 | 62.3a | |
| | 1112-1115 | 112 | 225 | 200 | 5.6 | 102.3 | 91.5 | |
| | 1115-1120 | 113 | 550e | 275c | 6.4 | 65.6 | 55.2a | |
| | 1120-1126 | 114 | 550e | 300c | 5.5 | 62.4 | 57.1a | |
| | 1126-1129 | 115 | 250 | 125 | 5.7 | 68.8 | 58.7 | |
| | 1130-1135 | 116 | 575e | 275c | 6.1 | 39.2 | 39.2a | |
| | 1135-1139 | 117 | 250e | 175 | 5.5 | 58.8 | 48.5 | |
| | 1143-1147 | 118 | 275 | 200 | 6.2 | 70.0 | 66.4 | |
| | 1147-1151 | 119 | 250 | 150 | 6.4 | 71.6 | 57.3 | |
| | 1151-1156 | 120 | 275e | 150 | 7.0 | 124.7 | | 132.0b |

COSPEC II

The 54 $SO_2$ fluxes for the COSPEC II are presented in Figure 8 and Table 3. The averages and standard deviations for all values are summarized below:

| DATA SETS | $SO_2$ MASS FLUX MEAN (MT/D) | σ (% of MEAN) |
|---|---|---|
| COSPEC II/LDV' | 63.4 | 28.2 |
| COSPEC II/TS | 50.6 | 37.3 |
| COSPEC II/PB | 51.7 | 32.0 |

The plots and tabulations are identical to the preceding COSPEC III presentations.

GFC

The 57 $SO_2$ fluxes for the GFC are presented in Table 4. The averaged and standard deviations for all values are summarized below:

| DATA SETS | $SO_2$ MASS FLUX MEAN (MT/D) | σ (% of MEAN) |
|---|---|---|
| GFC/LDV' | 204.8 | 20.2 |
| GFC/TS | 139.4* | 50.3 |
| GFC/PB | 109.8 | 50.4 |

*Includes four night traverses

The GFC flux calculations were limited to one day only, 5 August 1976, because of an accumlulation of dust on the instrument mirror and other problems that occurred in the field.

The tabulation is the same as the preceding COSPEC III presentation. No plot of the GFC results is offered as they are clearly divergent by a factor of two or more from the COSPEC/ Method 6 values.

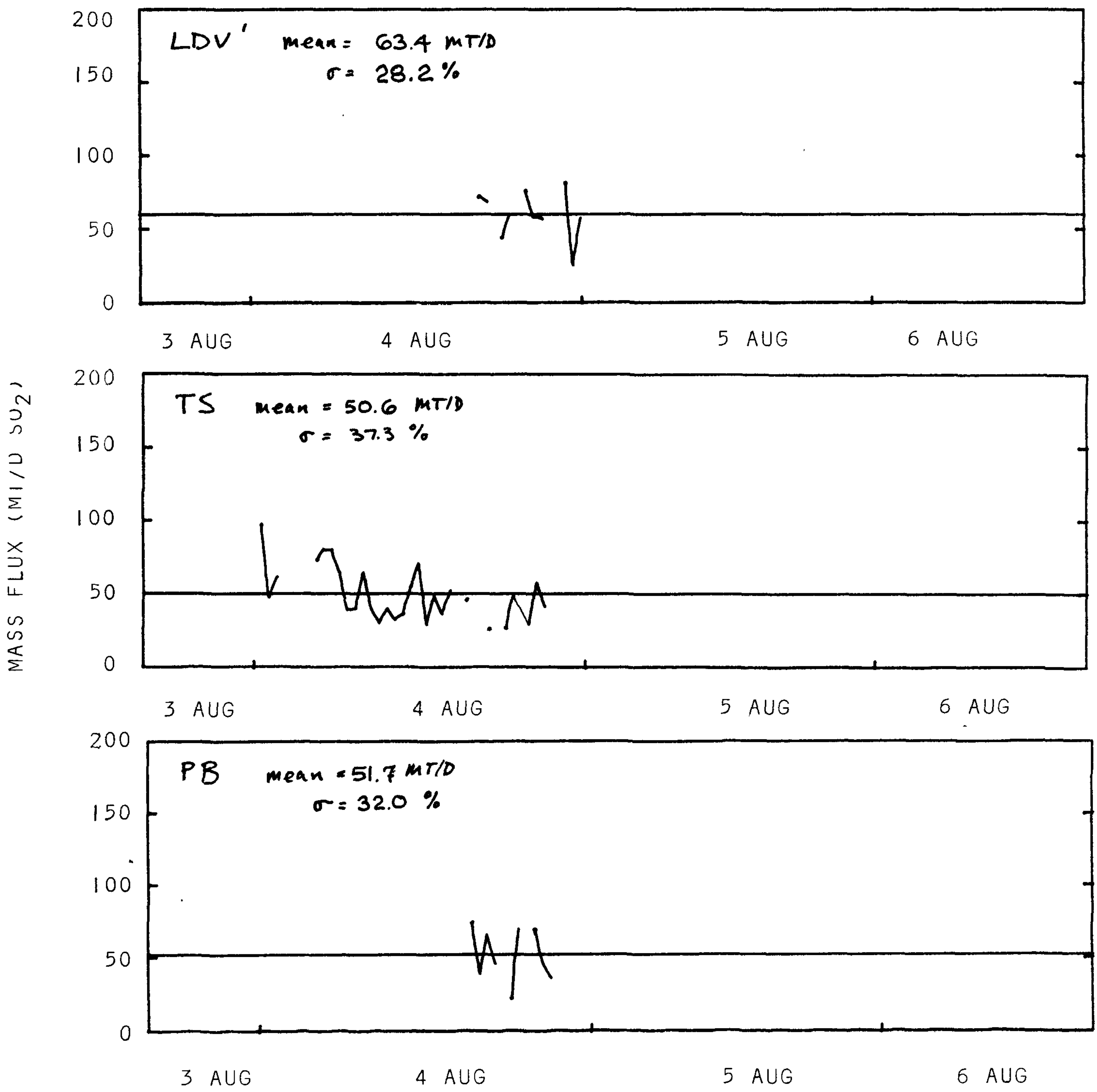


Figure 8. COSPEC II $SO_2$ Mass Flux Results

TABLE 3. $SO_2$ MASS FLUX RESULTS - COSPEC II

| DATE AUG 1976 | TIME (MDT) | TRAVERSE NO. | STACK DIST. (M) | PLUME WIDTH (M) | WIND SPEED (M/S) | $SO_2$ MASS FLUX (MT/D) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | LDV' | TS | PB |
| 4 | 0856-0901 | 15 | 225 | 200 | 5.9 | | 97.2 | |
| | 0904-0908 | 16 | 225 | 200 | 6.8 | | 47.3 | |
| | 0908-0913 | 17 | 225 | 225 | 6.4 | | 61.5 | |
| | 0913-0916 | 18 | 225 | 175 | 6.1 | | | |
| | 0917-0920 | 19 | 225 | 200 | 5.8 | | | |
| | 0925-0929 | 20 | 225 | 125 | 6.0 | | | |
| | 0931-0934 | 21 | 225 | 125 | 5.7 | | | |
| | 0935-0938 | 22 | 225 | 150 | 5.7 | | 72.7a | |
| | 0938-0942 | 23 | 225 | 175 | 5.7 | | 80.1a | |
| | 0954-0959 | 24 | 225 | 200 | 4.4 | | 80.2 | |
| | 1000-1003 | 25 | 225 | 175 | 4.2 | | 65.0 | |
| | 1007-1010 | 26 | 575e | 275c | 3.6 | | 39.0a | |
| | 1011-1015 | 27 | 575e | 300c | 3.1 | | 40.1a | |
| | 1016-1022 | 28 | 550e | 300c | 3.6 | | 64.1a | |
| | 1022-1027 | 29 | 475e | 350c | 3.8 | | 39.4a | |
| | 1029-1034 | 30 | 525e | 300c | 3.8 | | 30.1a | |
| | 1034-1038 | 31 | 575e | 275c | 3.1 | | 39.6a | |
| | 1038-1042 | 32 | 550e | 300c | 3.0 | | 32.3a | |
| | 1047-1051 | 33 | 550 | 325 | 4.0 | | 35.8a | |
| | 1052-1055 | 34 | 550e | 325c | 4.0 | | 55.0a | |
| | 1055-1059 | 35 | 575 | 300c | 3.7 | | 70.4a | |
| | 1138-1141 | 36 | 250 | 200c | 5.9 | | 28.6a | |
| | 1141-1146 | 37 | 250e | 275 | 5.9 | | 48.5a | |
| | 1149-1154 | 38 | 300e | 175 | 4.3 | | 36.3a | |
| | 1158-1204 | 39 | 300e | 375 | 4.6 | | 52.0a | |
| | 1247-1251 | 40 | 250 | d450 | 2.9 | | 87.4a | |
| | 1257-1304 | 41 | 250 | 275 | 3.4 | | 45.9a | 74.2b |
| | 1305-1310 | 42 | 275 | 150c | 5.5 | | | 38.7b |
| | 1316-1321 | 43 | 250 | 200 | 4.9 | 72.1 | | 65.0b |
| | 1321-1328 | 44 | 250 | 400 | 4.9 | 69.2a | 25.9a | 46.1b |
| | 1330-1336 | 45 | 250 | d450 | 6.2 | 63.0 | 49.0a | 44.8 |
| | 1338-1341 | 46 | 275 | 175 | 6.1 | 44.6 | 26.5a | 22.3b |
| | 1342-1347 | 47 | 300 | 275 | 6.5 | 60.2 | 48.7a | 69.2b |
| | 1444-1448 | 49 | 275 | 275 | 5.2 | 75.6 | 29.4a | 69.3b |
| | 1449-1452 | 50 | 300 | 250 | 4.3 | 58.5 | 57.1a | 45.9 |
| | 1452-1456 | 51 | 325 | 250 | 4.3 | 57.2 | 41.0a | 35.6 |
| | 1456-1501 | 52 | 275 | d425 | 5.8 | 95.8 | 43.5a | 57.5b |
| | 1506-1512 | 54 | 250e | 225 | 7.1 | 81.4 | | |
| | 1533-1538 | 55 | 450 | 175c | 6.7 | 25.5 | | |
| | 1538-1543 | 56 | 500 | 400c | 6.6 | 57.2 | | |

TABLE 4. $SO_2$ MASS FLUX RESULTS - GFC

| DATE AUG 1976 | TIME (MDT) | TRAV-ERSE NO. | STACK DIST. (M) | PLUME WIDTH (M) | WIND SPEED (M/S) | $SO_2$ MASS FLUX (MT/D) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | LDV' | TS | PB |
| 5 | 0932-0937 | 58 | 225 | 250 | 5.2 | 140.3 | 157.0 | 147.0 |
| | 0937-0941 | 59 | 200 | 250 | 4.3 | 128.3 | 164.5 | 144.8 |
| | 0941-0948 | 60 | 225 | 275 | 4.3 | 176.8 | 204.0 | 199.5b |
| | 0948-0952 | 61 | 200 | 350 | 4.6 | 167.5 | 176.3 | |
| | 0952-0957 | 62 | 225 | 250 | 5.2 | 222.9 | 186.6 | |
| | 1000-1004 | 63 | 200 | 275 | 3.7 | 169.0 | 151.6 | |
| | 1008-1013 | 65 | 200 | 200 | 3.8 | | 77.5 | |
| | 1013-1018 | 66 | 500 | 250 | 3.4 | | 39.7 | |
| | 1019-1023 | 67 | 500e | 350 | 4.3 | | 61.0 | |
| | 1036-1039 | 68 | 200 | 375 | 5.3 | 28.5 | 22.7 | 13.7 |
| | 1100-1108 | 70 | 250 | 275 | 4.5 | 223.0 | 118.3 | |
| | 1116-1120 | 71 | 200 | 350 | 5.4 | 250.6 | 244.4 | |
| | 1121-1126 | 72 | 200e | 375 | 4.4 | 120.6 | 42.6 | 81.5b |
| | 1126-1132 | 73 | 475e | 425c | 3.6 | 120.9 | 124.8a | 89.7 |
| | 1132-1138 | 74 | 475e | 475c | 4.2 | | 141.5a | 108.5 |
| | 1138-1143 | 75 | 525e | 575c | 4.2 | | 234.0a | |
| | 1150-1155 | 76 | 350e | 675 | 2.5 | | 267.5a | |
| | 1156-1201 | 77 | 375e | 575 | 1.7 | | 212.6a | |
| | 1211-1216 | 78 | 500e | 500 | 3.8 | 372.2b | 372.2a | |
| | 1221-1227 | 80 | 500e | 475 | 4.6 | 207.1 | 139.8a | |
| | 1308-1310 | 81 | 250 | 400 | 5.4 | 94.8b | 92.2a | |
| | 1310-1313 | 82 | 250 | 325 | 5.4 | 181.8 | 113.0a | |
| | 1314-1318 | 83 | 375 | 300c | 4.0 | 73.8a | 44.3a | |
| | 1319-1323 | 84 | 275 | 525 | 5.0 | 406.4 | 147.8a | |
| | 1328-1331 | 85 | 300 | 700 | 4.2 | 601.6 | 423.3a | |
| | 1331-1334 | 86 | 275 | 400 | 4.6 | | 99.6a | |
| | 1351-1354 | 88 | 300 | 500 | 5.9 | | 124.7a | 93.6 |
| | 2032-2035 | 89 | 250e | 275 | 2.0 | | 85.1a | |
| | 2035-2038 | 90 | 200 | 450 | 1.9 | | 25.7a | |
| | 2052-2055 | 92 | 50e | 350 | 1.8 | | 10.4 | |
| | 2059-2102 | 93 | 50 | 375 | 1.8 | | 15.5 | |

REFERENCE METHOD 6

The 25 stack sampling results are presented in Figure 9 and Table 5. The plot is to the same scale as the remote sensor for ease of comparison of the two sets of data. The overall average and standard deviations are:

| DATA SETS | $SO_2$ MASS FLUX MEAN (MT/D) | σ (% of MEAN) |
|---|---|---|
| Method 6 / Method 2 | 67.4 | 8.7 |

It must be noted that no corrections for moisture have been applied to these reference method data. Any further analysis that compares the Method 6 results with the COSPEC results should first make the necessary correction before making the comparisons.

The "annulus" results quantify the $SO_2$ flux between the inner and outer stacks; less than 1% of the $SO_2$ was found in the annulus.

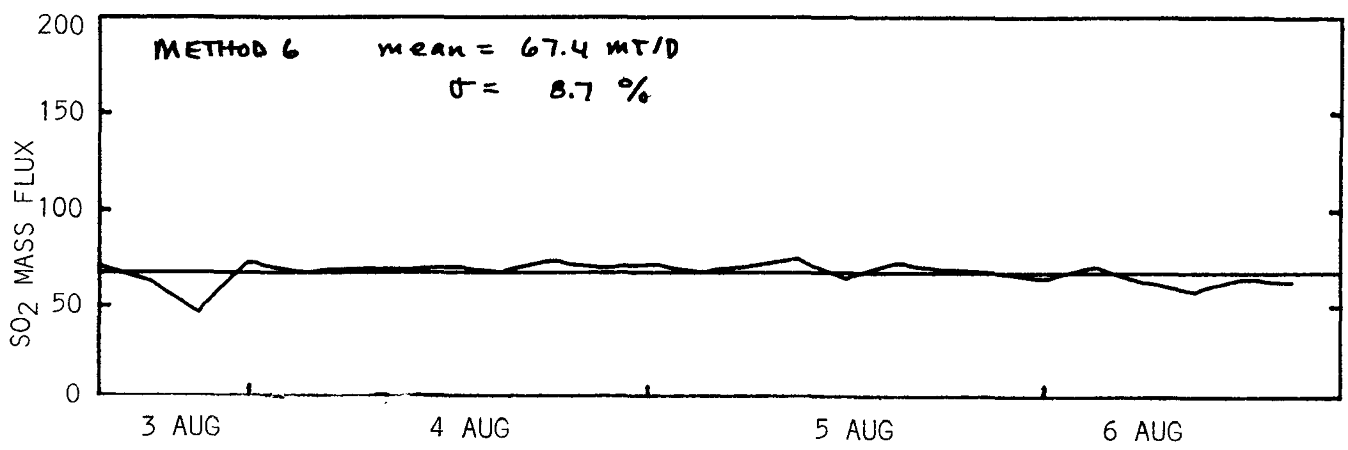


Figure 9. Reference Method 6 Mass Flux

TABLE 5. STACK SAMPLING RESULTS - EPA METHOD 6

| DATE AUG 1976 | TIME (MDT) | RUN NO. | STACK GAS FLOW RATE (ScFm) | SULFUR DIOXIDE CONC. (ppmv) | SULFUR DIOXIDE FLUX (MT/D) |
|---|---|---|---|---|---|
| 3 | 1020-1040 | 1 | 782,000 | 830.9 | 70.8 |
| | 1153-1113 | 2 | 782,000 | 744.3 | 63.4 |
| | 1125-1145 | 3 | 782,000 | 551.8 | 47.0 |
| | 1320-1340 | 4 | 782,000 | 856.0 | 72.9 |
| 4 | 0851-0911 | 5 | 758,000 | 822.9 | 67.9 |
| | 0923-0943 | 6 | 758,000 | 840.2 | 69.4 |
| | 1005-1025 | 7 | 758,000 | 835.3 | 69.0 |
| | 1041-1101 | 8 | 765,000 | 846.5 | 70.5 |
| | 1143-1203 | 9 | 765,000 | 812.8 | 67.7 |
| | 1319-1339 | 10 | 765,000 | 885.5 | 73.8 |
| | 1358-1418 | 11 | 771,000 | 837.7 | 70.3 |
| | 1500-1520 | 12 | 771,000 | 856.3 | 71.9 |
| 5 | 0912-0932 | 13 | 761,000 | 820.9 | 68.0 |
| | 0942-1002 | 14 | 766,000 | 847.6 | 70.7 |
| | 1039-1059 | 15 | 766,000 | 899.3 | 75.0 |
| | 1105-1125 | 16 | 766,000 | 776.4 | 64.8 |
| | 1131-1151 | 17 | 770,000 | 866.2 | 72.6 |
| | 1210-1230 | 18 | 770,000 | 825.2 | 69.2 |
| | 1304-1324 | 19 | 769,000 | 807.9 | 67.7 |
| | 1343-1403 | 20 | 767,000 | 773.1 | 64.5 |
| 6 | 0915-0935 | 21 | 752,000 | 864.9 | 70.8 |
| | 0945-1005 | 22 | 752,000 | 769.0 | 63.0 |
| | 1015-1035 | 23 | 756,000 | 702.7 | 57.9 |
| | 1056-1116 | 24 | 756,000 | 780.7 | 64.3 |
| | 1129-1149 | 25 | 756,000 | 758.2 | 62.4 |
| ANNULUS | | | | | |
| 4 | 1130-1150 | 1 | 43,500 | 140.6 | 0.67 |
| | 1240-1300 | 2 | 57,400 | 53.7 | 0.34 |
| 5 | 1008-1028 | 3 | 52,300 | 94.5 | 0.54 |
| | 1328-1348 | 4 | 52,700 | 139.0 | 0.80 |
| 6 | 1106-1126 | 5 | 44,500 | 34.2 | 0.17 |

## ANALYSIS of RESULTS

### Measurement Errors

The initial analysis of the results was an attempt to identify known errors in the collection and processing of the remote sensor and wind data that could contribute to erroneous calculated $SO_2$ flux values. Five potential errors were identified:

| ERROR CODE | DESCRIPTION |
|---|---|
| *a* | Altitude of the selected wind speed was outside the assumed plume vertical dispersion (±75 meters from plume axis). |
| *b* | Time of the selected wind velocity was outside the time window for the traverse. |
| *c* | The Wind/Road angle was greater than ±50°. (Traverse road exactly normal to the plume axis is 0°.) |
| *d* | Double plume measurement based on criteria of one or more instruments returning to a 0-10% $SO_2$ optical depth reading, creating distinct double peaks. |
| *e* | Traverse route was on a corner, thus increasing the chances of non-normal plume crossing and double plume measurement. |

The wind velocity errors (*a*,*b*) were coded into the wind summary (Table 1) and carried through to the flux summaries (Tables 2, 3, 4). The plume profile and traverse road geometry errors (*c*,*d*,*e*) were coded into the flux results (Tables 2, 3, 4).

Figure 10 presents four examples of Error *c* (Wind/Road angle > ±50°). These happen to occur mostly at a corner, used for traversing when the wind was from the southeast. (Note the wind arrows labelled with wind speed in meters per second and letters identifying the source of the data.)

Figure 11 shows four examples of Error *e*, corner measurements. (Though many traverses had both *c* and *e* Errors, not all did.) Two different corners are shown. (Note different stack distance.) Error *d*, double plumes, is described below.

### Plume Bifurcation

Another phenomenon that must be considered in the processing of remote sensor data is the bifurcated plume, the division of the plume profile into two (or more) distinct peaks with a differing degree of separation.[7] Figure 12 shows four examples of bifurcated plumes, and Figure 13 shows two truly double plume profiles. This was also noted in 1975 work at the same power plant.[2]

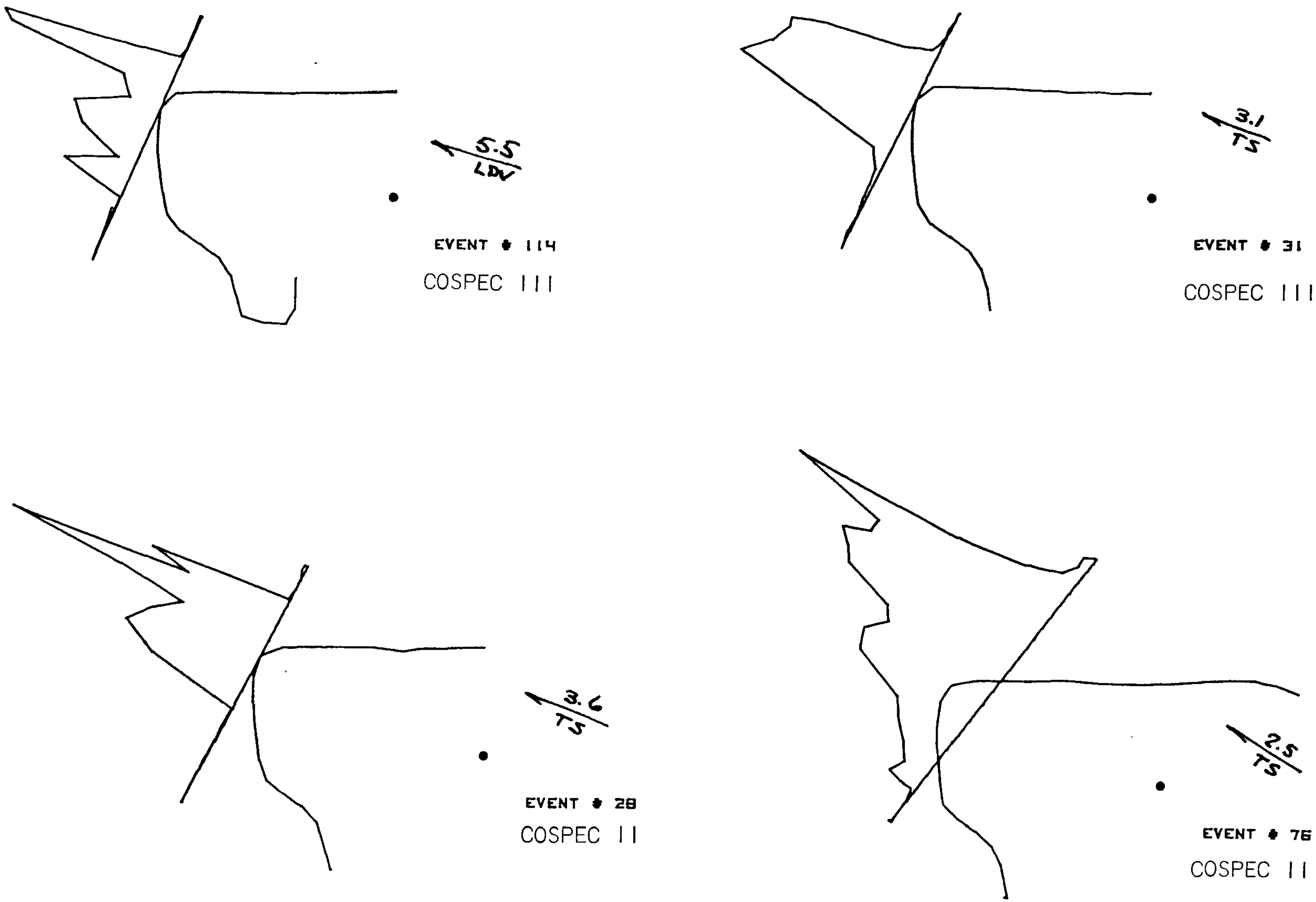


Figure 10. Wind/Road angle > ±50° plumes (Error code *c*)

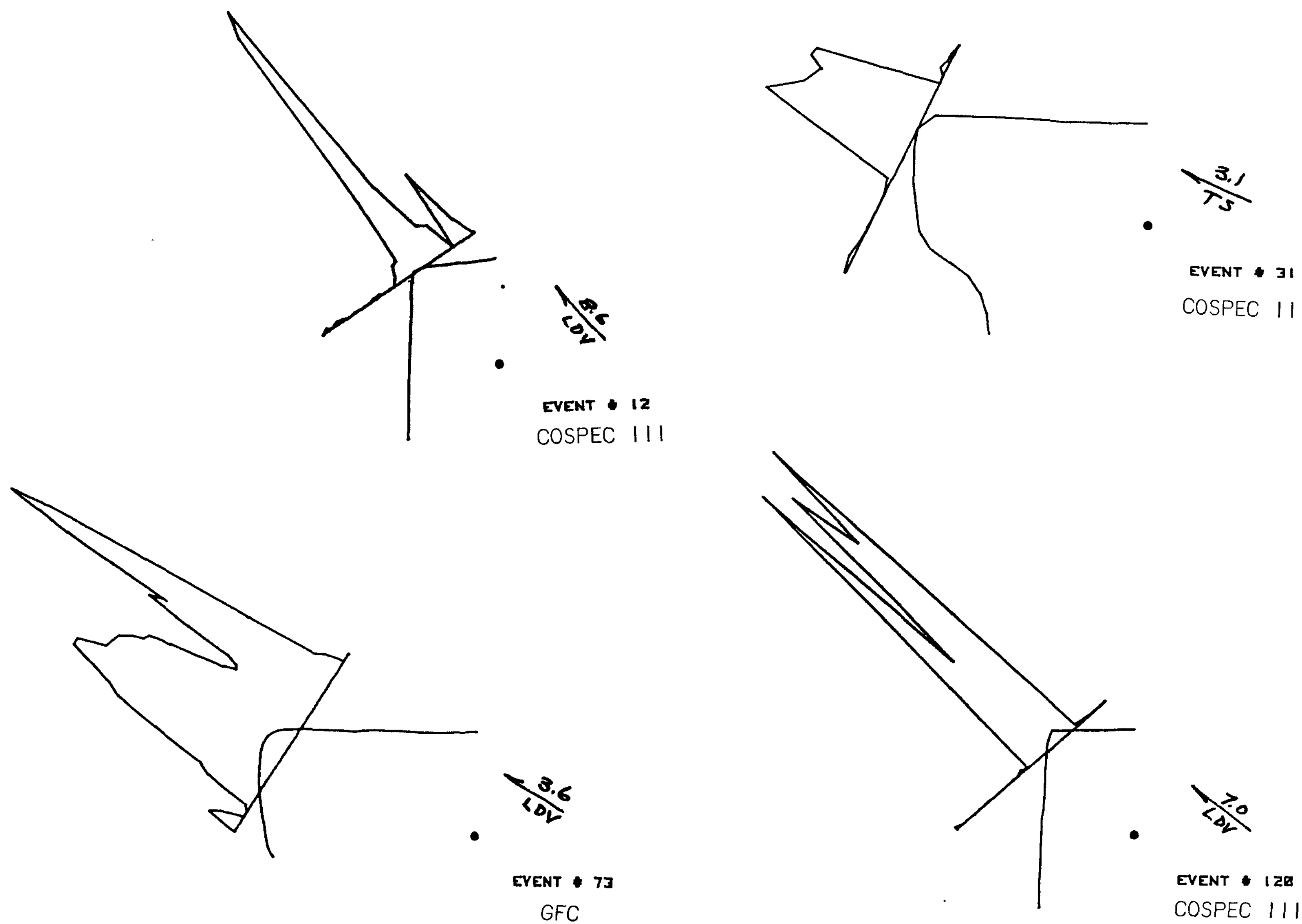


Figure 11. Corner plumes (Error code *e*)

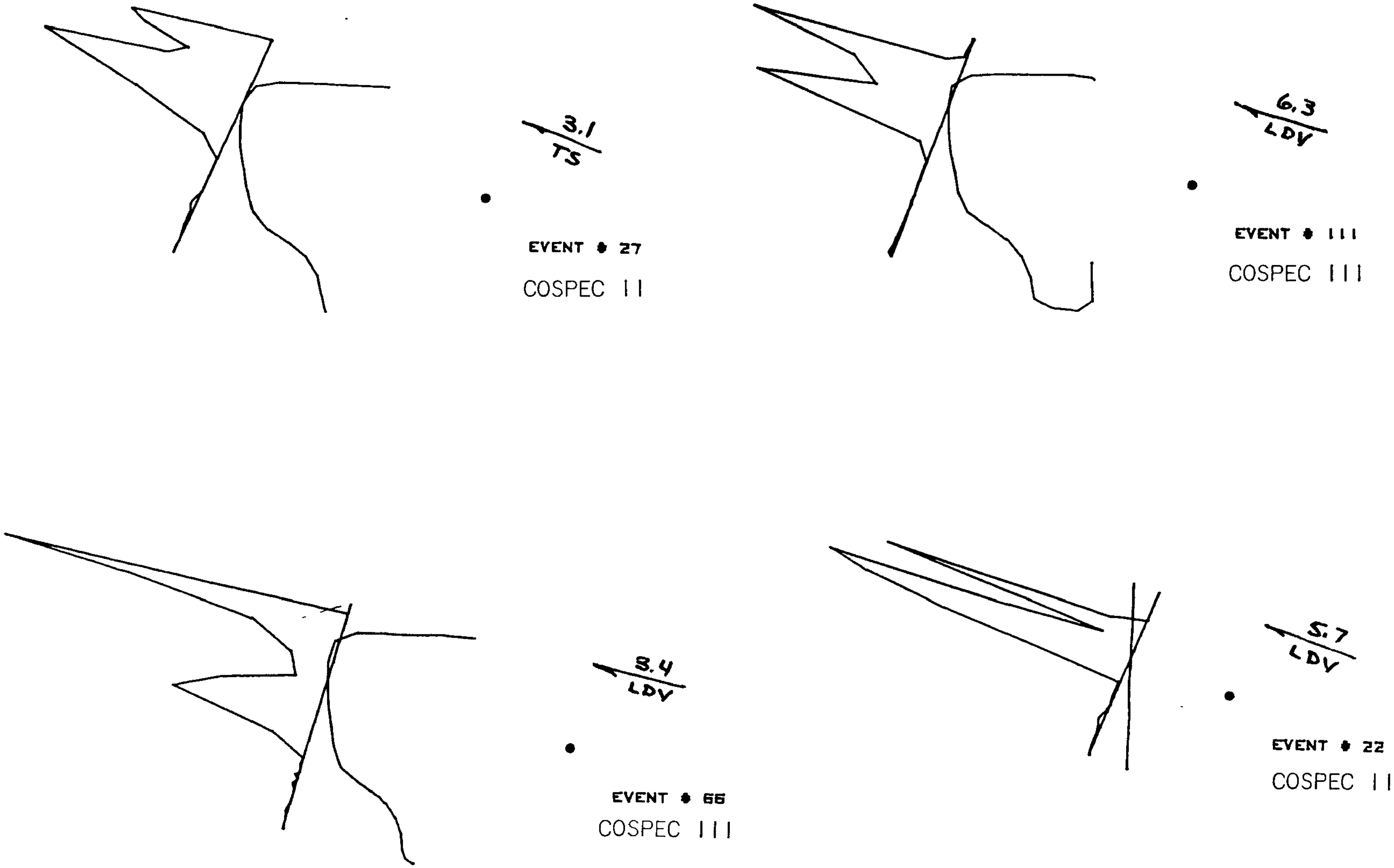


Figure 12. Bifurcated plumes

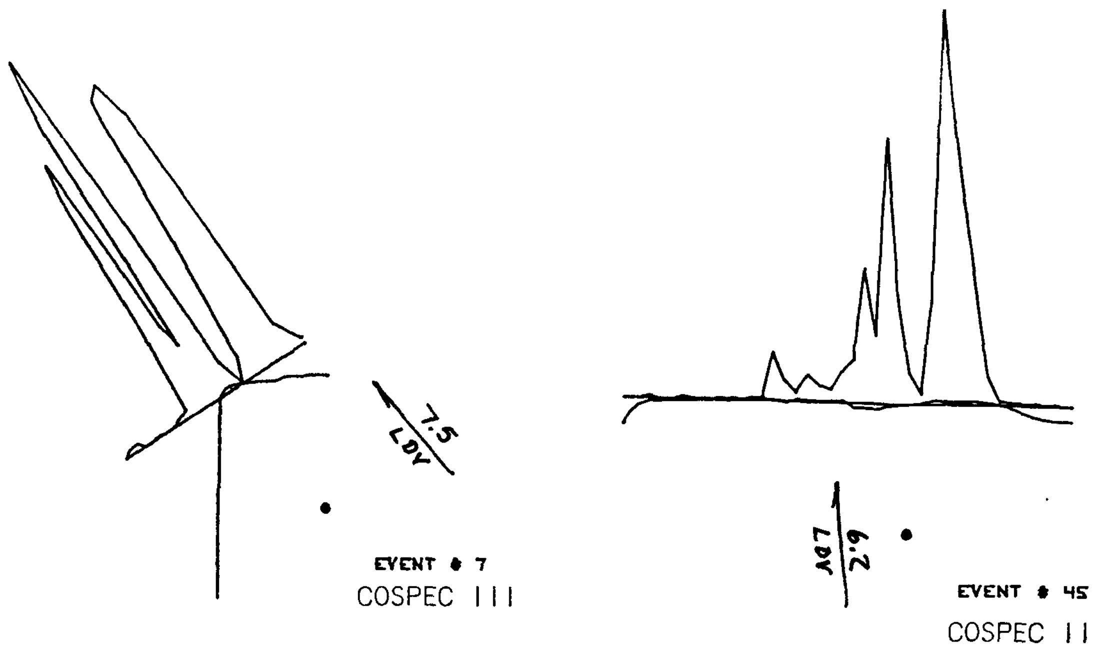


Figure 13. Double plumes

The problem caused by bifurcated plumes is difficulty in discrimination between cases in which the stack emissions have been physically divided by the mechanics of buoyant gases and those in which a plume has actually been measured twice. Because of velocity and/or directional shear, the plume may have separated into multiple parcels that reappear over the traverse route during a single survey.

Plume Sorting

The errors were studied to determine their relative impact on overall average $SO_2$ Mass Flux. Tables 6, 7, and 8 present COSPEC III and COSPEC II results for all four days with averages, excluding the individual Errors (*a*,*b*,*c*,*d*,*e*); finally, averages excluding all four Errors are given.

The differences in the four-day $SO_2$ Mass Flux averages caused by excluding these Errors range from -10.9 to +19.6 MT/D. No single Error caused the highest difference consistently, though Errors *c* and *e* usually had more impact than Errors *a* and *b*. Error *c* (orientation of the plume and route) had the largest influence by a slight amount on results obtained from LDV' winds and the second largest effect on TS winds as judged by reduction in the standard deviation of the average, expressed as "%". The *a* error (altitude of wind data) had the greatest influence on TS data, as might be expected because of tethersonde altitude constraints. Because of the noncontinuous nature of the pibal and profiles, the *b* Error dominated the results from this data set by a significant amount. The difference caused by excluding all four Errors was about equal to or less than that caused by individual Errors, indicated an expected cancelling effect.

In order to evaluate the effectiveness of the LDV under the desired conditions of the transport wind carrying the plume near the instrument, when the plume was directed toward the corner northwest of the plant, the times were preselected. These traverses had been highlighted as having a potential Error, *e*. The average of the twelve mean flux determinations with COSPEC III under these conditions is 70.11 (±37.2%)MT/D. The standard deviation of this subset, ±37.2%, is smaller than any of the other LDV' subsets shown in Table 6, indicating that, even though it is a smaller sample, it is more homogeneous than the rest of the determinations by LDV' winds.

Looking at the seven Method 6 determinations in the same time frame as the *e* traverses, the average $SO_2$ flux is 66.2 (±8.1%) MT/D. Thus the average of twelve *e* traverses is within 6% of the seven Method 6 determinations -- the best agreement with Method 6 of any subset of the field measurements.

Additional error analyses were performed. Correlations were sought between traverse time, wind speed, and plume width and excessively high flux values; none were found.*

*Note added in review: Millân Millân suggested that error analyses might extend to consideration of "plume aspect", i.e.: Whether or not it was a cohesive or non-cohesive plume, in light of the unstable condition during the study. Such conditions may well require a larger number of profiles in a set to improve the correlation with stack measurements.

TABLE 6. ANALYSIS of RESULTS - LDV'. WINDS

| TRAVERSES INCLUDED | NO. | COSPEC III AVG $SO_2$ FLUX (MT/D) | NO. | COSPEC II AVG $SO_2$ FLUX (MT/D) |
|---|---|---|---|---|
| ALL | 59 | 78.9 (±40.9%) | 12 | 63.4 (±28.2%) |
| ALL EXCEPT *a* ERRORS | 56 | 78.5 (±42.5%) | 11 | 62.8 (±29.8%) |
| ALL EXCEPT *b* ERRORS | 57 | 79.4 (±41.2%) | 10 | None - See ALL |
| ALL EXCEPT *c* ERRORS | 51 | 82.2 (±39.8%) | 10 | 67.8 (±14.8%) |
| ALL EXCEPT *d* ERRORS | 57 | 77.9 (±41.2%) | 10 | 60.2 (±27.1%) |
| ALL EXCEPT *e* ERRORS | 47 | 81.2 (±41.7%) | 11 | 61.7 (±28.8%) |
| ALL EXCEPT *a, b, c, d, e* ERRORS | 42 | 79.6 (±43.6%) | 6 | 61.4 (±18.2%) |

Error Codes:

*a* - altitude of wind data outside limits (±75m)

*b* - time of wind data outside limits

*c* - plume axis/traverse route angle outside ±50° limits

*d* - double plume measured

*e* - plume traverse on corner

TABLE 7. ANALYSIS of RESULTS - TS WINDS

| TRAVERSES INCLUDED | NO. | COSPEC III AVG $SO_2$ FLUX (MT/D) | NO. | COSPEC II AVG $SO_2$ FLUX (MT/D) |
|---|---|---|---|---|
| ALL | 87 | 64.4 (±37.0%) | 31 | 50.6 (±37.3%) |
| ALL EXCEPT *a* ERRORS | 39 | 64.6 (±33.4%) | 5 | 70.2 (±27.2%) |
| ALL EXCEPT *b* ERRORS | 87 | See ALL | 31 | See ALL |
| ALL EXCEPT *c* ERRORS | 68 | 66.9 (±35.7%) | 21 | 53.9 (±37.5%) |
| ALL EXCEPT *d* ERRORS | 84 | 64.4 (±37.0%) | 28 | 49.6 (±37.4%) |
| ALL EXCEPT *e* ERRORS | 58 | 66.7 (±36.5%) | 20 | 54.7 (±39.2%) |
| ALL EXCEPT *a, b, c, d, e* ERRORS | 36 | 65.4 (±39.3%) | 5 | 70.2 (±27.2%) |

Error Codes:

*a* - altitude of wind data outside limits (±75m)

*b* - time of wind data outside limits

*c* - plume axis/traverse route angle outside ±50° limits

*d* - double plume measured

*e* - plume traverse on corner

TABLE 8. ANALYSIS of RESULTS - PB WINDS

| TRAVERSES INCLUDED | NO. | COSPEC III AVG $SO_2$ FLUX (MT/D) | NO. | COSPEC II AVG $SO_2$ FLUX (MT/D) |
|---|---|---|---|---|
| ALL | 30 | 68.4 (±38.9) | 11 | 51.7 (±32.0%) |
| ALL EXCEPT *a* ERRORS | 31 | None -- See ALL | 3 | None -- See ALL |
| ALL EXCEPT *b* ERRORS | 9 | 63.9 (±18.2%) | 3 | 42.1 (±13.4%) |
| ALL EXCEPT *c* ERRORS | 28 | 68.5 (±40.3%) | 10 | 53.0 (±31.8%) |
| ALL EXCEPT *d* ERRORS | 28 | 68.4 (±40.0%) | 9 | 51.8 (±35.2%) |
| ALL EXCEPT *e* ERRORS | 24 | 66.5 (±38.3%) | 11 | See ALL |
| ALL EXCEPT *a, b, c, d, e* ERRORS | 6 | 64.3 (±21.5) | 2 | 40.8 (±17.9%) |

Error Codes:

*a* - altitude of wind data outside limits (±75m)

*b* - time of wind data outside limits

*c* - plume axis/traverse route angle outside ±50° limits

*d* - double plume measured

*e* - plume traverse on corner

## SECTION 6

## COMPARISON of RESULTS

### TIME-AVERAGED RESULTS

The COSPEC III results were chosen for comparison with the Method 6 data because there was a larger data base for statistical analysis. The sets of values were first prepared by averaging over common time intervals. The 20-minute Method 6 runs defined the time intervals for which COSPEC III fluxes were averaged; two to five traverses were averaged for each Method 6 test. The 20-minute average are tabulated in Tables 9, 10, and 11. There are seven to eighteen resulting sets of 20-minute averages, depending on which of the four sets of wind data were used.

Similarly, 60-minute averages were calculated for three to thirteen COSPEC III traverses. These are listed in Tables 12 and 13. There are seven to twelve resulting sets of 60-minute averages, depending on which wind data were used. No 60-minute averages were done for the pibal wind data because of insufficient data.

(These averages were calculated without making any correction for moisture in the stack sampling $SO_2$ mass fluxes in this first-order analysis.)

These five tables reveal considerable variability in the $SO_2$ mass flux results with respect to the three wind measuring systems. The individual 20-minute remote sensing averages differ up to +95%. The greatest differences occur in the LDV' data (reprocessed), followed by the tethersonde (TS) results. The pibal (PB) results have the best agreement with Method 6 among the 20-minute averages. The range of the percentage differences for each data set (after a single worst value was discarded) are summarized below:

| DATA SET | DIFFERENCES BETWEEN REMOTE and STACK $SO_2$ FLUXES | |
|---|---|---|
| | 20-Minute Averages | 60-Minute Averages |
| COSPEC III/LDV' | +42%, -45% | +24%, -19% |
| COSPEC III/TS | +31%, -54% | +18%, -20% |
| COSPEC III/PB | +23%, -17% | -- -- |

TABLE 9. COMPARISON of RESULTS
COSPEC III/LDV' vs METHOD 6 - 20-MINUTE AVERAGES

| DATE AUG 1976 | REMOTE SENSING | | | STACK SAMPLING | | |
|---|---|---|---|---|---|---|
| | TIME (MDT) | NO. OF TRAVERSES | $SO_2$ FLUX (MT/D) | TIME (MDT) | RUN NO. | $SO_2$ FLUX (MT/D) |
| 3 | 1020-1032 | 3 | | 1020-1040 | 1 | 70.8 |
| | 1057-1112 | 2 | | 1053-1113 | 2 | 63.4 |
| | 1143-1150 | 2 | | 1125-1145 | 3 | 47.0 |
| 4 | 0856-0916 | 4 | | 0851-0911 | 5 | 67.9 |
| | 0925-0942 | 4 | | 0923-0943 | 6 | 69.4 |
| | 1007-1027 | 4 | | 1005-1025 | 7 | 69.0 |
| | 1047-1059 | 3 | | 1041-1101 | 8 | 70.5 |
| | 1141-1158 | 3 | | 1143-1203 | 9 | 67.7 |
| | 1316-1341 | 3 | 86.0 | 1319-1339 | 10 | 73.8 |
| 5 | 0924-0937 | 2 | 73.0 | 0912-0932 | 13 | 68.0 |
| | 0941-1004 | 4 | 85.4 | 0942-1002 | 14 | 70.7 |
| | 1040-1108 | 2 | 58.7 | 1039-1059 | 15 | 75.0 |
| | 1100-1132 | 4 | 81.7 | 1105-1125 | 16 | 64.8 |
| | 1132-1155 | 3 | | 1131-1151 | 17 | 72.6 |
| | 1211-1227 | 2 | 37.9 | 1210-1230 | 18 | 69.2 |
| | 1308-1323 | 4 | 122.9 | 1304-1324 | 19 | 67.7 |
| 6 | 0918-0941 | 4 | 52.7 | 0915-0935 | 21 | 70.8 |
| | 0944-1008 | 5 | 55.7 | 0945-1005 | 22 | 63.0 |
| | 1057-1120 | 5 | 91.2 | 1056-1116 | 24 | 64.3 |
| | 1130-1156 | 5 | 72.9 | 1129-1149 | 25 | 62.4 |

TABLE 10. COMPARISON of RESULTS
COSPEC III/TS vs METHOD 6 - 20-MINUTE AVERAGES

| DATE AUG 1976 | REMOTE SENSING | | | STACK SAMPLING | | |
|---|---|---|---|---|---|---|
| | TIME (MDT) | NO. OF TRAVERSES | $SO_2$ FLUX (MT/D) | TIME (MDT) | RUN NO. | $SO_2$ FLUX (MT/D) |
| 3 | 1020-1032 | 3 | | 1020-1040 | 1 | 70.8 |
| | 1057-1112 | 2 | | 1053-1113 | 2 | 63.4 |
| | 1143-1150 | 2 | | 1125-1145 | 3 | 47.0 |
| 4 | 0856-0913 | 3 | 53.8 | 0851-0911 | 5 | 67.9 |
| | 0935-0942 | 2 | 82.1 | 0923-0943 | 6 | 69.4 |
| | 1007-1027 | 4 | 52.8 | 1005-1025 | 7 | 69.0 |
| | 1047-1059 | 3 | 67.6 | 1041-1101 | 8 | 70.5 |
| | 1141-1158 | 3 | 56.0 | 1143-1203 | 9 | 67.7 |
| | 1321-1341 | 2 | 27.5 | 1319-1339 | 10 | 73.8 |
| 5 | 0924-0937 | 2 | 82.7 | 0912-0932 | 13 | 68.0 |
| | 0941-1008 | 5 | 83.0 | 0942-1002 | 14 | 70.7 |
| | 1040-1108 | 2 | 44.9 | 1039-1059 | 15 | 75.0 |
| | 1100-1132 | 4 | 66.3 | 1105-1125 | 16 | 64.8 |
| | 1132-1155 | 3 | 93.2 | 1131-1151 | 17 | 72.6 |
| | 1211-1227 | 2 | 31.9 | 1210-1230 | 18 | 69.2 |
| | 1308-1323 | 4 | 69.6 | 1304-1324 | 19 | 67.7 |
| 6 | 0918-0941 | 4 | 49.5 | 0915-0935 | 21 | 70.8 |
| | 0944-1001 | 4 | 56.0 | 0945-1005 | 22 | 63.0 |
| | 1057-1120 | 5 | 84.3 | 1056-1116 | 24 | 64.3 |
| | 1130-1151 | 4 | 52.9 | 1129-1149 | 25 | 62.4 |

TABLE 11. COMPARISON of RESULTS
COSPEC III/PB vs METHOD 6 - 20-MINUTE AVERAGES

| DATE AUG 1976 | REMOTE SENSING | | | STACK SAMPLING | | |
|---|---|---|---|---|---|---|
| | TIME (MDT) | NO. OF TRAVERSES | $SO_2$ FLUX (MT/D) | TIME (MDT) | RUN NO. | $SO_2$ FLUX (MT/D) |
| 3 | 1020-1035 | 3 | 67.8 | 1020-1040 | 1 | 70.8 |
| 4 | 1316-1314 | 4 | 61.5 | 1319-1339 | 10 | 73.8 |
| | 1444-1501 | 4 | 76.3 | 1500-1520 | 12 | 71.9 |
| 5 | 0924-0948 | 4 | 83.3 | 0912-0932 | 13 | 68.0 |
| | 1036-1044 | 2 | 38.0 | 1039-1059 | 15 | 75.0 |
| | 1121-1138 | 3 | 63.4 | 1105-1125 | 16 | 64.8 |
| 6 | 0947-1001 | 3 | 53.1 | 0945-1005 | 22 | 63.0 |

TABLE 12. COMPARISON of RESULTS
COSPEC III/LDV' vs METHOD 6 - 60-MINUTE AVERAGES

| DATE AUG 1976 | REMOTE SENSING | | | STACK SAMPLING | | |
|---|---|---|---|---|---|---|
| | TIME (MDT) | NO. OF TRAVERSES | $SO_2$ FLUX (MT/D) | TIME (MDT) | RUN NO. | $SO_2$ FLUX (MT/D) |
| 3 | 0936-1035 | 4 | | 1020-1040 | 1 | 70.8 |
| | 1047-1150 | 5 | | 1053-1145 | 2,3 | 55.2 |
| | 1103-1159 | 5 | | 1053-1159 | 2,3 | 55.2 |
| 4 | 0856-0959 | 10 | | 0856-0942 | 5,6 | 68.7 |
| | 1001-1059 | 11 | | 1005-1101 | 7,8 | 69.8 |
| | 1052-1154 | 5 | | 1041-1203 | 8,9 | 69.1 |
| | 1444-1543 | 6 | 79.9 | 1500-1520 | 12 | 71.9 |
| 5 | 0924-1004 | 7 | 78.0 | 0912-1002 | 13,14 | 69.4 |
| | 1036-1132 | 6 | 82.0 | 1039-1125 | 15,16 | 69.9 |
| | 1126-1227 | 3 | 57.2 | 1131-1230 | 17,18 | 70.9 |
| 6 | 0918-1008 | 10 | 57.2 | 0915-1005 | 21,22 | 66.9 |
| | 1033-1135 | 13 | 75.5 | 1015-1116 | 23,24 | 61.1 |
| | 1057-1156 | 12 | 79.3 | 1056-1149 | 24,25 | 63.4 |

TABLE 13. COMPARISON of RESULTS
COSPEC III/TS vs METHOD 6 - 60-MINUTE AVERAGES

| DATE AUG 1976 | REMOTE SENSING | | | STACK SAMPLING | | |
|---|---|---|---|---|---|---|
| | TIME (MDT) | NO. OF TRAVERSES | $SO_2$ FLUX (MT/D) | TIME (MDT) | RUN NO. | $SO_2$ FLUX (MT/D) |
| 3 | 0936-1035 | 4 | - | 1020-1040 | 1 | 70.8 |
| | 1047-1150 | 5 | - | 1053-1145 | 2,3 | 55.2 |
| | 1103-1159 | 5 | - | 1053-1159 | 2,3 | 55.2 |
| 4 | 0856-0959 | 6 | 69.1 | 0856-0942 | 5,6 | 68.7 |
| | 1001-1059 | 11 | 55.7 | 1005-1101 | 7,8 | 69.8 |
| | 1052-1154 | 5 | 62.1 | 1041-1203 | 8,9 | 69.1 |
| | 1257-1347 | 4 | 43.3 | 1319-1339 | 10 | 73.8 |
| 5 | 0924-1023 | 11 | 77.7 | 0912-1002 | 13,14 | 69.4 |
| | 1036-1138 | 7 | 67.7 | 1039-1125 | 15,16 | 69.9 |
| | 1126-1227 | 7 | 76.3 | 1131-1230 | 17,18 | 70.9 |
| | 1308-1354 | 7 | 71.2 | 1304-1403 | 19,20 | 66.1 |
| 6 | 0918-1001 | 9 | 55.8 | 0915-1005 | 21.22 | 66.9 |
| | 1033-1135 | 13 | 72.0 | 1015-1116 | 23,24 | 61.1 |
| | 1057-1151 | 11 | 68.1 | 1056-1149 | 24,25 | 63.4 |

The LDV' wind data corrected most of the bias, which would have been part of the LDV data set. However, the tethersonde (TS) results have generally better agreement with the stack sampling values, and the pibal (PB) results are an improvement on all three other wind measuring systems for 20-minute averages.

## MEANS and DIFFERENCES

Further analysis of the 20-minute and 60-minute averages elucidated the relative accuracy of the remote sensing mass fluxes. In this simple, first-order analysis, the means of the time-averaged data were calculated; the percent differences from the stack sampling averages over the same time period were also figured. These means reduce all of the results to single values; they represent seven to twelve hours of measurements or 25 to 75 traverses.

The results of this analysis are tabulated in Tables 14 and 15. These two tables offer the most succinct summary of the findings of this study. By comparing the two columns of $SO_2$ mass flux numbers and studying the third column of percent differences it is clear that:

- The LDV' wind data were a significant improvement over LDV values, showing agreement to the reference method within +7.6% (and 6% for winds over the instrument).
- The TS wind data had negative differences up to -9.6%.
- The PB showed the closest agreement (for 20-minute averages only) at +1.0%.

TABLE 14. MEANS and DIFFERENCES of 20-MINUTE AVERAGES

| | $SO_2$ MASS FLUX (MT/D) | | |
|---|---|---|---|
| | REMOTE | STACK | DIFF. (%) |
| COSPEC III/LDV' | 73.4 | 68.2 | + 7.6 |
| COSPEC III/TS | 62.0 | 68.6 | - 9.6 |
| COSPEC III/PB | 70.3 | 69.6 | + 1.0 |

TABLE 15. MEANS and DIFFERENCES of 60-MINUTE AVERAGES

| | $SO_2$ MASS FLUX (MT/D) | | |
|---|---|---|---|
| | REMOTE | STACK | DIFF. (%) |
| COSPEC III/LDV' | 72.7 | 67.6 | + 7.5 |
| COSPEC III/TS | 65.4 | 68.1 | - 4.0 |

It is apparent that the three different sets of wind data (LDV', TS, and PB) produced $SO_2$ mass fluxes in agreement with Method 6 within ±10% when considering long-term (7-12 hour) averages. This reinforces earlier studies[1,7]; individual COSPEC derived flux calculations are not representative of the true value, but time-averaged data are within ±10% of the accepted reference stack sampling method.

The obvious conclusion is that, the longer the averaging time, the better the remote sensing results. Thus, if only 20-minute remote sensing tests of two to five traverses are used, the expected spread in the results would be about ±35%; for 60 minutes of testing (four to thirteen traverses) the results would have a spread of about ±20%. And, if seven to twelve hours of data are gathered (25 to 75 traverses), the difference is reduced to about ±10%.

Further statistical analyses may sharpen the assessment of relative accuracy by expressing the differences between the remote and in-stack methods in terms of error intervals and confidence limits.

## WIND MEASUREMENT ACCURACY

The analysis in Section 5 showed the good agreements of LDV' related flux values to Method 6 determinations if the plume being measured by the COSPEC was transported toward the LDV monitoring site. This improved agreement indicates that the conditions in which the COSPEC and LDV are in the same sector as the plume are the best for reliable measurements. These measurements will be improvements of the use of pibal winds.

The reason for the need for the COSPEC and LDV to be close together to produce good results arises from the fact that the LDV is essentially a point monitor of wind velocity aloft, as opposed to pibal, which determines more of a velocity average over an altitude range between readings. If the point measurements (even those of the tethersonde) are not made near the plume, they will not reflect the transport winds in the plume accurately enough under mid-day turbulent conditions. The averaged pibal data thus can do a better job of approximating the average transport conditions, even though they may not be in the same sector as the plume.

The expense of the LDV system would be justified if it could be capable of readily responding to changes in wind direction in a mobile sense. It would be sufficient to have it relocatable and not necessarily capable of measurements while moving.

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## TECHNICAL REPORT DATA
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16. ABSTRACT

Remote sensing data of single-stack power plant emissions and local wind speed have been analyzed to determined $SO_2$ mass flux for comparison with EPA referenced methods. Four days of $SO_2$ data were gathered from a moving platform by three upward-viewing remote sensors -- two ultraviolet absorption spectrometers and an infrared gas filter spectrometer. Wind velocity data were gathered by a laser-doppler velocimeter (LDV); supplemental data were obtained from a tethered balloon (telemetered) and pilot balloons (optical theodolite). The data matrix ($SO_2$, X-Y position, wind velocity for 120 traverses) was computer processed; the end result was the $SO_2$ mass flux derived from the remote sensing data. Comparisons were made between these $SO_2$ fluxes (averages for 20 minutes and 60 minutes) and those derived from in-stack measurements. The results of the comparisons show the relative accuracy of the remote sensing technique for quantifying $SO_2$ mass emission rates. The analysis shows that as averaging time increases from 20 minutes to 12 hours the difference between the remotely measured $SO_2$ mass flux and the stack sampling $SO_2$ mass flux decreases from about ±35% to ±10%. In general, no single wind measuring system produced superior results over te other two. The LDV and COSPEC, however, produced the best agreement with Method 6 (+6%) when the plume was transported near the LDV instrument.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| * Air pollution<br>* Sulfur dioxide<br>* Remote sensing<br>Weight (mass)<br>Emissions<br>Rates (per time)<br>* Accuracy<br>Thermal power plants<br>* Ultraviolet spectrometers<br>* Infrared spectrometers<br>Wind velocity | | 13B<br>07B<br>14B<br>10B<br>04B |

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