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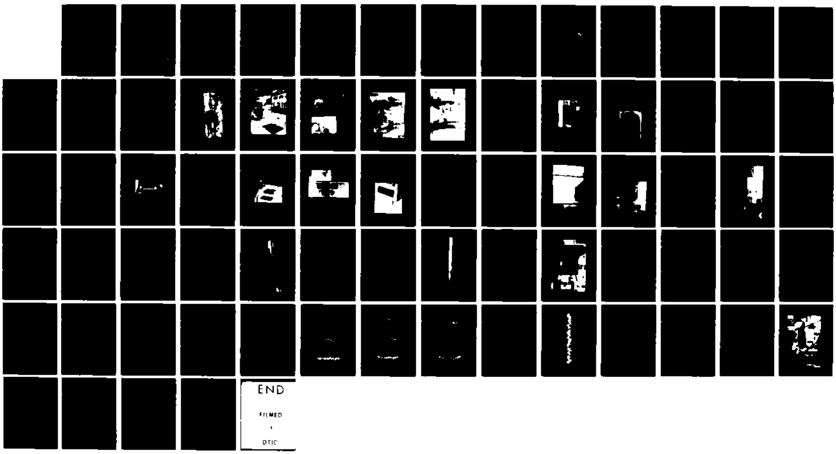

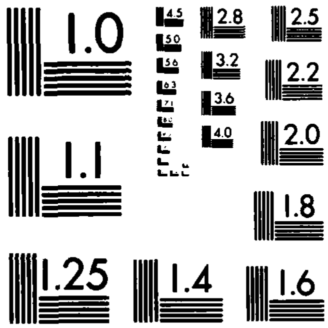

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CHEMICAL REMOTE SENSING
"Proof of Concept"

B.Y. Bartschi
F.P. DelGreco
M. Ahmadjian

Electro-Dynamics Laboratories
Utah State University
Logan, Utah 84322

Scientific Report No. 8

31 March 1981

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Noise equivalent spectral radiance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Field measurements were conducted under controlled experimental conditions to aid in developing a correlation model. Instrumentation consisted of a high resolution interferometer viewing a remotely located simulated smokestack through an 8" telescope.

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INTRODUCTION

This report describes the instrumentation, field site, and the experiment which were utilized in successfully gathering "proof of concept" data for remote chemical sensing.

The instrumentation consisted of a high resolution Michelson interferometer-spectrometer with a liquid N_2 cooled background limited Indium Antimonide (InSb) detector. This interferometer was coupled to an 8" Cassegrain telescope for the measurement and characterization of remote effluents. This system was interfaced to and controlled by a disk based fast-fourier transform (FFT) computer. The entire system was housed in a mobile van which allowed measurements to be conducted at several remote field sites.

In order to provide a well-documented data base, a 3-wall simulated smokestack source was developed which would allow trace gases of interest to be mixed in a laminar-flow mainstream of air. The trace constituents could then be detected against a uniform background using spectral subtraction. This source was separated 273 meters from the sensor.

The work was performed at Atmospheric Radiation Consultants, Inc. for the Air Force Geophysics Laboratory under subcontract F19628-77-C-0203.

2. PROGRAM DEVELOPMENT

The purpose of this program was twofold; to provide a facility capable of making remote spectral measurements of trace gases using fourier transform infrared (FT-IR) techniques and, second, served to verify theoretical models presently being used to predict trace gas detection levels using FT-IR methods. This experimental verification has important relevance to the remote sensing applications shown in Figure 2.1.

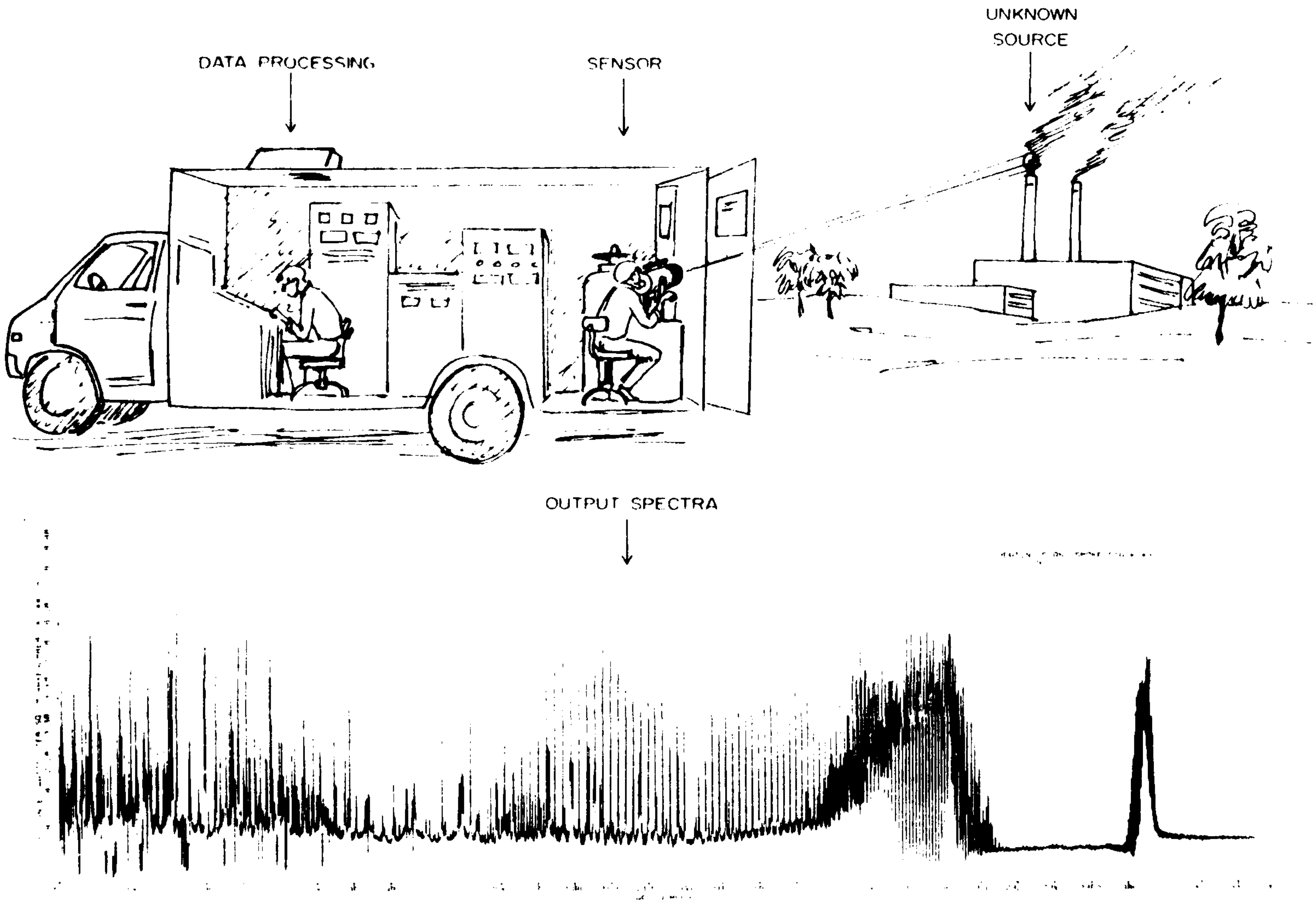


Figure 2.1   Applications for remote sensing

Utah State University has a demonstrated capability in FT-IR field measurements and was contracted by the Air Force Geophysics Laboratory (AFGL) to construct and operate a mobile, self-sufficient FT-IR spectroscopic facility.

A mobile van was procured and its interior modified to provide a mini-laboratory environment. A Nicolet 7199 data system was then installed and interfaced to an existing USU interferometer.

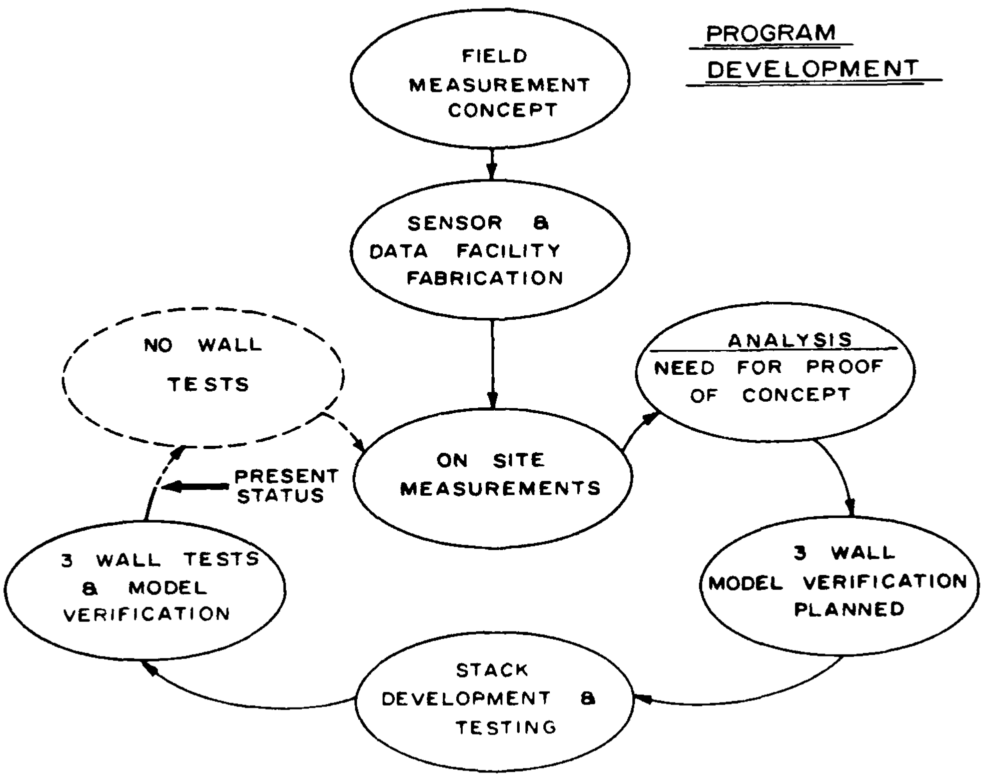
Field measurements were performed at several sites including Batelle Northwest Laboratories, Richland, Washington, Thiokol Chemical Corporation, Brigham City, Utah, and Utah State University Physical Plant, Logan, Utah. Analysis of these measurements revealed a need to more thoroughly characterize the variables in this kind of a measurement. Consequently, the program's main thrust was redirected toward a "proof of concept" experiment.

The "proof of concept" experiment required a source in which precise trace gas levels could be injected into a carefully monitored airstream. A 3-wall smokestack simulator was constructed to provide this required highly-controlled source.

After fabrication and laboratory testing, the stack was moved to a remote site where spectral measurements were made. The interferograms were collected on a disc, transformed to spectra, transferred to magnetic tape, and sent to AFGL. After being reformatted at AFGL for use on a larger computer, analysis by Atmospheric Radiation Consultants (ARC)was performed. Based on the results of these analyses, new experiments were developed and improvements were incorporated into the next set of measurements.

With the sensor fully characterized, and the measurements conducted under controlled and documented conditions, it was possible for the ARC model to establish detection thresholds with excellent repeatability.

The 3-wall tests have been successfully completed and documented. Excellent agreement between predicted and measured values was obtained and results indicate that the no-wall tests should be pursued which will eventually lead to the applications listed in table 2.1. Figure 2.1 is a summary of the progress to date.



Fi[illegible]re 2.2 [illegible]ogram Development

3. HARDWARE DESCRIPTION

3.1 Sensor

The sensor consists of a Michelson interferometer-spectrometer interfaced to a Nicolet 7199 Fourier Transform infrared FT-IR data system. Sometimes referred to as a Fast Fourier Transform (FFT) system.

The spectrometer (USU HR-3000 interferometer) is in a standard Michelsen configuration with a 2" diameter collection optics. The beamsplitter that was utilized in the measurements described herein was CaF_2, but components for other spectral regions can be inserted. The instrument utilizes a gas-lubricated bearing and is capable of 0.12 cm^{-1} resolution. An 8" Cassegrain telescope is used for energy collection and the detector is nitrogen cooled InSb. Figures 3.1 and 3.2 show the system optical layout and block diagram. A list of sensor specifications is contained in Table 3.1.

The sensor optically collects energy from a remote source. The modulator portion of the sensor converts the light frequencies into audio frequencies which can then be detected by a photovoltaic detector. The analog signal from the detector is amplified and converted into a digital signal via an analog to digital converter (ADC). It is (digitized) so that Fourier processing techniques can be used to produce a spectrum of the energy collected. Also generated are two additional signals which are required for digitizing; the laser position reference which tells the ADC where to sample and the white light reference which tells the ADC when to start sampling.

The interferometer sensor and Nicolet computer are housed in a Dodge KaryVan with an 8' x 15' cargo area. The interior has been insulated with foam, carpeted, and paneled. Table 3.2 gives the vehicle description and

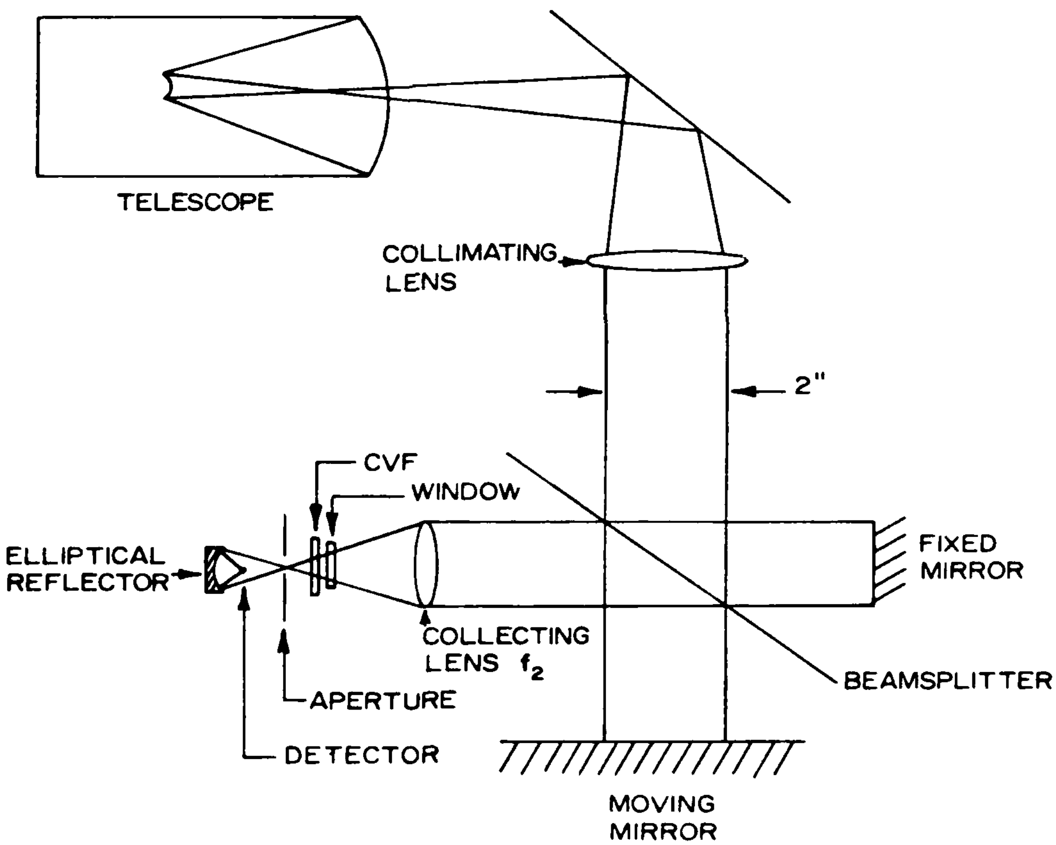


Figure 3.1 Optical Layout

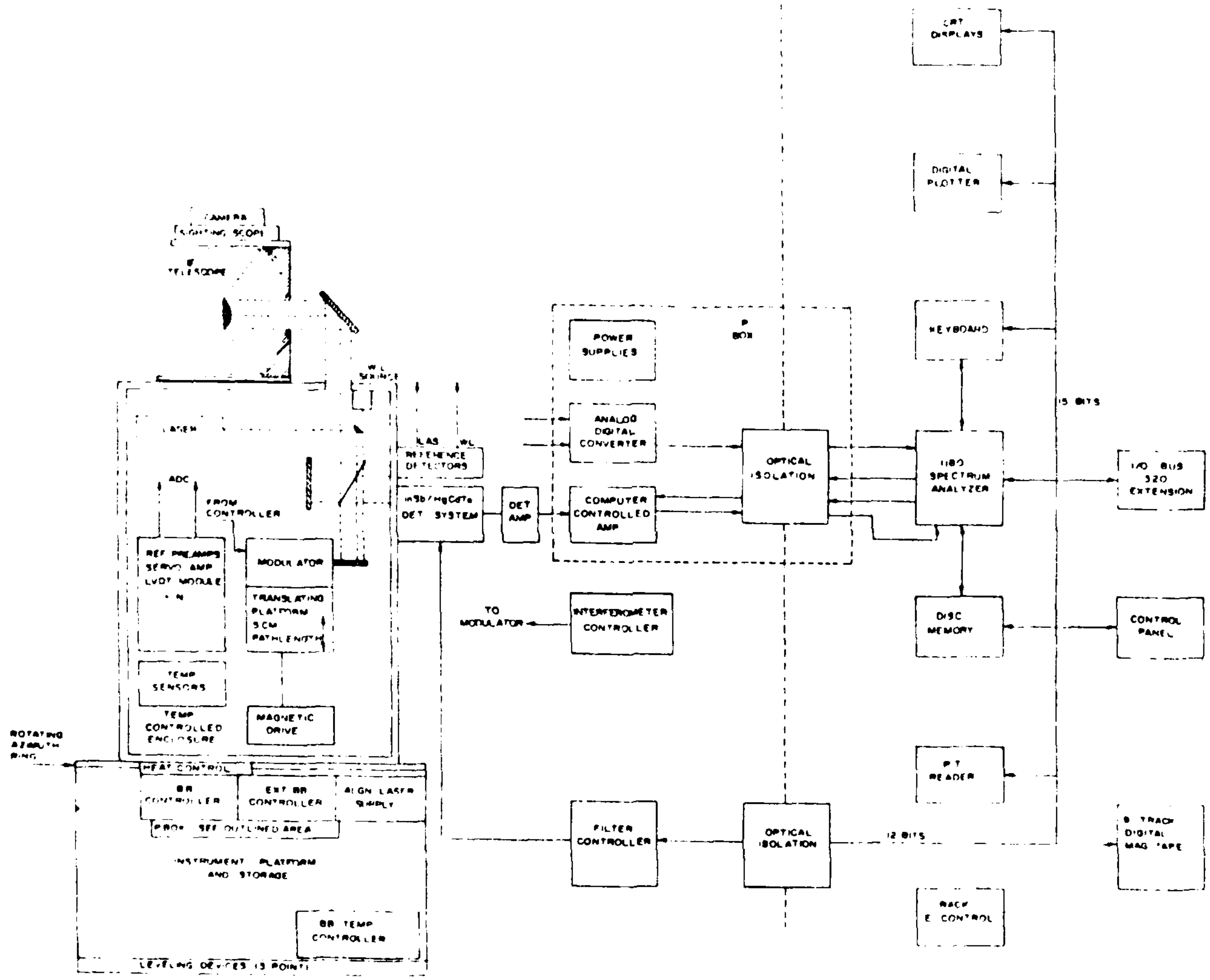


Figure 3.2 Block Diagram

Table 3.1

USU HR-3000

Interferometer Specifications

Item	Specification
Spectral Range	2 μm to 16 μm f (Det, Bmspltr)
Resolution	0.12 cm^{-1}
NESR Full Resolution	$1.6 \times 10^{-8} \frac{w}{cm^2\ sr\ cm^{-1}}$ (InSB Det)
Throughput (AΩ)	5×10^{-4} cm sr
Field-of-View (Full Θ w/out tele.)	0.7°
Collection Lens, Aperture	f/2, 5 cm dia
Instrument Operating Temperature	25°C controlled to within 1°C
Ambient Operating Temperature	-10°C to 35°C
Translating Slide	Gas Lubricated
Drive Type	Electromagnetic
Drive Length (Max)	5.2 cm
Translation Accuracy, @ 5 cm	<1 arc sec
Gas Bearing Flow Rate at 10 psi	16 f^3/hr (SCFH)
Power	250 w 2.1A 120 Vac
Scan Rates (min, max)	1 cm/sec, 0.05 cm/sec
Postion Reference	.632 μm HeNe laser & 2000°K W.L.
Scan Period for Max Resolution (min, max)	4 sec, 80 sec
Detector	InSb or HgCdTe
Beamsplitter	CaF for InSb Det KBr for MCT Det

Figures 3.3 - 3.7 are external and internal photos of the mobile facility.

Figure 3.8 shows the mobile facility floor plan.

Table 3.2

CRS VEHICLE DESCRIPTION

Item	Description
Vehicle Type	Dodge KaryVan
Model	CB 400
Serial	C40CA8V707974
Length	22.6'
Height	8' + 1.2' for AC
Width	7.84'
Cubic feet required for shipment	1417'
Gross vehicle weight (GVW)	11,500 lbs
Front axle weight	4,500 max
Rear axle weight	8,000 max
Center of gravity	8' from Front of Vehicle
Wheelbase	11.9'
Type of engine (HP and CI)	180, 440
Engine location	Front
Transmission	3 speed automatic
Headroom	5.9'
Seats suitable for use in transit	2 each
Floor	Carpet covered wood
Windows in work area	1 each rear doors
Alternator	63 amps
Brakes	Hydraulic 13" x 3.5"
Insulation	3 cm foam and paneling
Body construction	All steel
Fuel tank capacity	36 gal
Type of door	Swing out (full size)
Differential ratio	4:10
Tires (size and quantity)	800-16.5E, 10 ply, 6 each
Instrumentation	oil, fuel, temp, water, speedometer
Ground clearance	11.8"

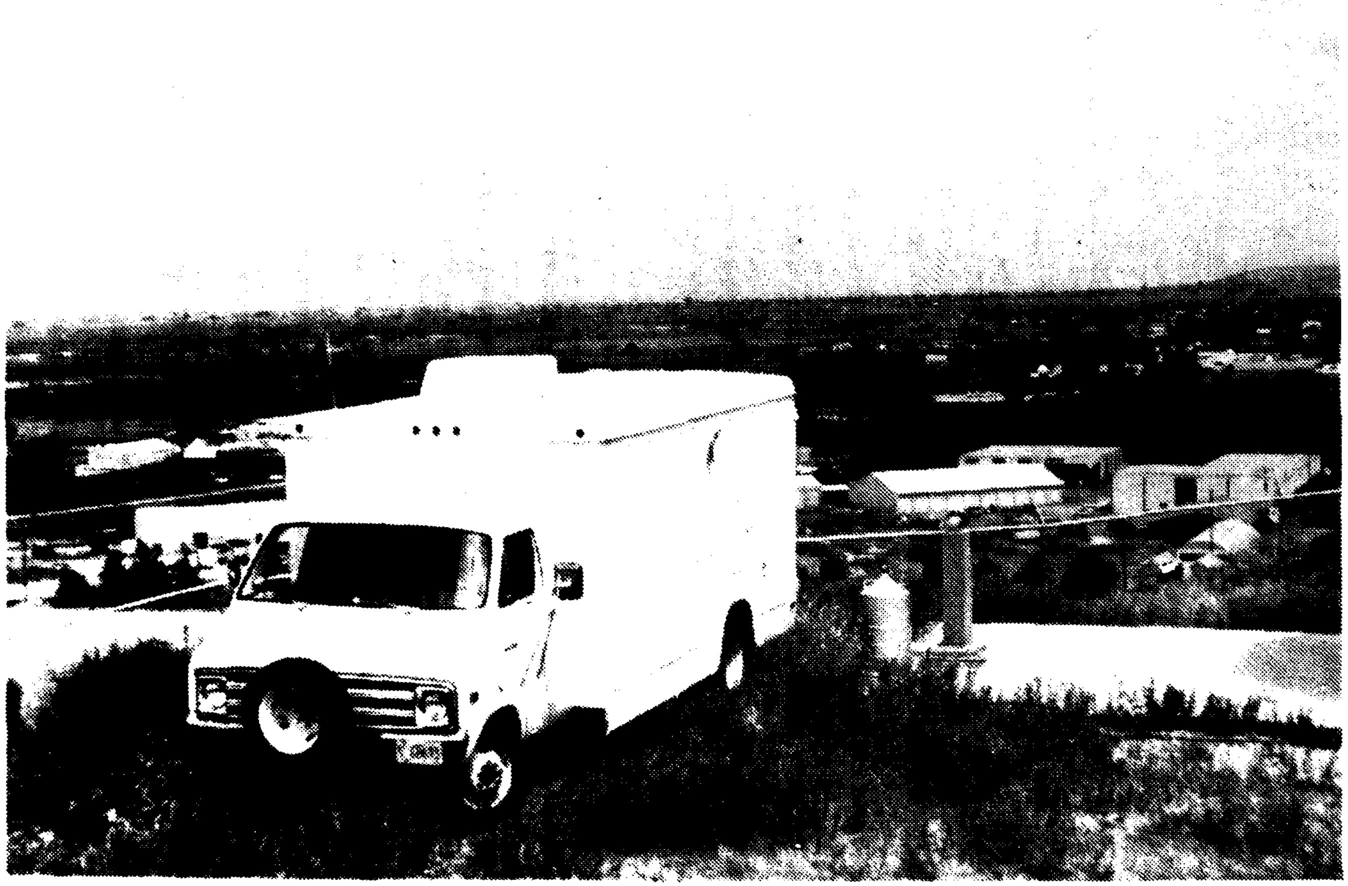


Figure 3.3 Mobile Sensor Facility

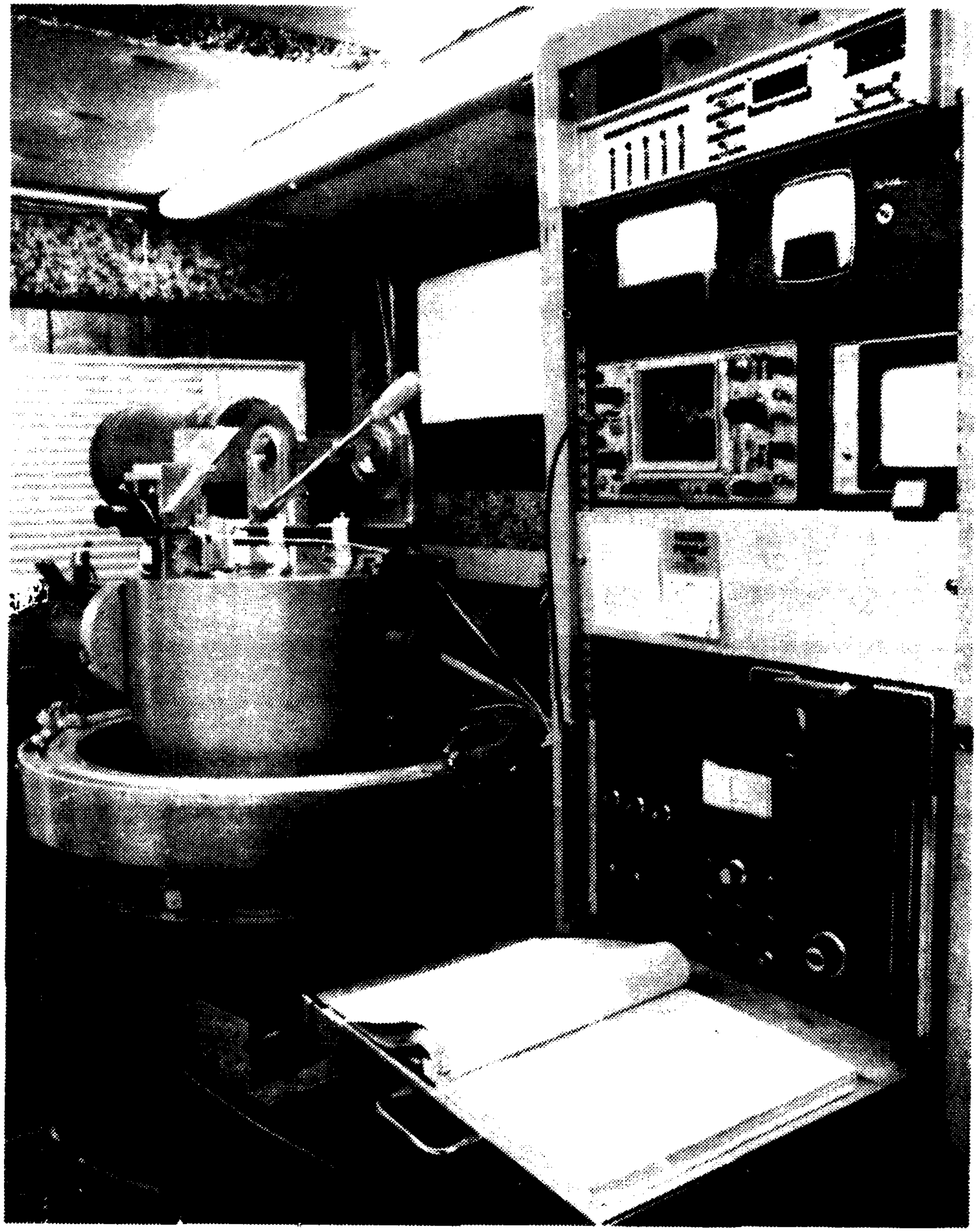


Figure 3.4 Interferometer-Spectrometer with Telescope in Position to View Through Back Part of Van

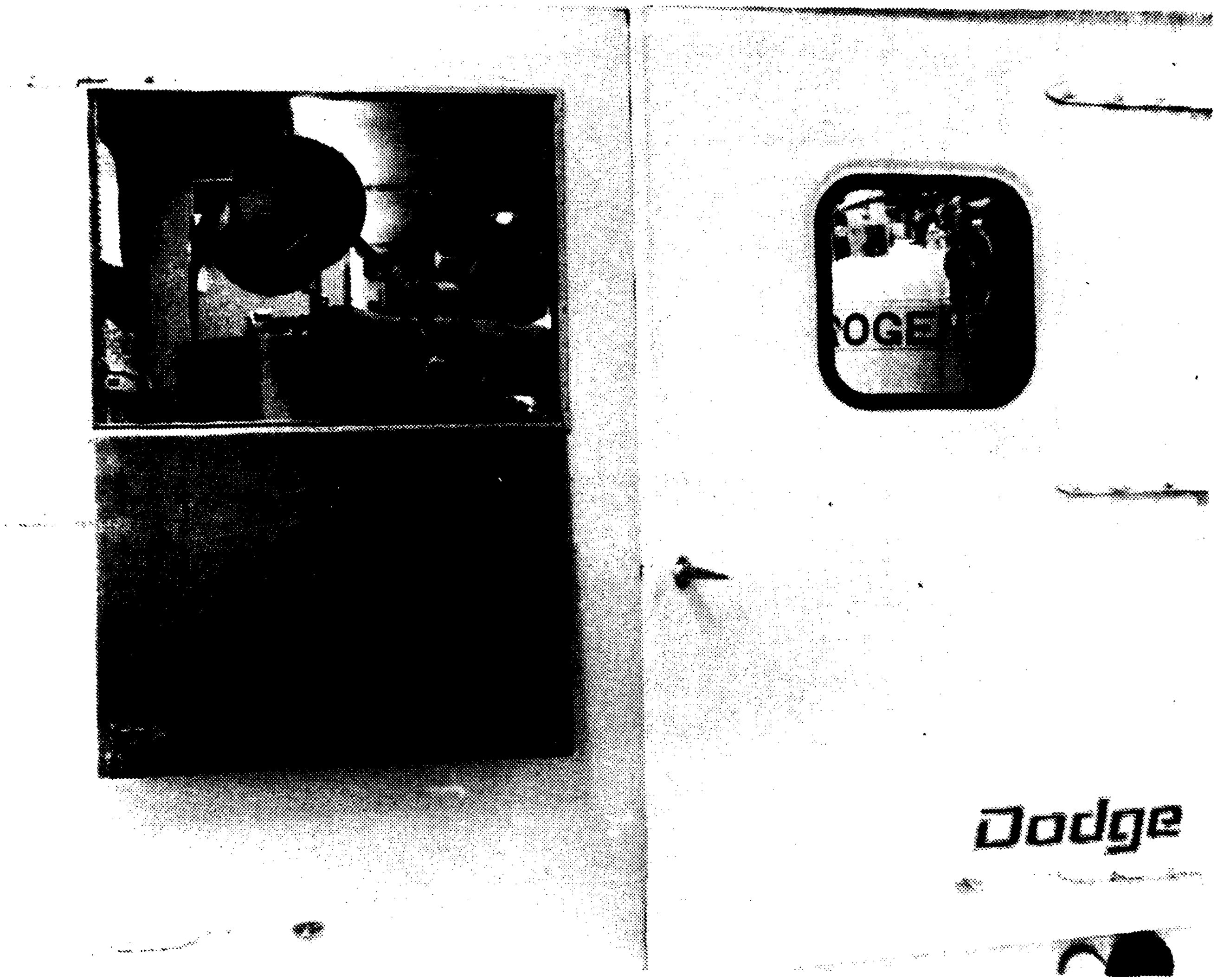


Figure 3.5 Sensor Viewing Port

Figure 3.6 Sensor Facility Interior View (Rear)

Figure 3.7 Sensor Facility Interior View (Front)

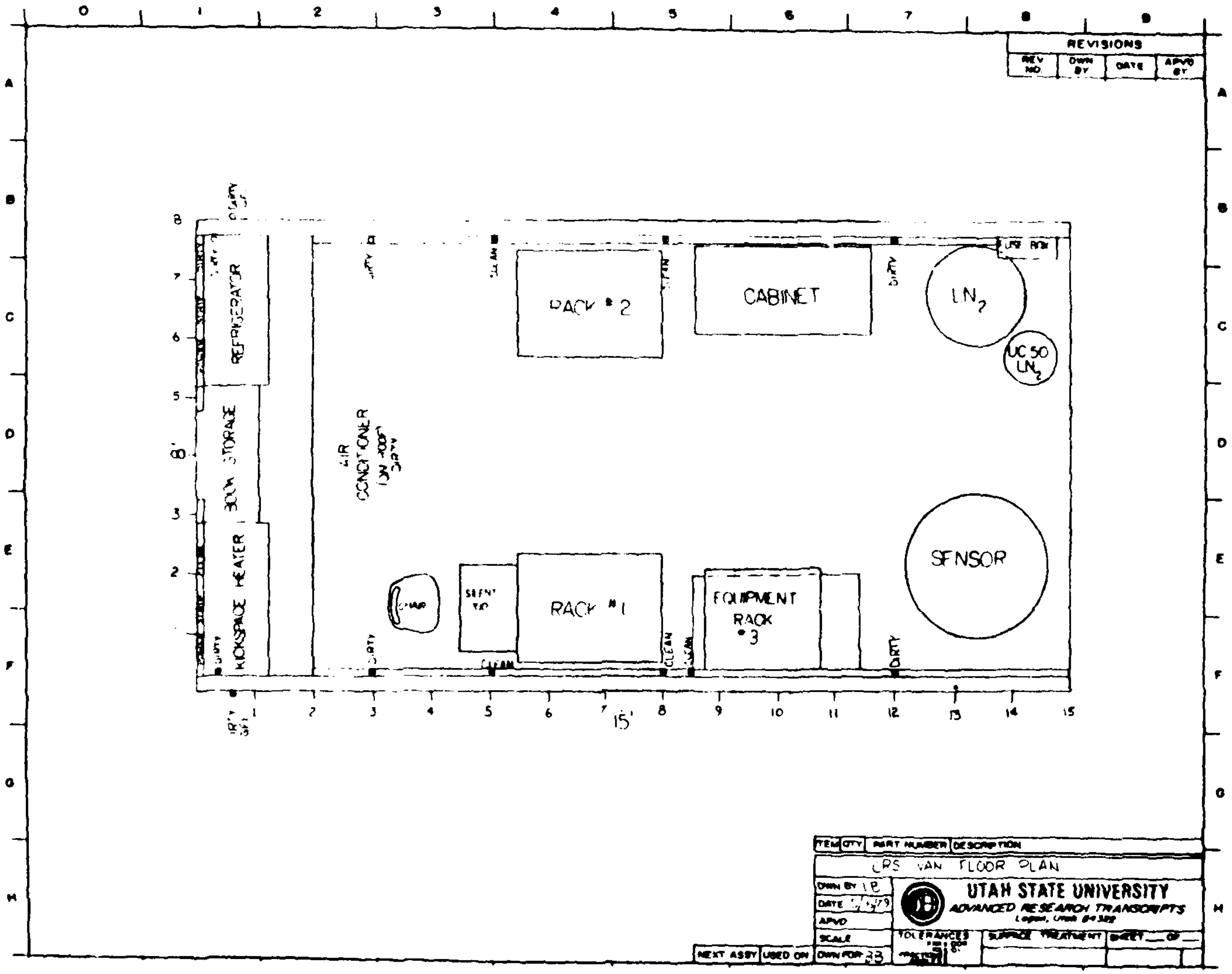


Figure 3.8   Facility Floorplan

3.2 Data System

The Data System is configured as shown in Figure 3.9 and 3.10 and consists of an 1180 CPU, 294B disk drive, Kennedy 9000 tape drive, Texas Instrument Silent 700 keyboard and Zeta plotter.

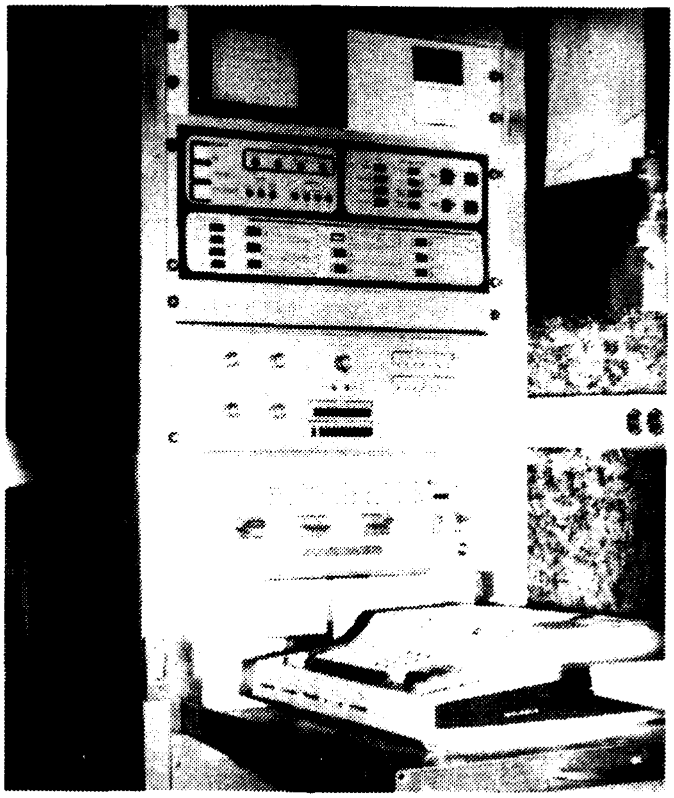


Figure 3.9 Rack 1 Nicolet 7199 data system.

The FT-IR software package is a collection of routines designed to perform data recording, data reduction, display, and plotting. With the use of the Nicolet 15-bit A/D converter and gain ranging software, adequate speed and dynamic range are available to properly handle very low noise systems.

The digital plotter included in the system allows output in transmittance, absorbance, radiance, irradiance, or radiant intensity to be plotted and labeled versus wavelength, wavenumber or data point. With the high density dual disk drive, interferograms up to 512 K point may be accumulated and transformed, permitting full utilization of the high resolution capability of the USU HR-3000 interferometer.

The oscilloscope display and the front panel are the key to this system's ease of operation. Once the desired set of instructions are linked together through the use of "macros," almost all experiments can be run directly from the front panel without keyboard intervention.

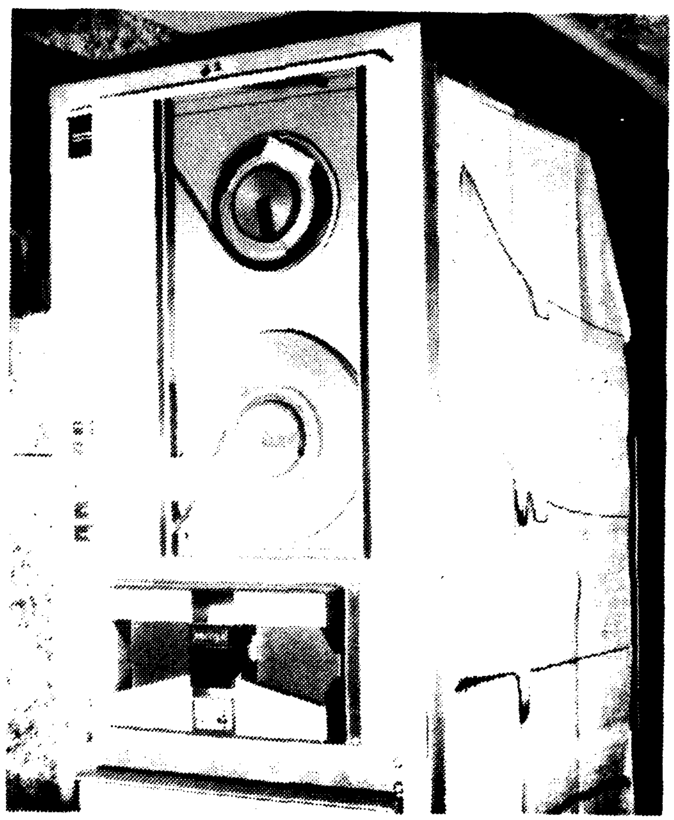


Figure 3.10 Rack 2 Kennedy 9000 magnetic tape drive, paper tape reader, and Diablo 294B disk drive

3.2.1 General System Organization

The FT-IR software package runs in a Disk Operation System (DOS) environment. All I/O routines support the interrupt structure of the 1180 and, therefore, the operating system is capable of multi-task programming. In recent years the terminology of "Foreground" and "Background" has become common for the description of a system capable of handling two tasks simultaneously. The 1180 I/O structure allows not only two but many programs to operate essentially simultaneously by using a priority stacking technique to assign priority levels to the individual programs.

The FT-IR software operates in a minimum of 40 K of resident memory with 22 K nominally allocated to data storage buffers. This leaves 18 K of 20-bit words for program storage and associated display and test buffers. This 18 K is more than adequate because the Nicolet DOS software supports program overlay calls. This means that a program may be kept on the disk when it is not actually operating and then brought into resident memory (overlaying the previously executing program) and executed when required.

The 18 K for programs is sufficient to allow 15 K to be allocated for resident memory IR routines that can operate at all times at lower priority levels. This 15 K of resident memory code is used to operate the display, plot, and subtraction routines along with many other I/O service routines. In this way the user can always plot, display or subtract data even while the high priority software is data collecting or performing a FFT calculation.

3.2.2 Data Collection

The IR data collection program is a fully disk-interactive routine designed explicitly for IR data collection onto a moving head disk. There are several powerful features built into the data collection program to ensure reliable, reproducible, and trouble-free operation. Each of these features is discussed below in detail.

a. Double-Precision Co-adding of Interferogram Peak:

After as few as 32 scans, the peak of the interferogram (15 bits possible per scan) might overflow the 20-bit word. To ensure against this possibility the first 1024 data points, which include the interferogram peak, are co-added in double-precision (40-bit) format. This ensures that well over 32 million scans are possible before the peak will overflow the 40 bits. The data collection program automatically protects against the possibility of overflow outside the initial 1024 points.

b. Error Check:

Since the first 1024 points are collected in double precision, these data points are not co-added into the resultant array until all have been collected. This allows a background software program to perform certain tests on the validity of the data. All these checks can be completed on the first 512 data points before the end of the first 1024 point data collection and hence prior to the co-add' of any data into the permanent storage array. This allows a "bad scan" t. be rejected without adding it to a good interferogram that may have been the result of a significant measurement time.

c. Switched Gain:

The high sensitivity and resolution of a good FT-IR system with a cooled detector generates an interferogram signal that has noise less than the least significant bit of the 15-bit ADC system. To detect these weak signals Nicolet has implemented a technique called Gain Ranging. The IR interferogram is very large near the Zero Path Difference (ZPD) point and is very small near the end of a high resolution scan.

The gain ranging technique requires a precise adjustment of the gain which must be switched very rapidly under computer command. As soon as the interferogram has diminished sufficiently due to the passing of the ZPD, the input is switched to a second independent A/D converted channel with a gain increase that may be varied by the operator.

This change of gain is completed between data points and is completed in such a fashion that all switching is complete before the sample is taken by the sample-and-hold. Thus, the small signals at the end of the scan are amplified prior to the ADC so that they may be accurately sampled and converted in spite of their small amplitude. Prior to final storage of the interferogram all data are set to the same scale factor including double-precision data and switched gain data.

d. High Speed Di.ect Memory Collection:

For up to 22 K of data the FT-IR data buffer can hold the entire interferogram (up to 62 K with optional memory boards). In this case the disk throughput does not limit the speed of data collection. The 1180's DMA capability for the ADC allows the full ADC data rate of 100 KHz to be realized for these array sizes cf less than 22 K points.

This high speed data collection offers tremendous experimental flexibility for utilizing the advantages of variable mirror velocity. Experiments such as transient spectral observations are directly available because these data rates can result in time resolution scales of less than 50 ms.

e. True High Resolution:

The FT-IR system is capable of co-adding up to 512 K data points which result in spectral data that is non-aliased with .06 cm^{-1} resolution for the range of 0 to 15,798 cm^{-1}.

3.2.3 Fourier Transform

The Fourier transform algorithm used in the FT-IR system is the result of several years of optimization for the interferometer experiment. Most Fourier transforms found in analytical instruments are implemented with an algorithm developed by J.W. Cooley and J.M. Tukey in 1965 called the Fast Fourier Transform or FFT. The FFT is defined for complex data, i.e., each data point consists of two data values, the real and imaginary part.

The input data from the interferometer consists of only real numbers; by taking advantage of the fact that the imaginary part is zero, the 7199 software halves the required data storage and more than halves the transform time compared to a full complex transform.

3.2.4 Phase Correction

System phase errors are totally compensated in the FT-IR system. The phase correction process consists of two steps: first, the value of the phase array Θ must be measured; and second, the data array must be rotated in the complex plane by the angle Θ.

Before Θ can be measured, a demodulation correction is performed to remove the linearly varying phase angle resulting from the fact that the ZPD does not coincide with the first data point of the array. Θ is obtained by calculating a small (≈256) point transform of a few (16 to 32) data points near the ZPD point (the rest of the points are zero). Since the spectrum will provide a full definition of Θ.

The low resolution Θ function can then be used to linearly interpolate the values of Θ for any array size regardless of resolution.

3.2.5 Array Arithmetic

The applications of the FT-IR system require much more than a simple ratio routine. Some of the operations that are easily performed with this software are:

a. Addition of Arrays:

Addition of arrays with scalar multiplication (useful for generating simulated mixtures and for "block averaging" spectra or interferograms).

b. Subraction of Arrays.

Subtraction of arrays with scalar multiplication (useful for spectral "stripping").

c. Ratios of Arrays:

Ratios of arrays (useful for generating transmittance spectra or removing instrumental effects in emission spectra).

d. Transferring Arrays:

Transferring arrays from one file to another.

e. $-\log_{10}$ of an Array:

$-\log_{10}$ of an array (useful for generating absorbance spectra from transmittance spectra).

Figure 3.11 Texas Instrument Silent 700

3.2.6 Oscilloscope Display

The oscilloscope display is an integral part of the 7199 system. Using the roll and zoom switches on the control panel, the operator can view any small region of a spectrum or interferogram at any desired scale expansion. The expanded region can then be plotted; thus the oscilloscope can be used to set and preview the plot output, saving a great deal of time and paper.

The display scope is also the key to the spectral subtraction experiment where a sample and a reference spectrum are displayed on the scope, along with the result of the difference of two. The operator may continuously vary the multiplicative scale factor used in the subtraction, watching peaks null or shift.

The scope is also invaluable during the data collection. Either each interferogram or a spectrum of the first few points of the accumulated interferogram may be displayed. These give information on optimal settings or gain and velocity and on the instrument noise level and alignment.

In the CRS facility, two displays are provided, one at the 7199 console and one at the HR-3000 console.

3.2.7 Plotting Data

The 7199 system is supplied with a Zeta 160 digital plotter. Together with the Nicolet digital plotter software package this gives the system the capability to plot and annotate graphic output. Both X and Y axes are automatically annotated in the appropriate units: transmittance absorbance, radiance, irradiance or radiant intensity for the Y axis and wavenumbers, nanometers or data points for the X axis. The operator has the choice of using preset limits for each type of plot or of using the scope display to set the limits. All plotting is completely under interrupt control, as is scope display. This means data on a new sample may be acquired and processed as data from the last experiment is displayed or plotted unless data collection is being done under macro control. The plotter as used in the CRS facility is shown in Figure 3.12.

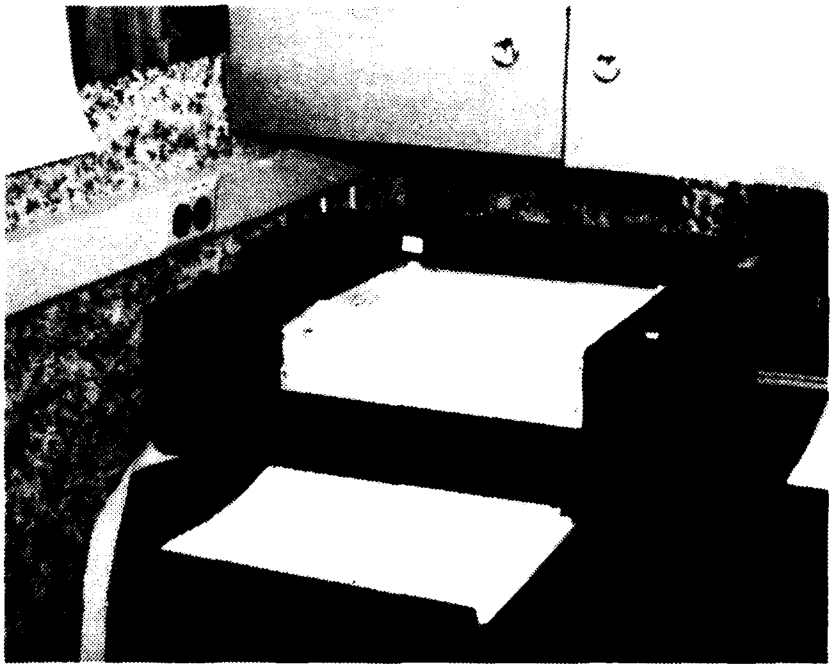


Figure 3.12 Zeta Plotter.

3.2.8 Pre-Programmed Experiments

During field operations, most experiments are repetitive and well-defined. Once they have been defined, the operator can program these into a preset experiment, which can then be run with either a single keyboard command or by merely pressing one of the front panel "EXPERIMENT" buttons. This greatly increases sample throughput and reduces the chance of operator error. The Nicolet 7199 control panel with "Experiment" buttons is shown in Figure 3.13 as it is configured in the CRS facility.

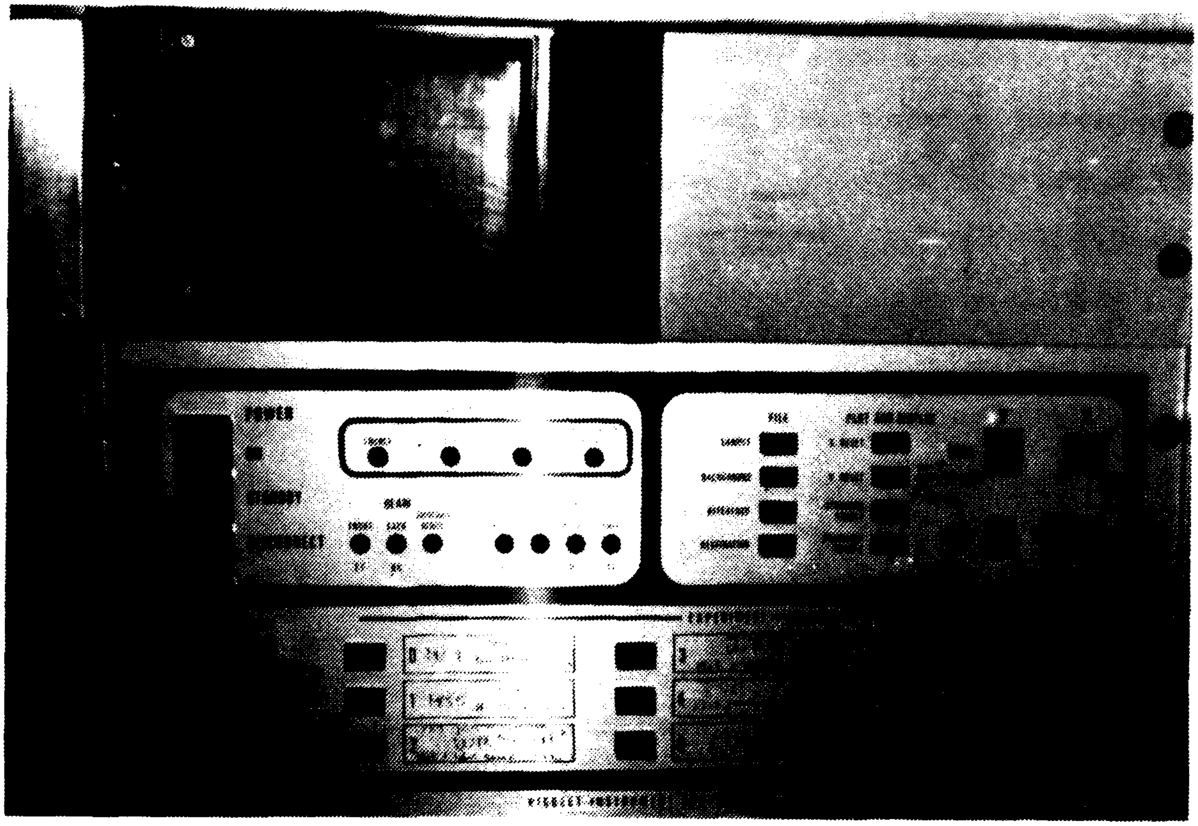


Figure 3.13 Nicolet 7199 Control Panel.

3.2.9 Software Organization

The Nicolet 7199 software is completely disk-based. Programs are called in from disk as needed, and all interferograms and spectra are stored on disk. The Nicolet 294B disk drive is a dual-disk system with one removable and one fixed plotter. The information on each cartridge is stored in groups of 352_{10} 20-bit words called <u>sectors</u>. Each cartridge has a capacity of 6496_{10} (14540_8) sectors, or $2,286,592_{10}$ words. For the total system, 4.57 megawords are thus available. Figure 3.14 shows the 294B as it is used in the CRS facility.

The 7199 software uses the bottom disk for storing all software, macros, and permanent IR files. All these files are stored using the Dexter monitor, a program that takes care of all the bookkeeping involved in keeping track of where the different files are stored. Each file is assigned a name and the monitor maintains a directory of the starting sector, file length, and protection status of each named file.

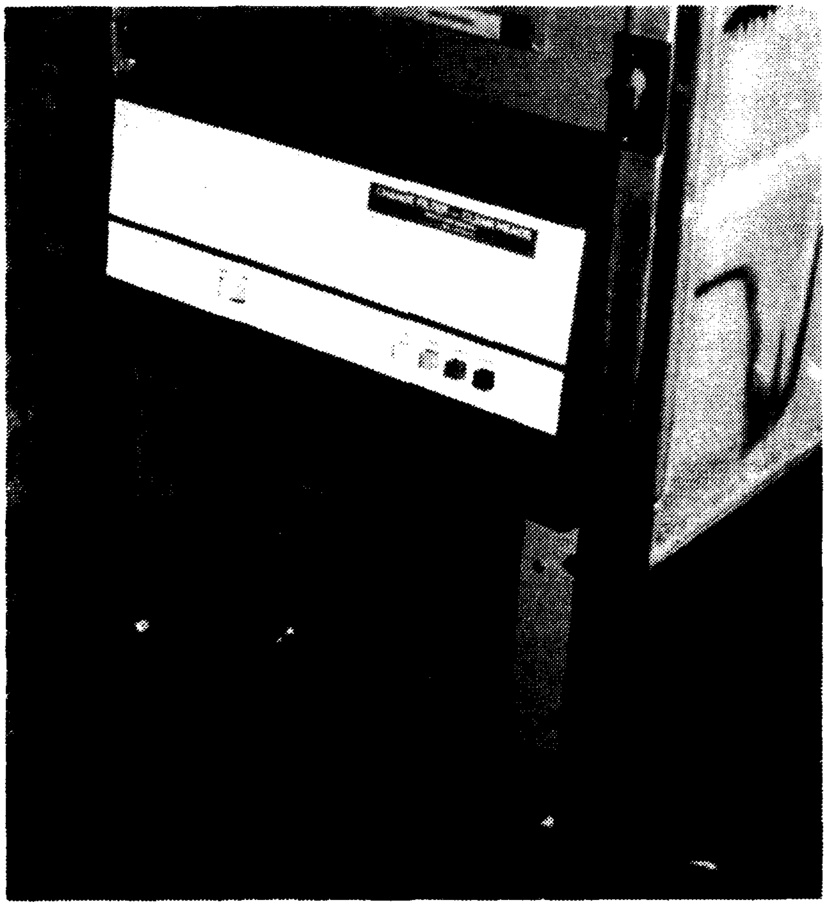


Figure 3.14 294B Disc Storage

The top platter is used exclusively for scratch (temporary) storage. All the numbered IR files, the parameter files, the phase spectra, and the interferogram files are kept on the upper disk. Files are not named and all bookkeeping is done by the FT-IR program rather than the Dexter monitor.

3.3 Simulated Smokestack and Supporting Instrumentation

For the controlled "proof-of-concept" experiment the following design objectives were incorporated into the simulated smokestack hardware.

1. Vertical uniform laminar airflow
2. Accurate injection of a trace gas into the airflow
3. Uniform mixing of all constituents
4. Background of uniform emissivity and temperature
5. Instrumentation to measure stack and meteorological parameters

A block diagram of the source is shown in figure 3.15 and pictures of the device are shown in Figures 3.16 and 3.17.

For ease of data interpretation, the measurement section volume for this device was designed to be 1 cubic meter. Gas flowing vertically through the measurement section was confined by "3 walls" with the back wall held at a controlled temperature. The front wall was removed to permit remote measurement of the gas against the controlled wall. It was determined that even though a windowed front wall would be desirable for gas containment, it would be prohibitively expensive.

In operation, two 1500 CFM blowers (see Fig. 3.17) pulled ambient air into the plenum and deflector area. Trace gas was injected and thoroughly mixed in the "squirrel cage" area of the blowers. The vertically rising mixture passed through a series of baffles and finally through a 12" thick section of 3/8" dia. honeycomb to produce a laminar flow. The gas

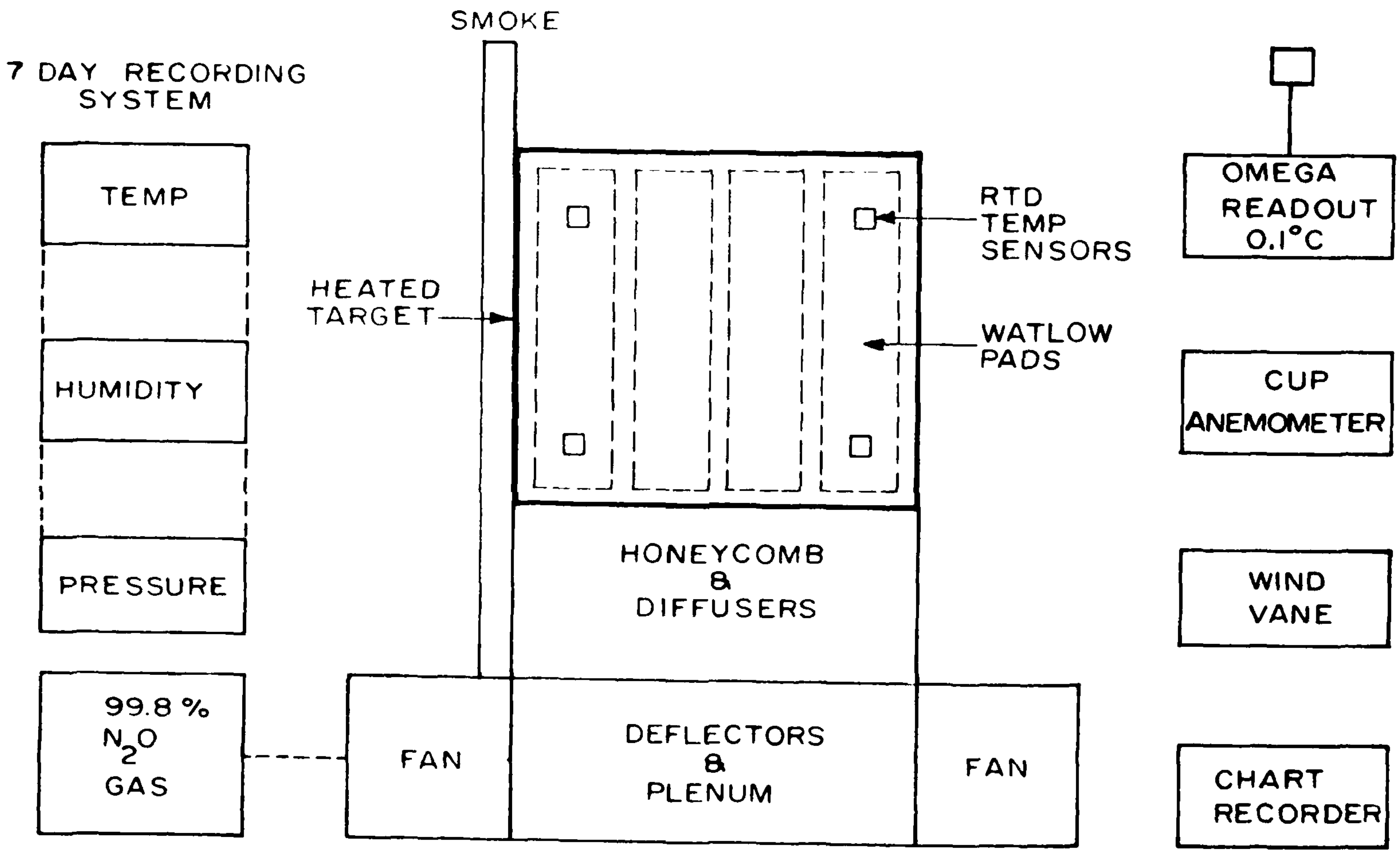


Figure 3.15 Block Diagram of simulated 3-wall smokestack source

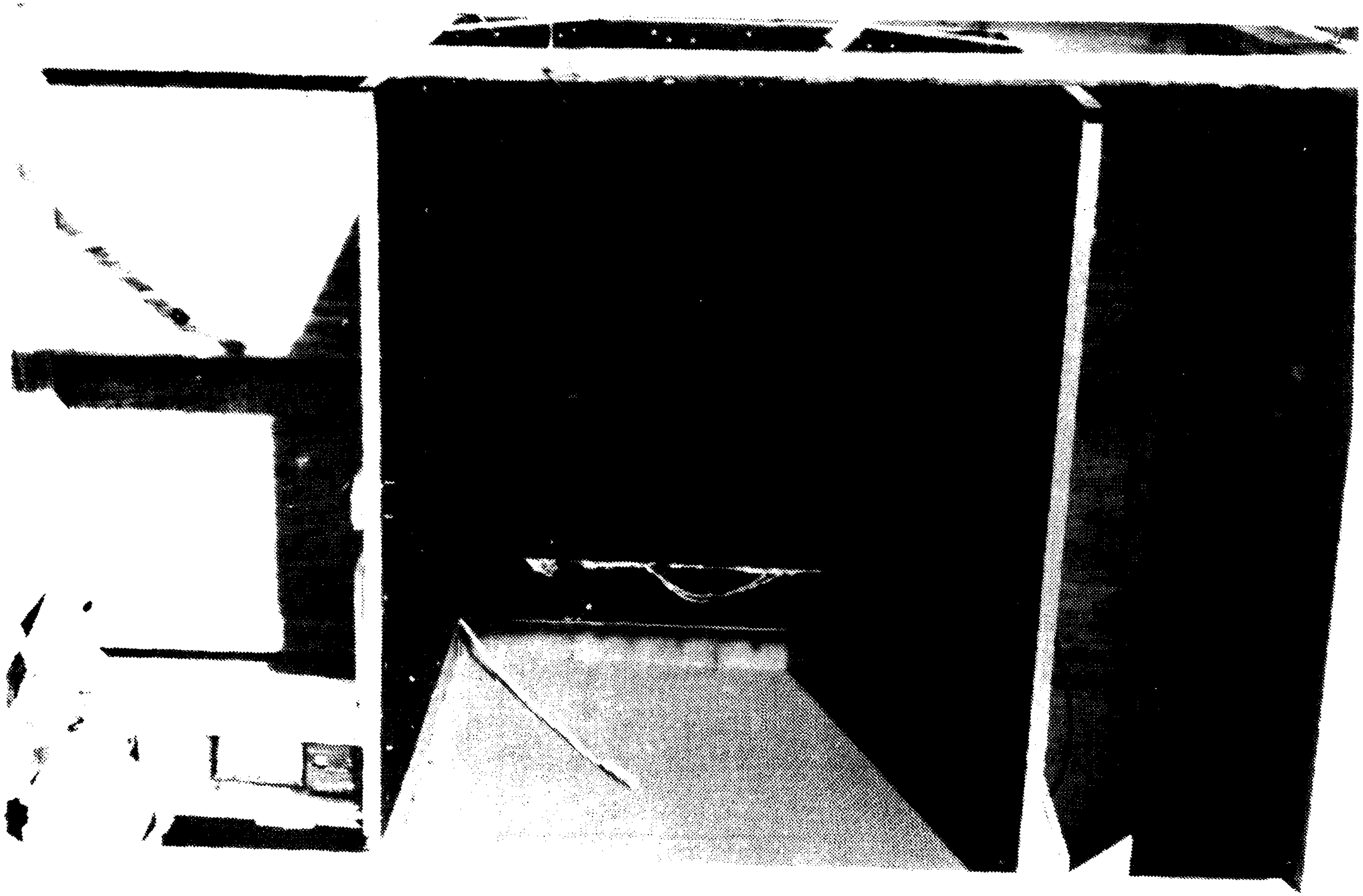


Figure 3.16 Pictorial of 3-Wall Source

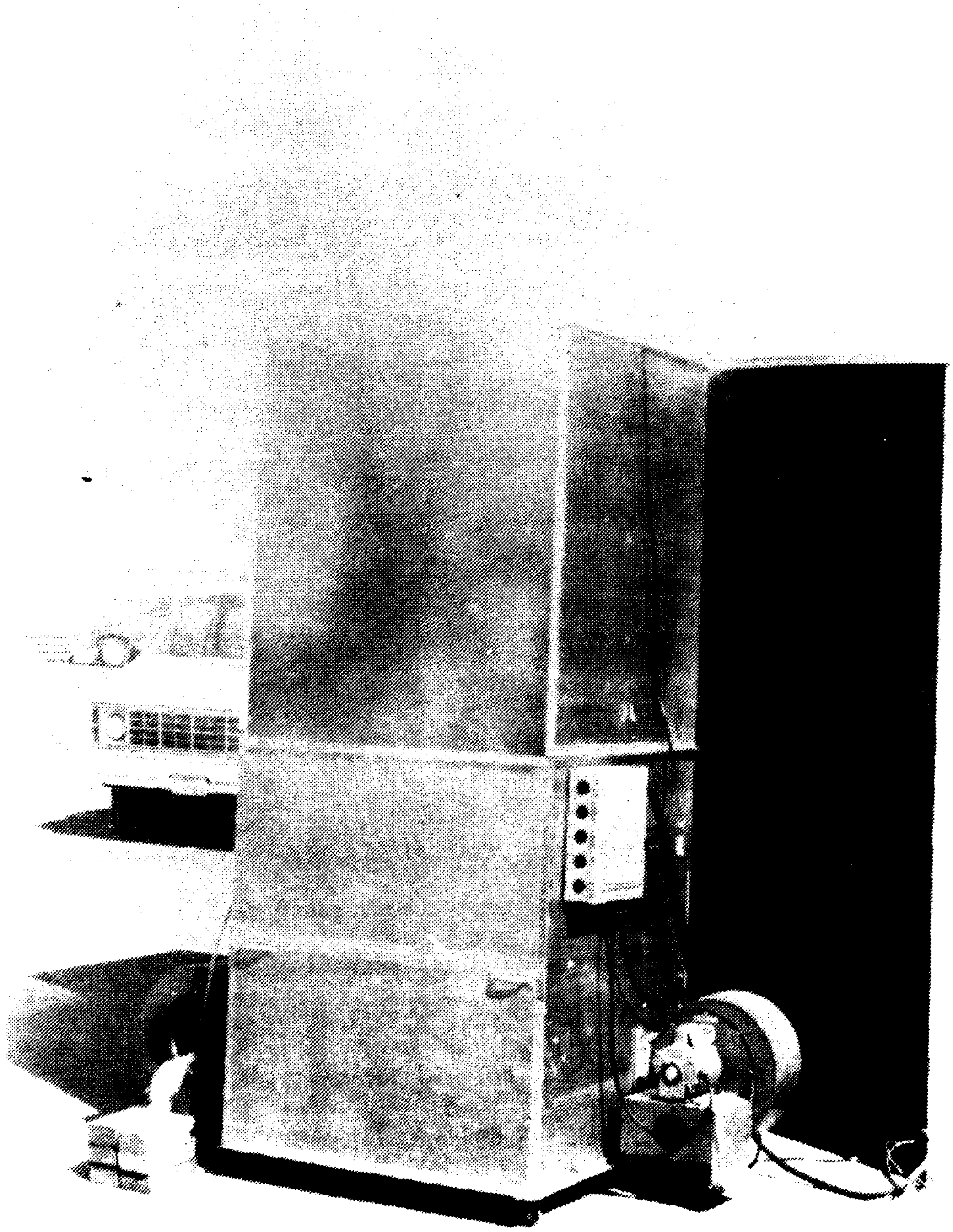


Figure 3.17 3-Wall Smoke Test

then passed to the 1 m^3 measurement section with a 1 m^2 temperature controlled plate as a background. The plate was coated with Bordens Krylon #1608 flat black paint which had an emissivity of 0.991 (China Lake Naval Weapons Center report #3818, March 21, 1977).

The plate temperature was controlled by Watlow heat pads which cover the entire back surface of the plate. The temperature controller was an RFL model 70 "stepless" full-wave phase-firing device which could be controlled to ± 0.05°C. The temperature was monitored by Omega Model 701 platinum RTD elements which were hand selected for 0.1°C accuracy when attached to the target plate (see fig. 3.16). The readout was an Omega Model 199P2 RTD with a resolution of 0.1°C and an accuracy of ±0.2°C. The sensor and the readout were calibrated in the lab and compensated for lead-wire resistance.

Attached to the side of the stack is a 3-inch pipe which was used to hold 5-minute smoke generators. These smoke devices were used in the early stages of field measurements to ascertain the effects of typical wind conditions on the effluents of the simulator (see fig. 3.18).

The seven-day meteorological recording system was a Weathertronics Model 5010. It was desirable to have a continuous record of temperature, humidity, and pressure. In addition, nonrecording devices for ambient temperature pressure and humidity were utilized as a double check to ensure correct recorded information. To document and characterize the wind conditions, a Weathermeasure Model W1034 low threshold recording wind system was used (see fig. 3.18). A kerosene lantern was used as a constant smoke source to provide a quick visual indication of wind conditions. Also shown in fig. 3.18 is a mobile laboratory owned by the Electro-Dynamics Laboratory at USU. It was utilized as a work station during the winter months of operation.

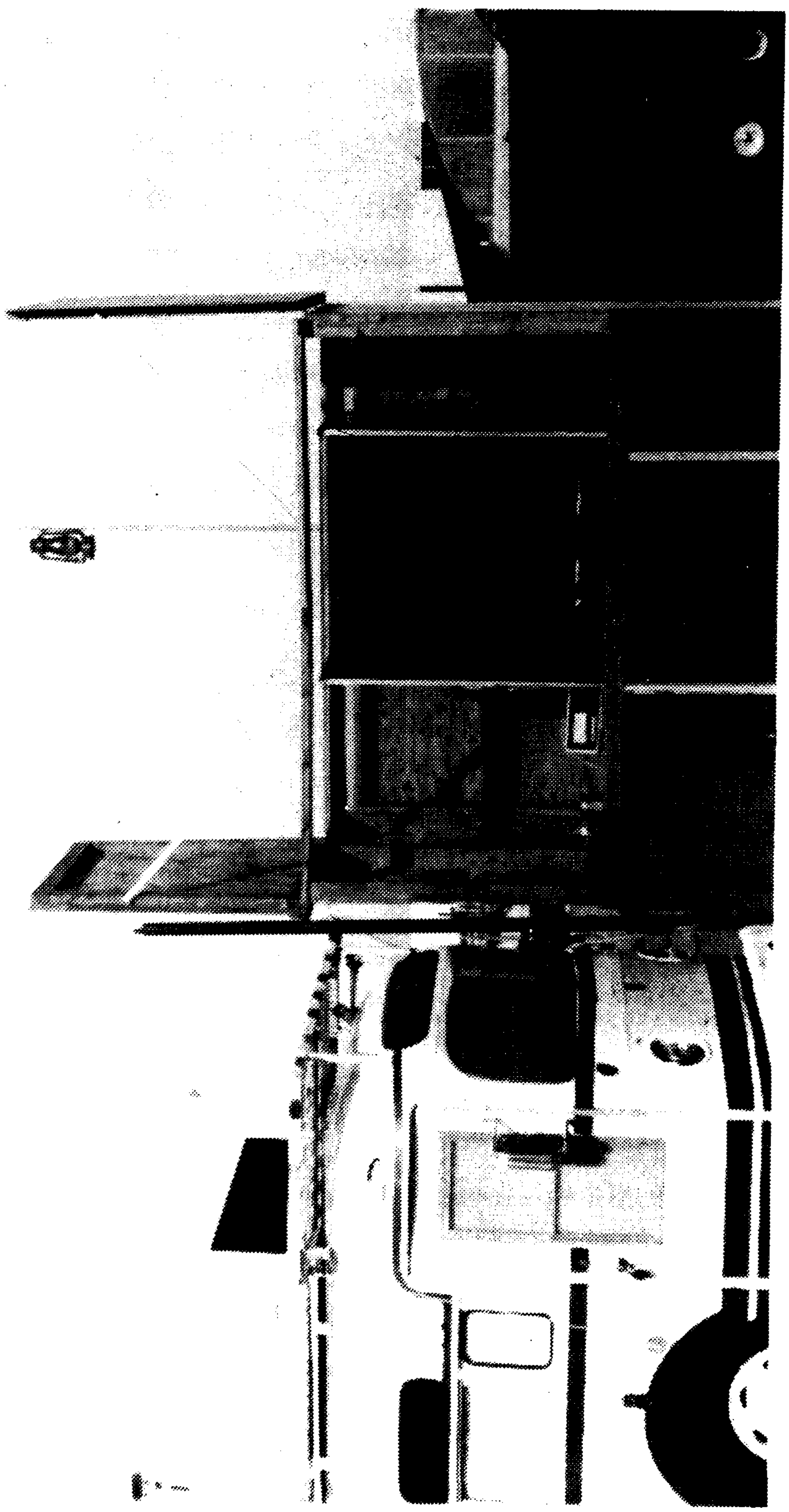


Figure 3.18 3-Wall Site

4. PROOF OF CONCEPT EXPERIMENT DESCRIPTION

4.1 Concept of Operation

The object of this experiment was to verify theoretical models and remote sensing techniques presently being used to determine trace gas concentrations and predict detection threshhold levels. The interferometer sensor previously described was used to detect and measure small quantities of N_2O gas injected in known concentrations into the simulated smokestack. The computed results obtained from these experimental remote sensing measurements were then compared with the injected levels to verify the theoretical models. The interferometer spectrometer measurements taken by USU were sent to AFGL and Atmospheric Radiation Consultants (ARC) for evaluation. It should be noted that the atmospheric and stack parameters were supplied to ARC, but the injected N_2O levels were not supplied until after the data had been evaluated. The detailed results of this verification comparison are contained in reports by ARC. This report deals mainly with the measurement technique and associated equipment.

A flow diagram of the experiment is shown in fig. 4.1. The simulated smokestack with associated monitoring and meteorological instrumentation was separated from the sensor by a distance of 273 meters. This separation distance resulted from an attempt to obtain as much separation as possible while still keeping the stack measurement section within the telescoped instrument field-of-view. The separation of the source and sensor introduces a considerable intervening air mass and duplicates to some degree actual remote sensing conditions.

The sensor remotely views the target and produces an interferogram which is stored on a magnetic disc. After the data collection was

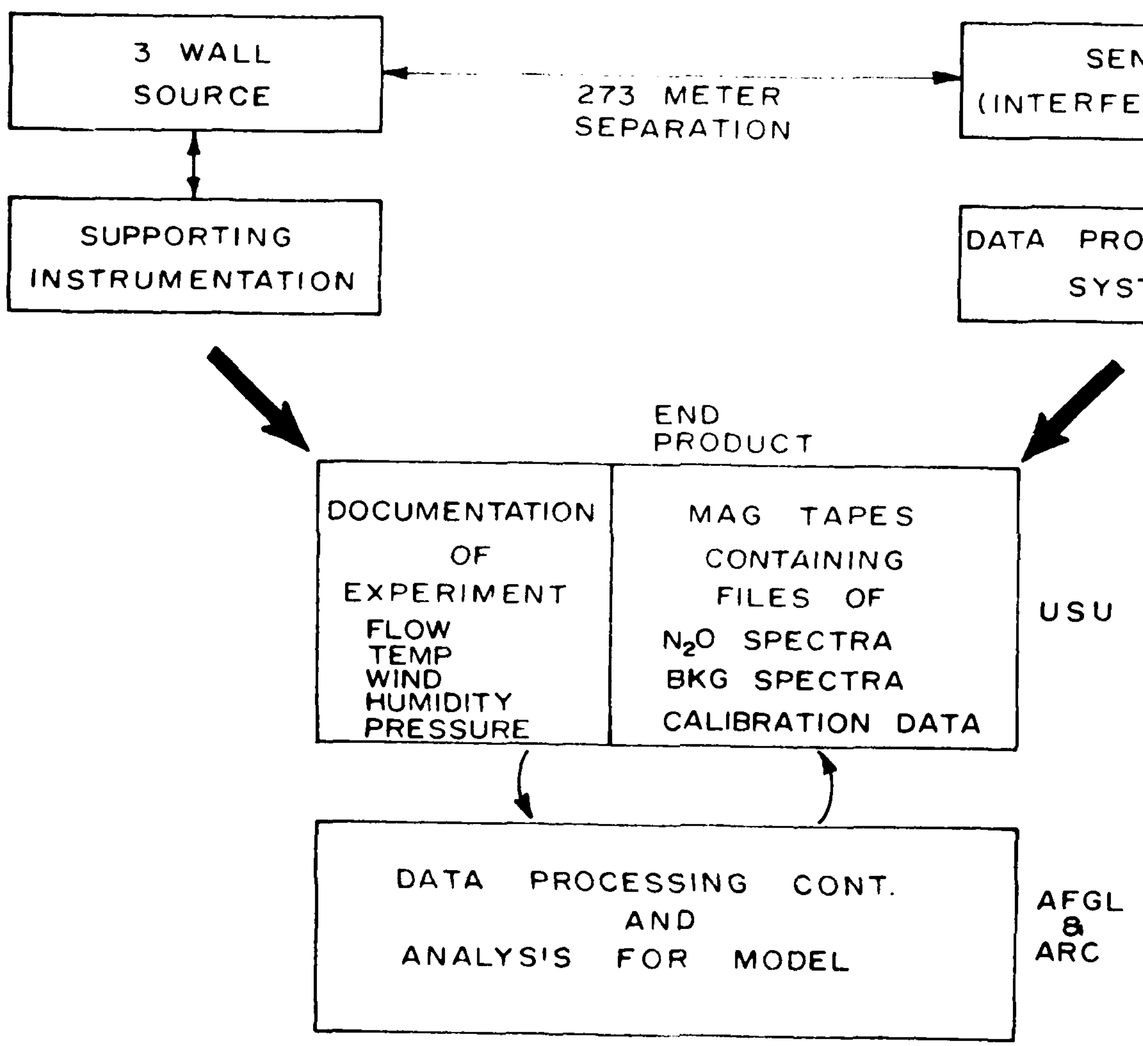


Figure 4.1 The 3-Wall Experiment

complete the interferograms were transformed into spectra. The target and background spectra were then transferred to 9-track 2400' magnetic tape along with an instrument response file which could be used to calibrate the data. The tapes along with a record of the physical conditions which existed during the measurement were forwarded to AFGL. At AFGL the tapes were read into a CDC 6600 computer where more sophisticated processing by ARC could occur. Experimental results were relayed to USU by AFGL to determine if concentrations and minimum detectable quantity (MDQ) correspond to actual concentration.

4.2 Physical Arrangement

The sensor facility was located at the USU physics observatory at approx. 1100 N. 1000 E. Logan, Utah (see fig. 4.2). This site was chosen for its security, low density population, availability of power and communications. A major drawback of this location (which was not anticipated) arose when it was found that during the major portion of a normal working day the sun illuminated portions of the background plate causing unacceptable temperature fluctuations (see fig. 4.3 and 3.16). Therefore, experiments were conducted at night or under uniform cloud conditions.

The source was located at approx. 1300 N. and 1000 E., also on university property. The source location also had a drawback which did not manifest itself until some months into the measurement program. The prevailing wind at this geographical location was from North to South during the winter months. This wind from the North tended to blow the simulated smokestack effluents into the measurement path between the sensor and source. Measurements therefore had to wait until favorable winds occurred. These restrictions along with the solar angle and the

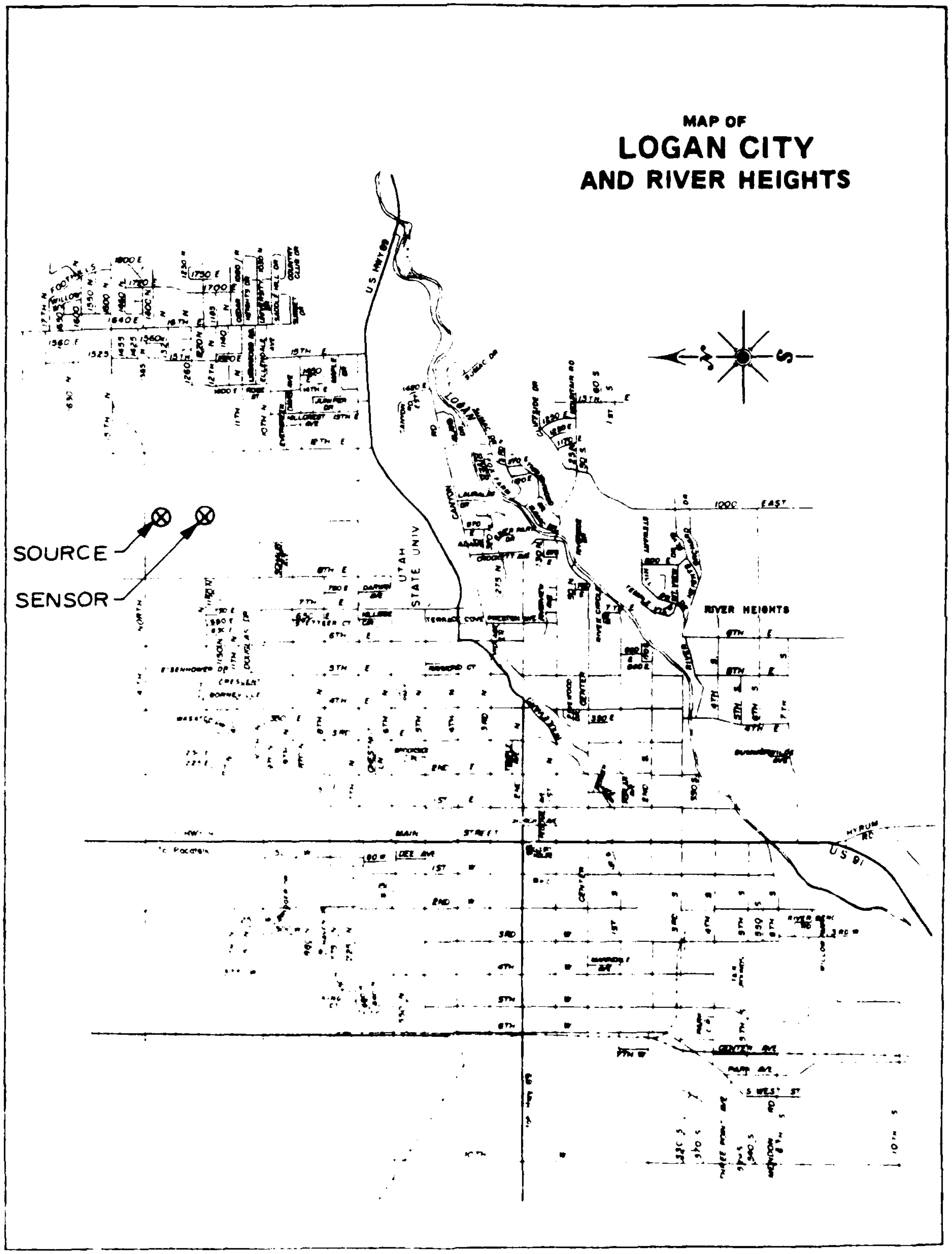


Figure 4.2 Logan map showing 3-Wall site

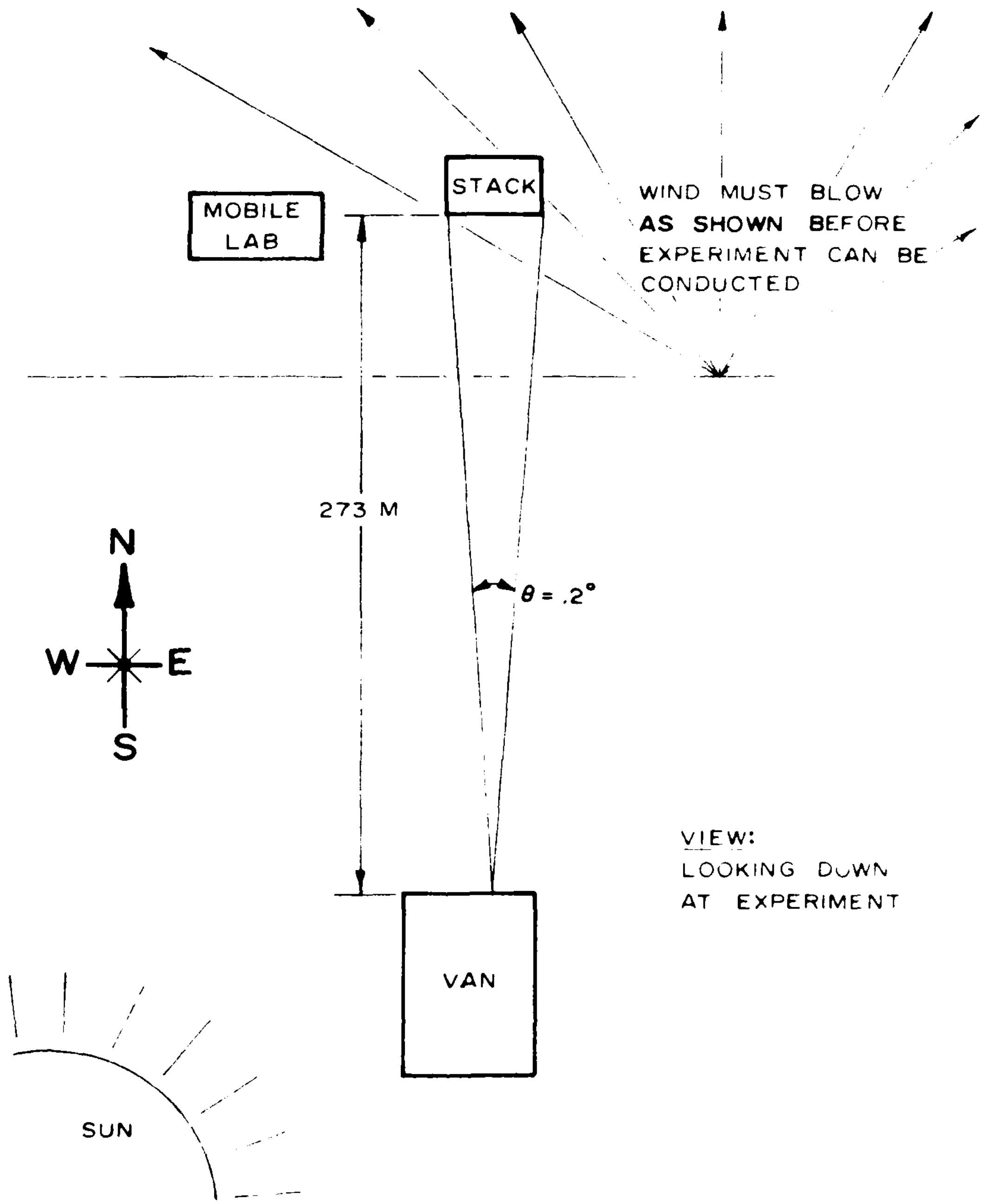


Figure 4.3 Experiment Layout

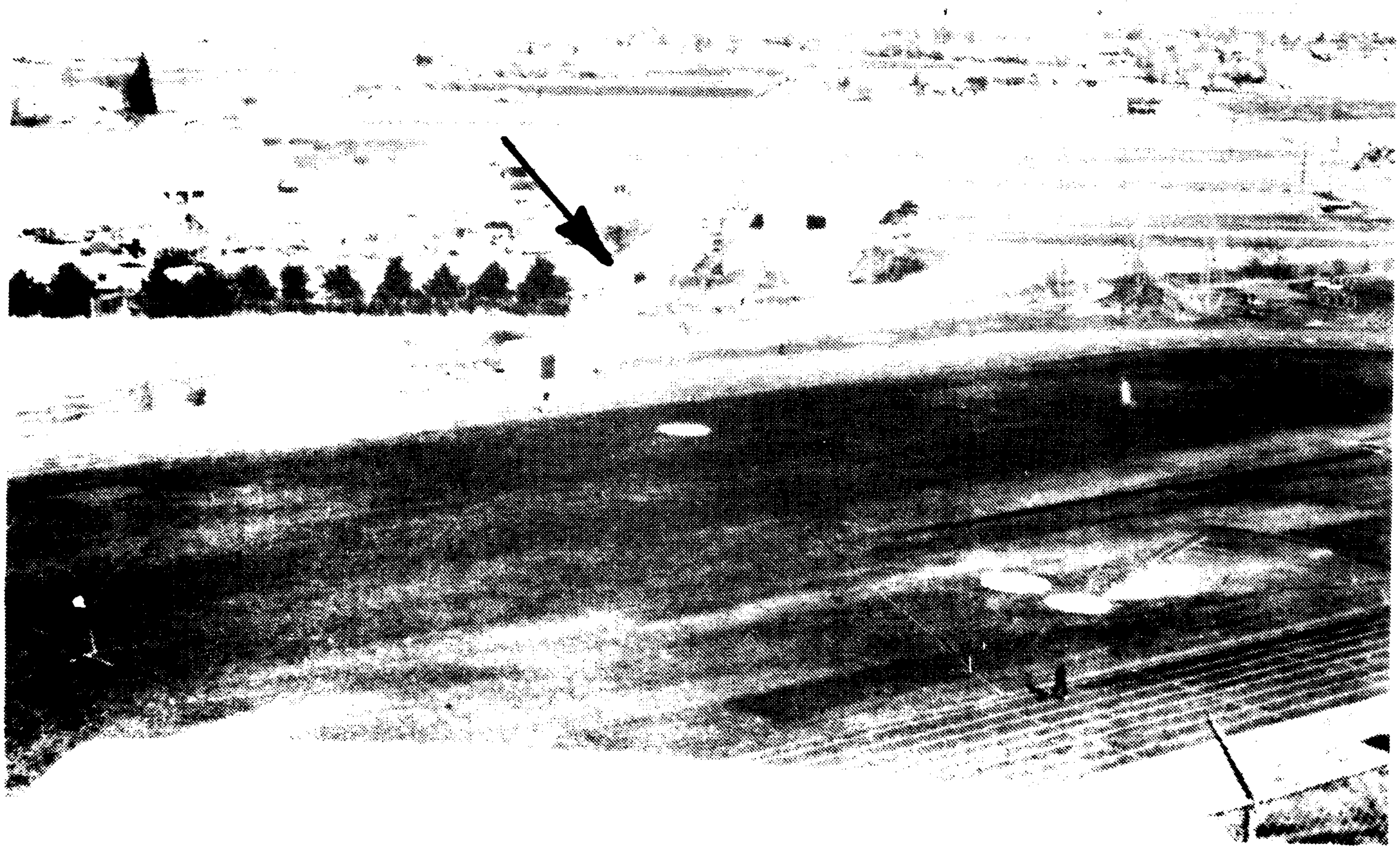


Figure 4.4 View from Sensor Showing Location of Source

extremely high number of foggy days, required that experiments be carefully coordinated with prevailing weather conditions.

Figure 4.4 is an aerial view of both the sensor and the source; the top edge of the van is visible in the foreground. The source is visible next to the red dot in the center.

4.3 Parameters and Conditions Required

Stable Atmospheric Conditions. Because of the controlled nature of this experiment, any variables should be minimized. Therefore, the optical path between source and sensor should remain a constant. This is normally not a problem unless there is rain, snow, fog, smoke, or dust present. During the period of 12 Dec. to 15 Jan., 95% of the available days fell into the above categories (mainly fog). A normal year would have been 45%. Another point to note is the sunset/sunrise transitions. The seven-day chart record showed very dramatically the rapid changes in temperature and humidity that occur. Measurements during these adverse conditions were avoided (see fig. 4.5).

Solar Radiation. Solar radiation illuminating the temperature controlled plate could vary the temperature in that area by as much as 40% (see fig.3.16). Therefore, it was necessary to conduct the experiment under uniform cloud conditions or at night.

Favorable Wind Pattern. Wind direction was monitored and recorded continuously to establish daily trends for prediction of possible measurement "windows." During data collection, direction and velocity were recorded in the format shown by fig. 4.6. If the direction shifted during measurement such that effluents would drift back into the FOV, that run was aborted and the sequence recycled.

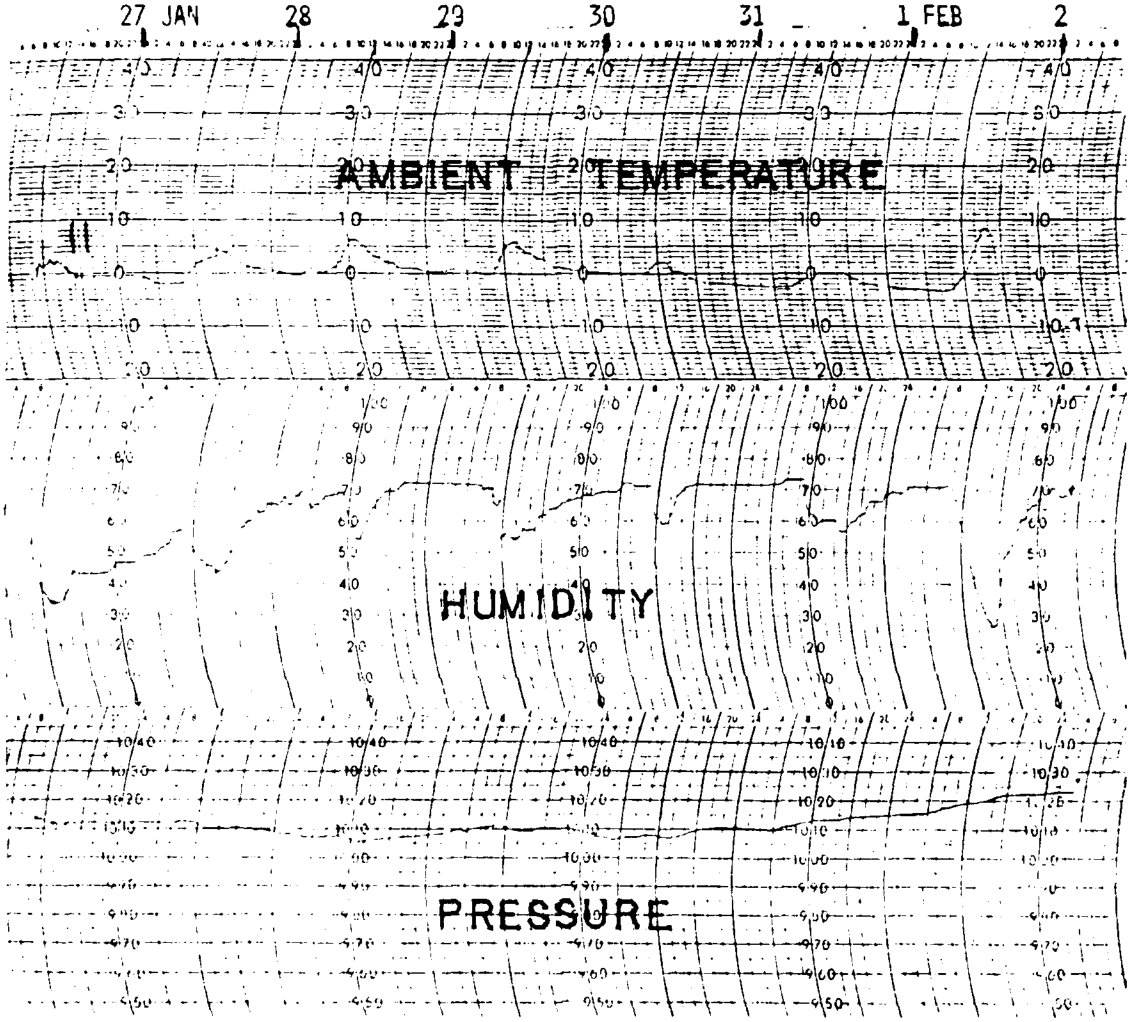


Figure 4.5 7-day chart recorded during measurements

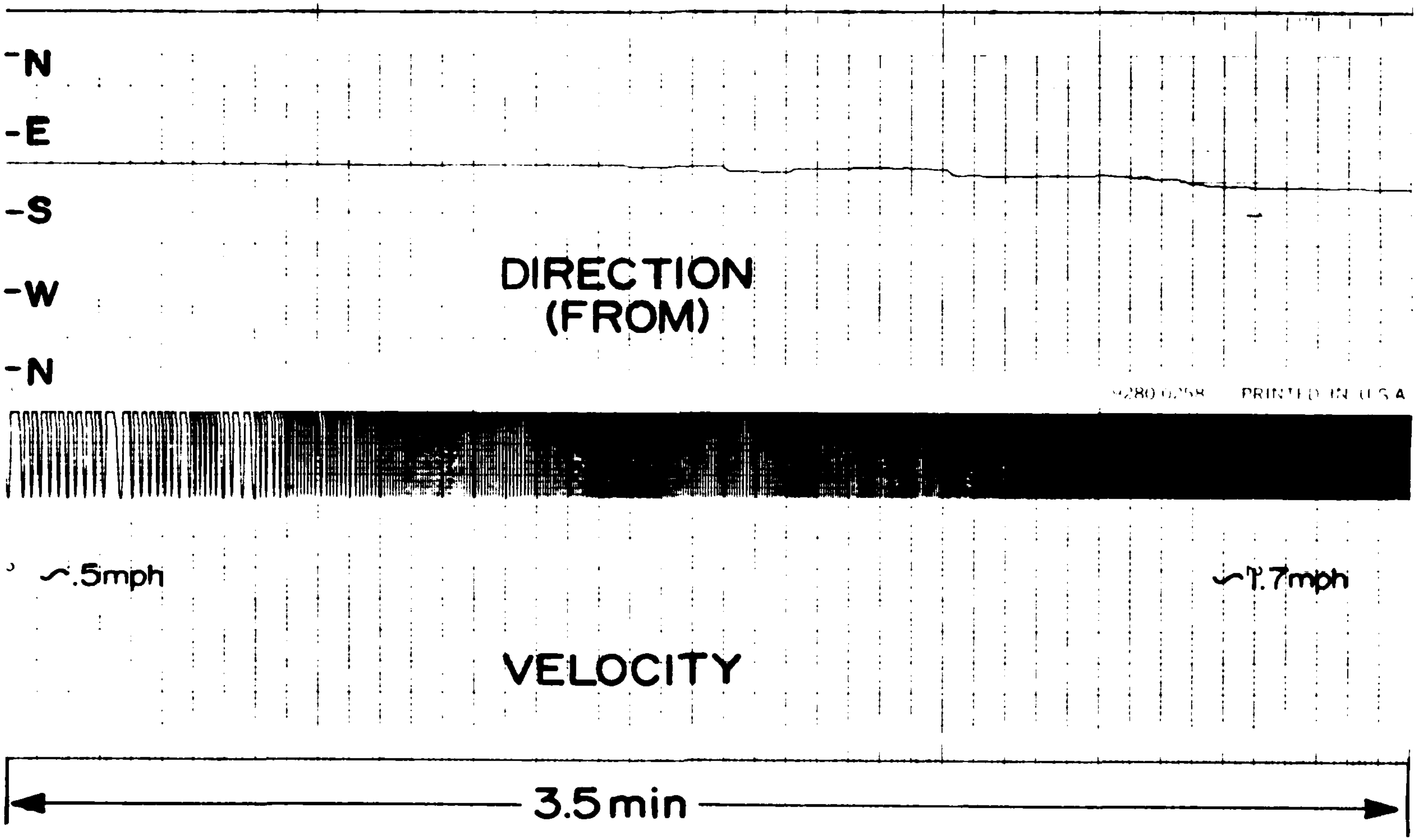


Figure 4.6 Wind conditions during the collection of 12 N_2O spectra

Wind direction from the East, Southeast, South or Southwest were the only directions that did not ultimately cause the effluents to drift back into the field-of-view of the sensor. This was based on the smoke tests conducted earlier.

A dead calm condition was also undesirable in the N_2O case because N_2O did not rise and dissipate resulting in contamination in the vicinity of the stack. To avoid this, all the measurements were conducted with wind velocities between 1 and 5 meters/sec.

Hardware Equilibrium. Each piece of equipment has its own warm-up characteristics.

For the temperature controlled background plate this could vary from 1 to 3 hours depending on the ambient conditions such as wind and temperature. Measurements were not conducted if the plate temperature rate of change was more than 1°C/hour. The blowers must have been running for at least one hour prior to data collection. All electronic equipment was on and stabilized for at least two hours. The calibration source for the interferometer was normally on for 6 hours prior to commencing operations.

Bore Sighting. A procedure is described below which maintained a nominal 3.8 cm shift in the 1.3 meter diameter "footprint" of the sensor. The front cover of the stack enclosure was constructed of pegboard with 1" center holes. Two sources were developed which could be moved about a circle which coincided with the "footprint" of the sensor. These sources allowed checking the sensor both as a radiometer and as an interferometer (see fig. 4.7). This method was also used to obtain data points which were used to create an FOV contour such as the one shown in fig. 4.8.

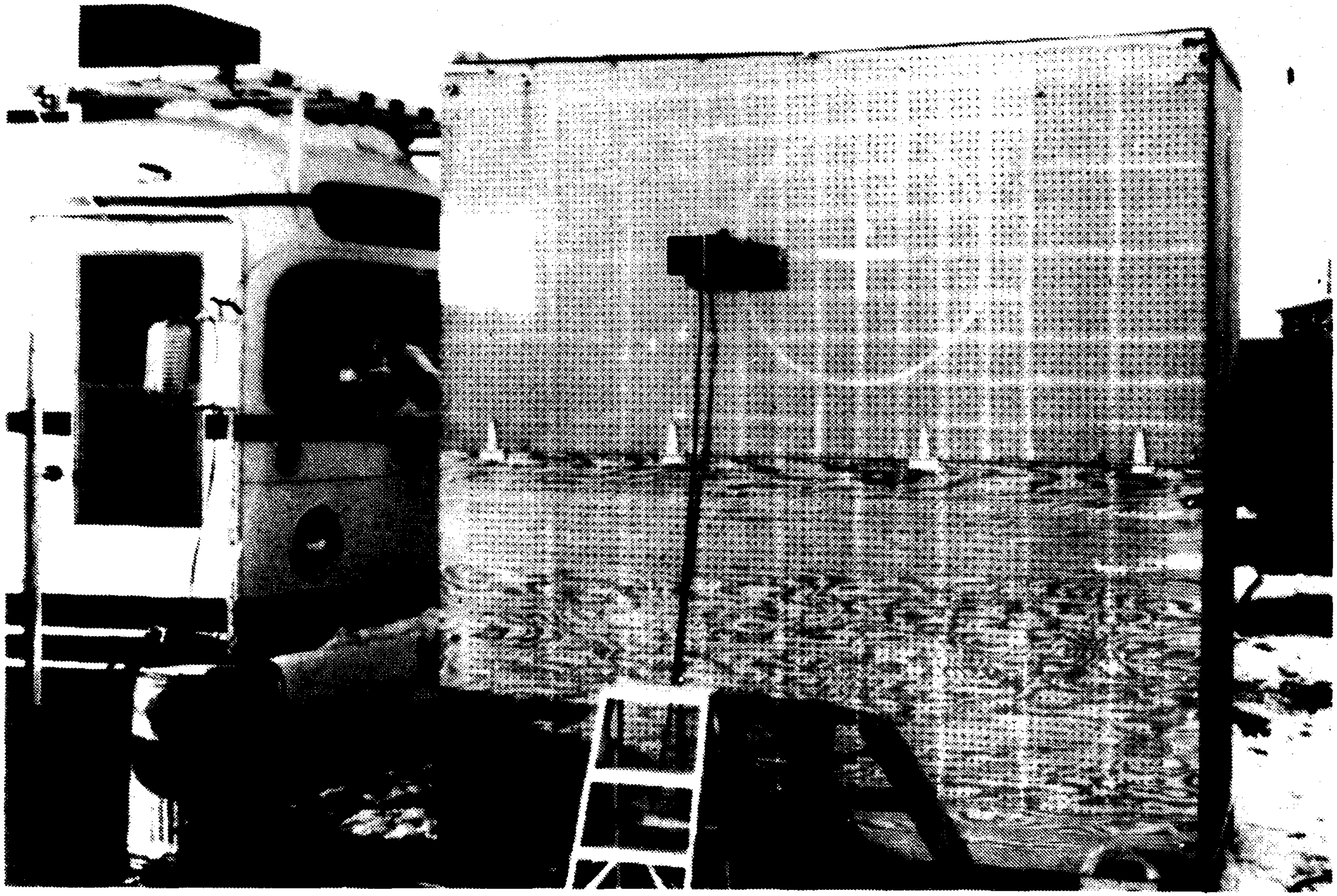


Figure 4.7 Hardware for Bore-sighting and FOV

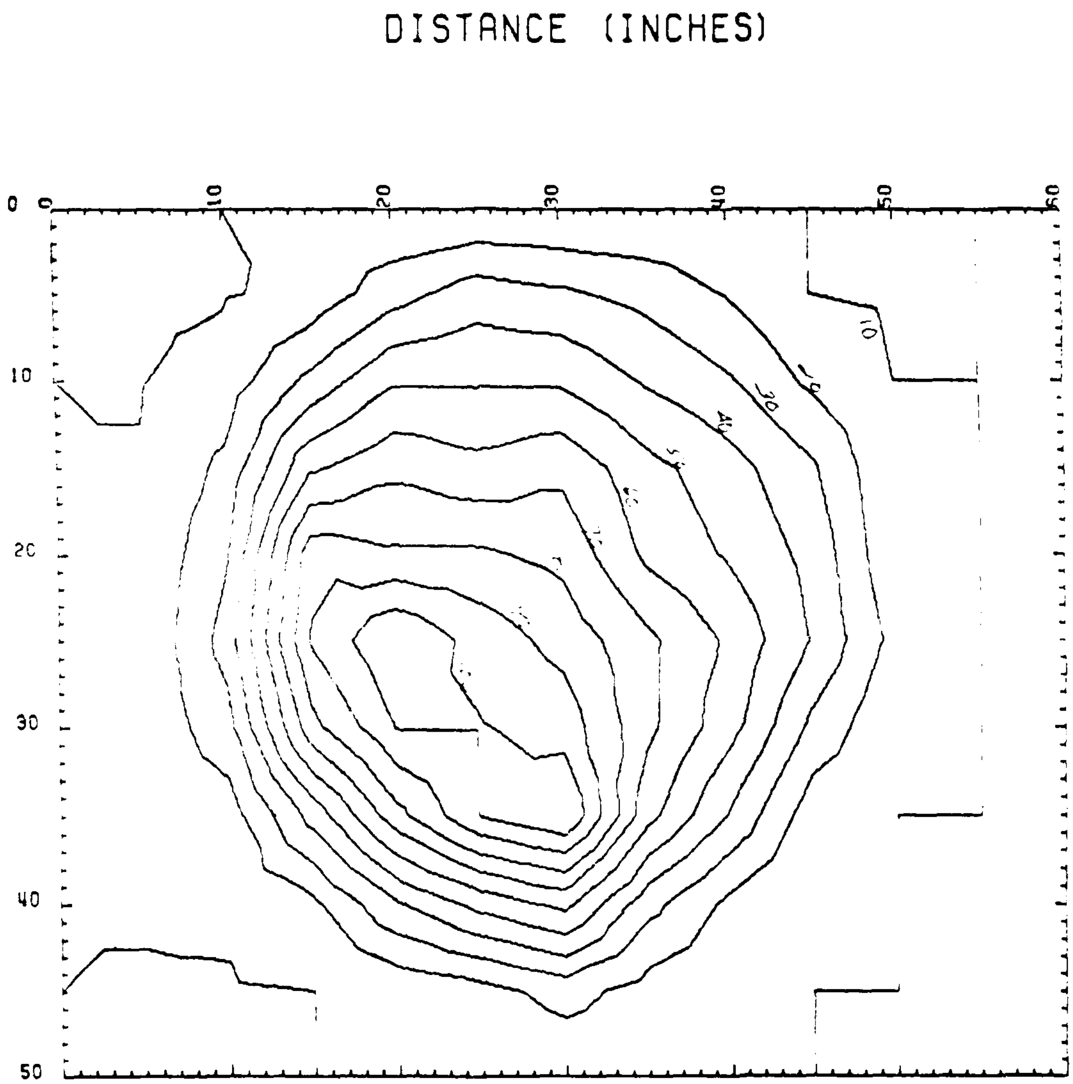


Figure 4.8 Field of View Contour

Calibration. The sensor is calibrated by generating and storing an instrument response function before and after each data set.

Using an extended high-emissivity temperature controlled source which completely fills the telescope FOV, an instrument response was created as follows:

1. All data system parameters were set to match intended data.
2. An interferogram (IFG) was collected using the hot extended source.
3. An IFG of a 77°K cold extended source was then collected.
4. The cold source IFG was then subtracted from the hot source IFG to eliminate emissions from instrument optics.
5. The resulting IFG was then transformed and stored in the sample file.
6. A *theoretical blackbody* (TBB) function was then generated and stored in the reference file.
7. The instrument response was then generated by dividing #5 by #6. A sample is included in the Appendix.

Maintaining Constant SNR. In order to achieve a signal to noise ratio (SNR) that was constant for each set of data taken on different days, it was necessary to adjust the flow rate of the trace gas to match the ΔT between ambient and plate temperature. The following method was used to determine the proper flow. A data system command called BBG was used to calculate the radiance of the experiment backplate and air temperature. Once these two radiance numbers were known, the flow could be set to compensate for varying ΔT using the following relationship.

$$(R_2 - R_1) \times \text{Flow} = K$$

4.4 Conditions and Procedures of Feb. 19, 1981

To further describe the measurement procedure, a detailed description of the process on February 19, 1981, is used for an example. Table 4.1 shows the source and sensor conditions on this day.

Thursday, February 19, 1981, began as a clear day. All equipment associated with this experiment was activated and exercised in the morning. The meteorological recording device was checked for accuracy, paper, and ink. LN tanks were refilled, and the detector cooled down.

Because of unfavorable wind conditions and solar effects, the experiment was put on a standby basis waiting satisfactory conditions. During this time an experiment was performed to verify interferometer system ability to evaluate N_2O bandstrength in a closed cell. The objective was to insert a cell (containing a known amount of N_2O) into the optical path. Using the spectra obtained in this manner, it is possible to measure the area absorbed by the spectral lines of an N_2O band and deduce the bandstrength. The results of this experiment are contained in Appendix B.

By early afternoon a uniform cloud cover existed such that solar effects were negligible. The wind, however, was blowing directly to the south. At 1600, the wind had shifted 180° to an ideal direction and the measurement sequence was started. The experiment sequence is shown below and Figure 4.9 is a summary.

1600 hours. Generate and store an instrument response. Wind recording devices were started and documented. Temperatures logged at 5 minute intervals. Proper flow for SNR calculated.

1615 hours. Twelve background spectra collected using a macro instruction set. Instrument response generated and stored for calibration.

Table 4.1 Source and sensor conditions on February 19, 1981.

A. Source Conditions

Volume of target gas	1 m^3
Mass flow rate	1.003 m/s
Ambient temp.	287.2°K
Background temp.	315.4°K
Temp accuracy	± 1°K
Temp resolution	0.1°K
Background area	1 m^2
Background emissivity	0.991
N_2O flow rate	Fig. 4.9
N_2O gas purity	99.8%
Calculated PPM @ F = 20	40 PPM
Prevailing Wind Direction	From S.
Wind velocity	2 m/s
Time of day	1615 hrs
Barometric Pressure	851 mb
Humidity	35%
Visibility	100%
Equip. "on" time	6 hrs.

B. Sensor Conditions

Field of view	0.21° full angle
Percent Source in FOV	70% ± 3%
Sensor responsivity	3.4×10^4 v/w
Spectral range InSb Det.	1800 - 3600 cm^{-1}
Resolution	0.12 cm^{-1}
Time/scan	17 sec.
Postamplifier gain	30
Calibration source temp.	373 K ± 1°K
Subtraction source temp.	77°K - 100°K
Data points	131, 072
Apodization function	Happ-Genzel
CVF position	open
Bore sighting	100%
Equip "on" time	6 hrs.

Flowmeter set at 22, max of 25 possible (see table 4.2 for conversion to liters/sec). Collect one scan at each flow starting at 22 and decreasing by 4 to the lower limit of 2 and then increasing back to 22. The last scan was taken again at 2 to recertify the lower concentration level.

1625 hours. Recalibrate

1730 hours. Begin transforming IFG's to spectra

2200 hours. Transfer spectra to magnetic tape.

20 February. Mail data tapes to AFGL

Other measurement days followed a similar sequence with the exception of the stair-step sequence.

Table 4.2. N_2O Flowmeter Conversion

Flowmeter reading	N_2O Flow in liters/sec
1	2.70 (-4)
2	1.31 (-3)
3	2.78 (-3)
4	4.58 (-3)
5	6.54 (-3)
6	8.42 (-3)
8	1.24 (-2)
10	1.70 (-2)
12	2.13 (-2)
14	2.56 (-2)
16	3.06 (-2)
18	3.48 (-2)
20	4.06 (-2)
25	5.23 (-2)

Gas @ 0°C
1 atm

	TIME →	1600	1605	1610	1615	1620	1625	1630	1635	1640	1645	1650
temp. readouts in °C during measure- ment.	BKG Upper left	44.7	44.6	44.5	44.3	44.6	44.5	44.6	44.5	44.6	44.9	
	BKG lower right	39.1	39.1	39.1	39.0	39.0	39.1	39.3	39.1	39.2	39.4	
	BKG lower left	40.2	40.1	40.0	39.8	40.0	39.9	39.9	39.9	40.0	40.2	
	BKG upper right	47.0	46.5	46.2	46.0	46.1	46.1	46.1	46.1	46.0	45.6	
	AMBIENT TEMP.	15.0	14.8	14.3	14.1	14.2	14.3	14.2	13.9	14.2	14.4	
	WIND DIRECTION	S	S	S	S	S	W	S	SE	SE	S-SE	

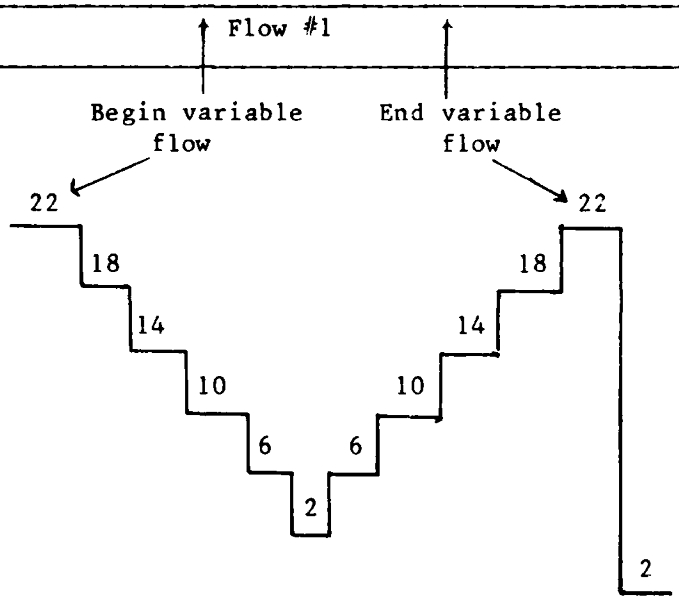


Figure 4.9 Experiment Documentation for February 19, 1981.

Other measurement days followed a similar sequence with the exception of the stair-step sequence.

5. SUMMARY

The analysis results provided by ARC at the end of the program indicate that detection threshold levels and trace gas concentration can accurately be measured remotely using this technique. Measured levels correspond closely with injected concentrations even though ARC did not know the concentration levels before analysis. Fig. 5.1 is an extraction of ARC's March 1981 report showing the actual analytical comparison of measured trace gas injected concentration with the levels deduced from the remote sensing method.

A summary of all data sets collected and processed by both USU, AFGL and ARC, are shown in figure 5.2. All conceivable sources of error have been double checked and procedures established to ensure measurement inetgrity.

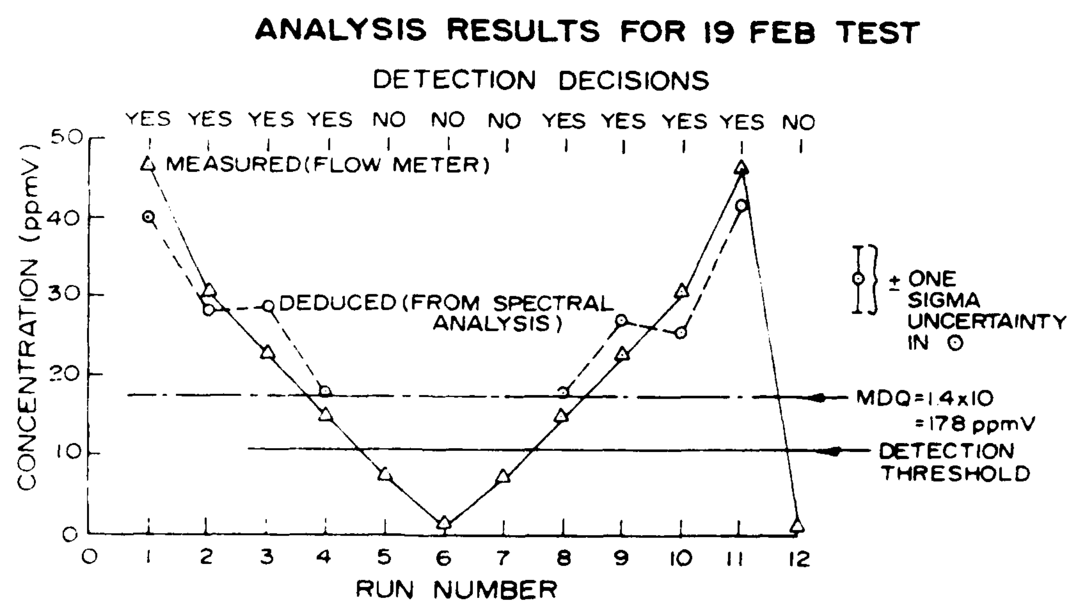


Figure 5.1 ARC analysis Results from Variable Flow

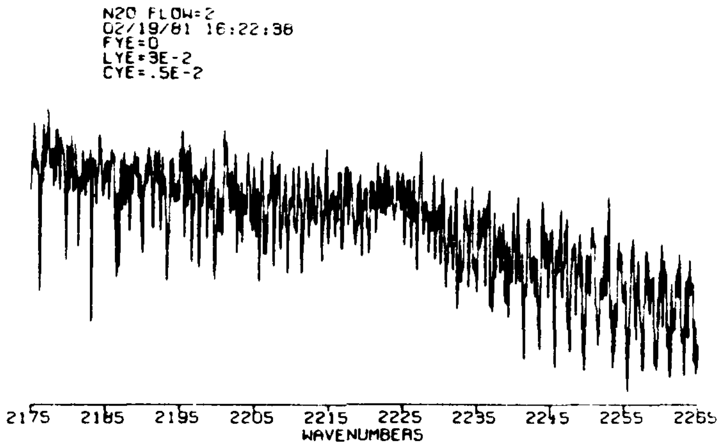
CRS MEASUREMENT SUMMARY 1981

DATE	MAGNETIC TAPE #	NO. DISCS COLLECTED	DATA	FLOW	AVERAGE PLATE TEMP. (°C)	AMBIENT TEMP. (°C)	HUMIDITY (%)	PRESSURE (MBAR)	WIND	
									DIRECTION (FROM)	METERS/SEC
26 JAN 1730 hrs	000091	2	12 BKG 12 N_2O 2 RSP	19	42.6	1.0	42	850	S	1-2
4 FEB 1800 hrs	000095	2	12 BKG 12 N_2O 2 RSP	19	38.9	-12.5	33	859	SE	1-2
4 FEB 1848 hrs	000064	2	12 BKG 12 N_2O 2 RSP	19	38.8	-12.7	35	859	S	2-3
5 FEB 1715 hrs	000097	2	12 BKG 12 N_2O 2 RSP	20	40.1	-9.4	47	855	NE	1-2
12 FEB 1655 hrs	000108	4 FILES	1 BKG 1 N_2O 1 RSP	25	64.5	4.6	53	865	SW	2-3
13 FEB 1630 hrs	000108	4 FILES	1 BKG 1 N_2O 1 RSP	25	65.3	3.8	58	864	S	1-2
19 FEB 1614 hrs	000103	2	12 BKG 12 N_2O 2 RSP	VARIED 2-22	42.4	14.2	38	849	S	1.3-1.6
19 FEB 1628 hrs	000107	2	12 BKG 12 N_2O 2 RSP	21	42.4	14.1	36	846	S	2-3

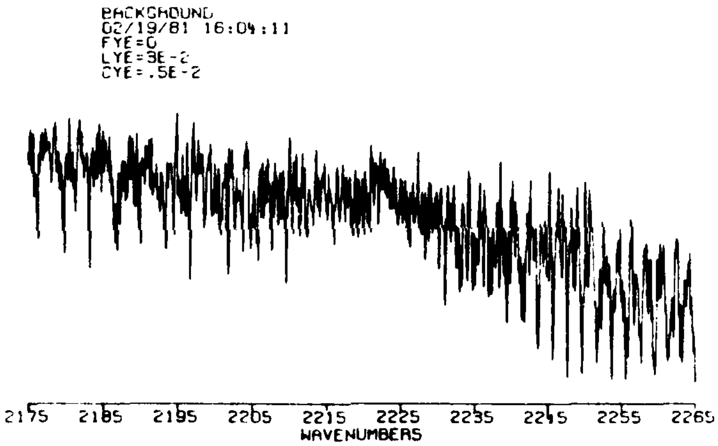
Figure 5.2 CRS Measurement Summary

APPENDIX A

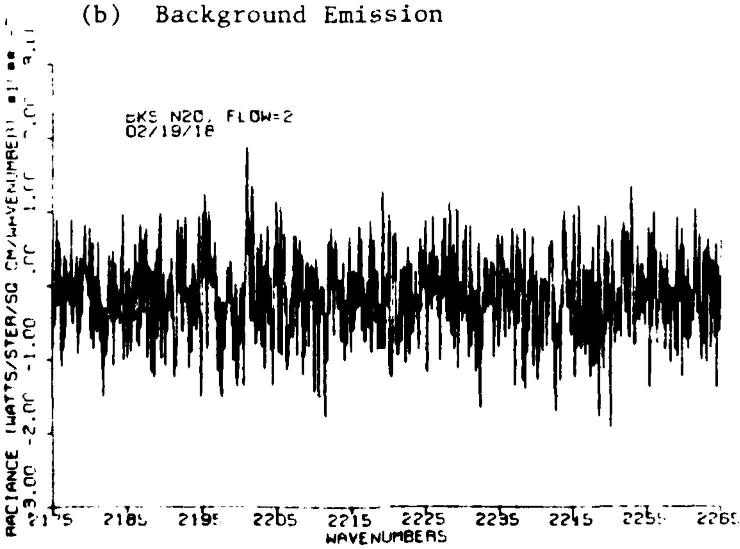
Results of Trace Gas Measurements



(a) N_2O Injected into Airflow

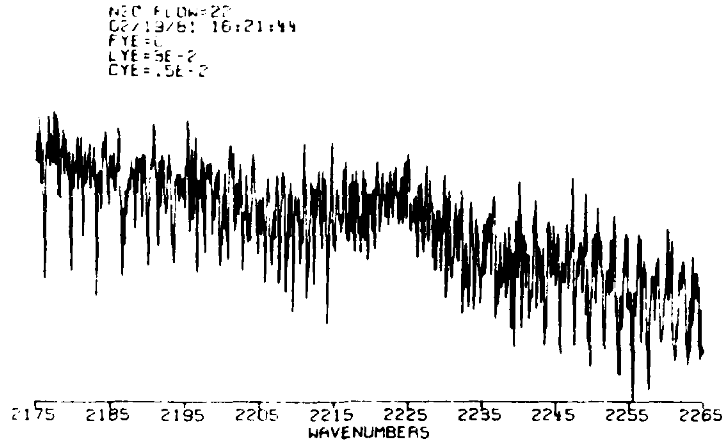


(b) Background Emission

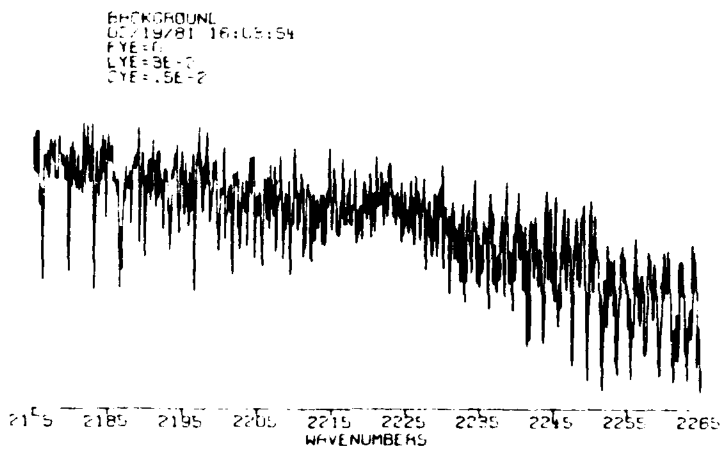


(c) Background Subtracted N_2O Signature

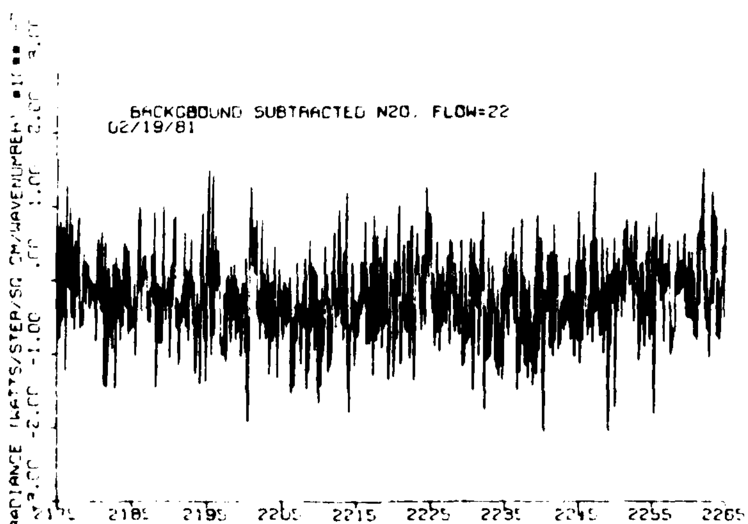
Figure A.1 Low SNR N_2O not detectable



(a) N_2O Injected into Airflow

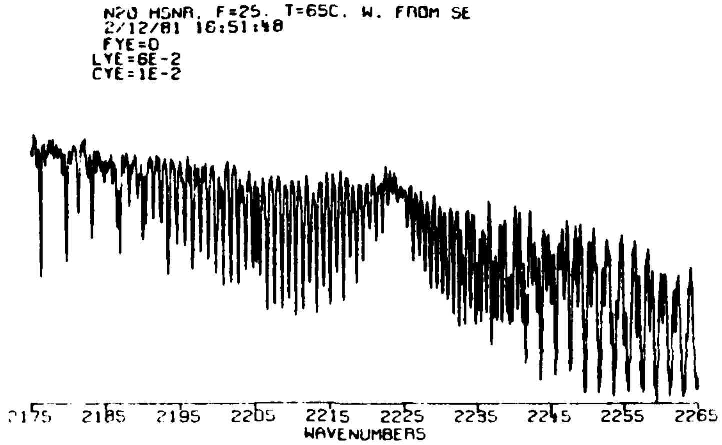


(b) Background Emission

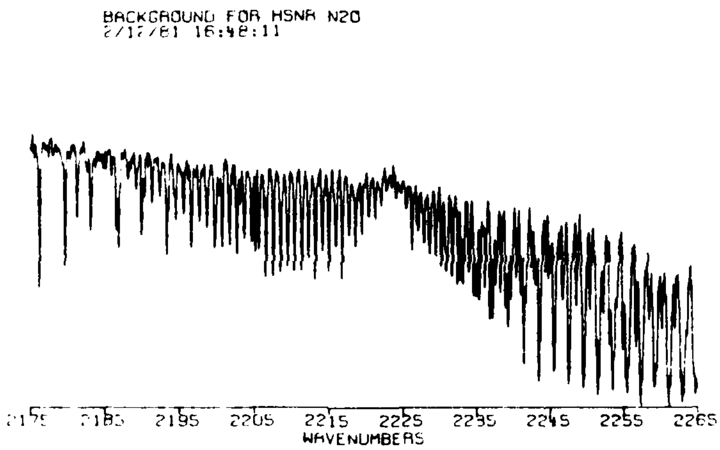


(c) Background Subtracted N_2O Signature

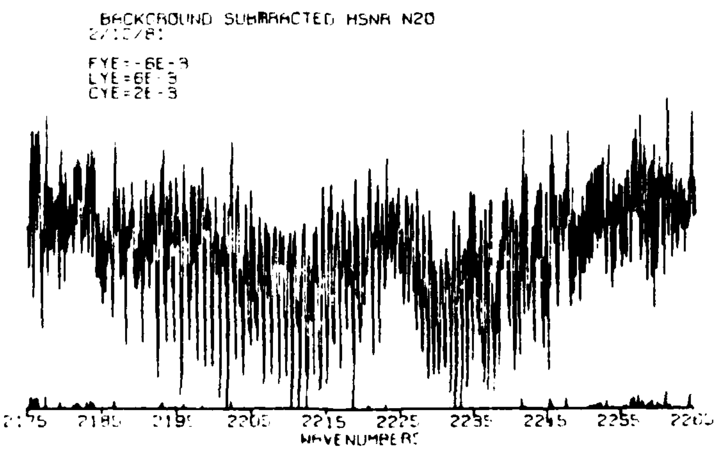
Figure A.2 Medium SNR N_2O slightly above detection



(a) N_2O Injected into Airflow



(b) Background Emission



(c) Background Subtracted N_2O Signature

Figure A.3 High SNR N_2O well above detection

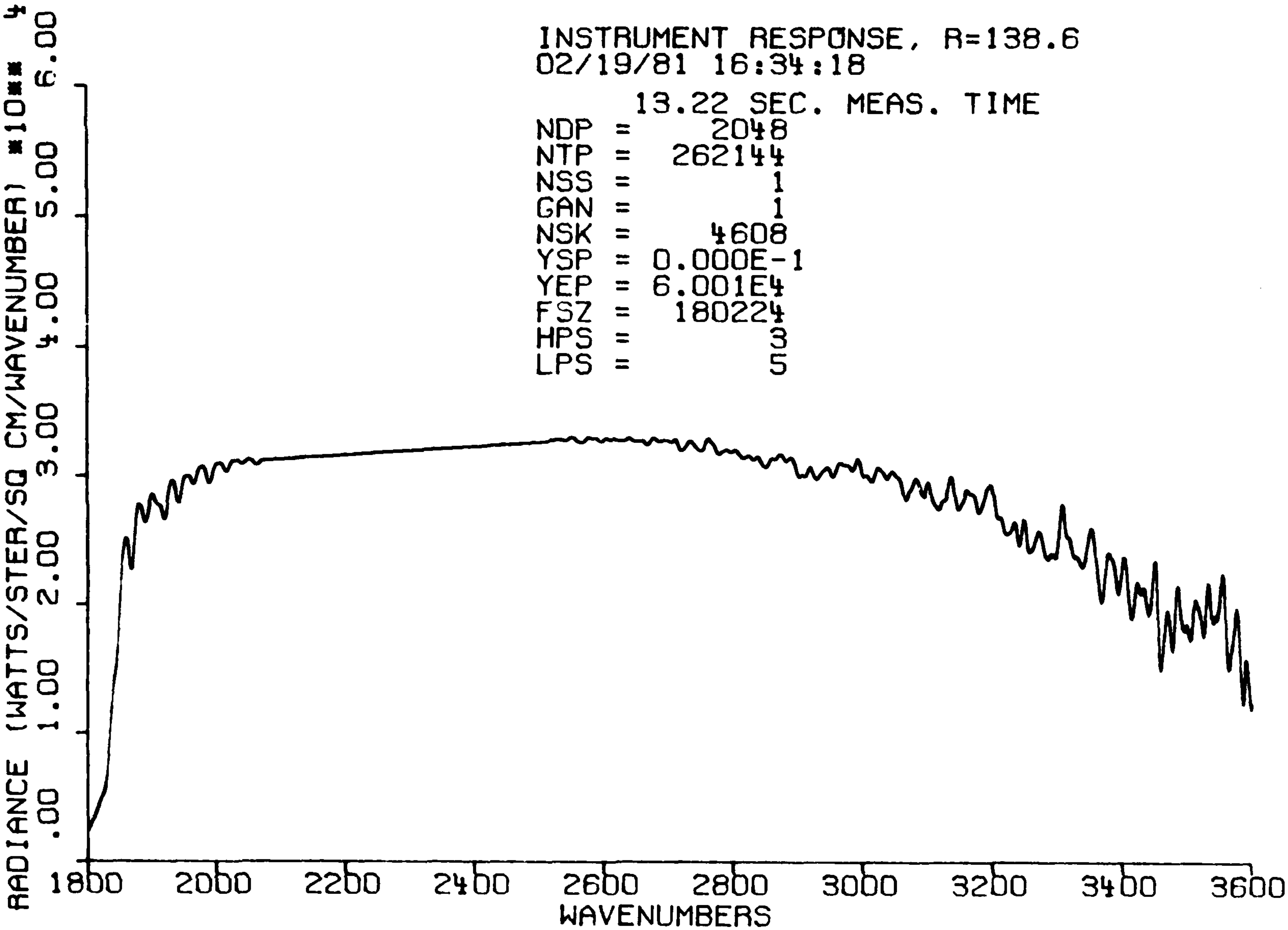


Figure A.4 Instrument Response

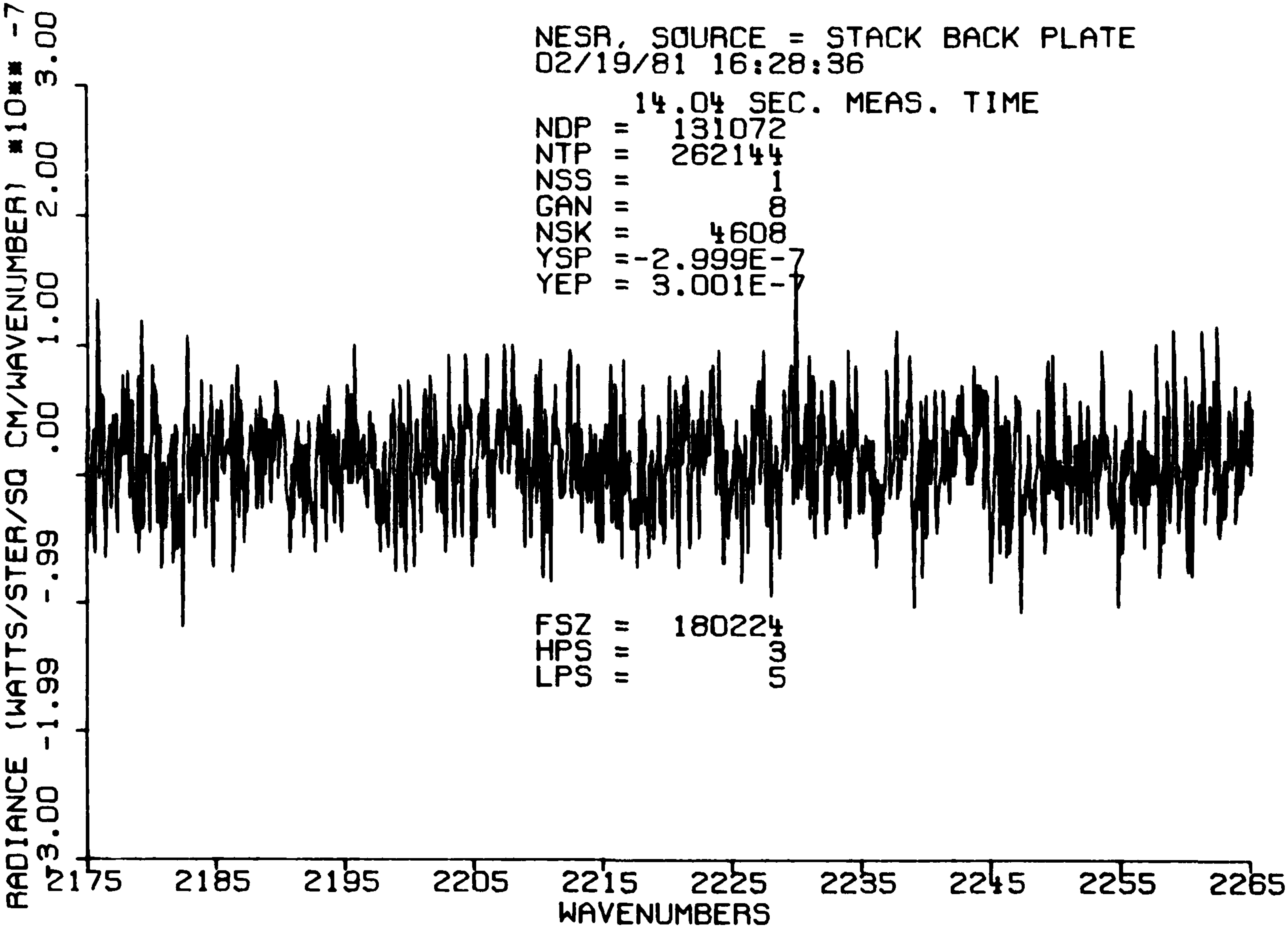


Figure A.5 NESR

APPENDIX B

N_2O Bandstr-ngth Determination

N_2O BANDSTRENGTH

N_2O BANDSTREN... ...BLISHED IN THE LITERATURE AS A NUMBER BETWEEN 1350 AND 1858 $ATMOS^{-1}CM^{-2}$

THE OBJECTIVE OF THIS EXPERIMENT WAS TO ARRIVE AT A CONSISTENT NUMBER IN THIS RANGE USING OUR SENSOR, THEN WORK BACKWARDS TO DETERMINE AN UNKNOWN CONCENTRATION

$$\frac{\underset{\text{NICOLET \# INTEGRATION VALUE } N_2O \text{ BAND}}{(1.003)} \quad \underset{\ell n}{(2.303)}}{\underset{\text{PARTS PER MILLION}}{(198.5)} \quad \underset{\text{PRESSURE CORRECTION LOGAN, UT}}{(.85)} \quad \underset{\text{PATH LENGTH OF CELL}}{(7.87)}} = 1740 \text{ BANDSTRENGTH } ATMOS^{-1}CM^{-2}$$

$$\frac{(\text{NIC \#}) \quad \overset{K}{(0.3443)}}{\underset{1740}{\text{BANDSTRENGTH}}} = \text{CONCENTRATION IN PPM}$$

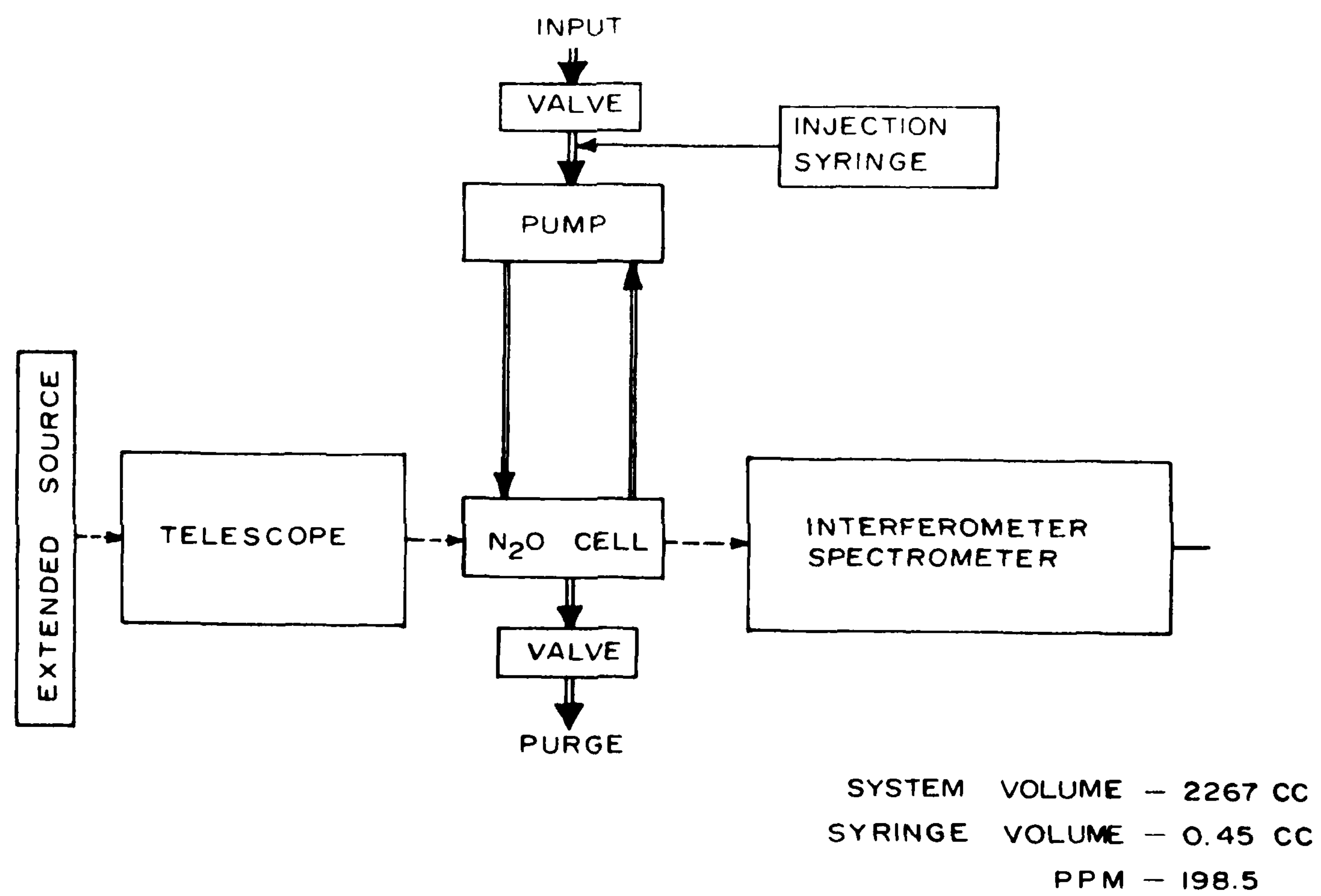


Figure B.1 METHOD OF VERIFYING CONCENTRATION

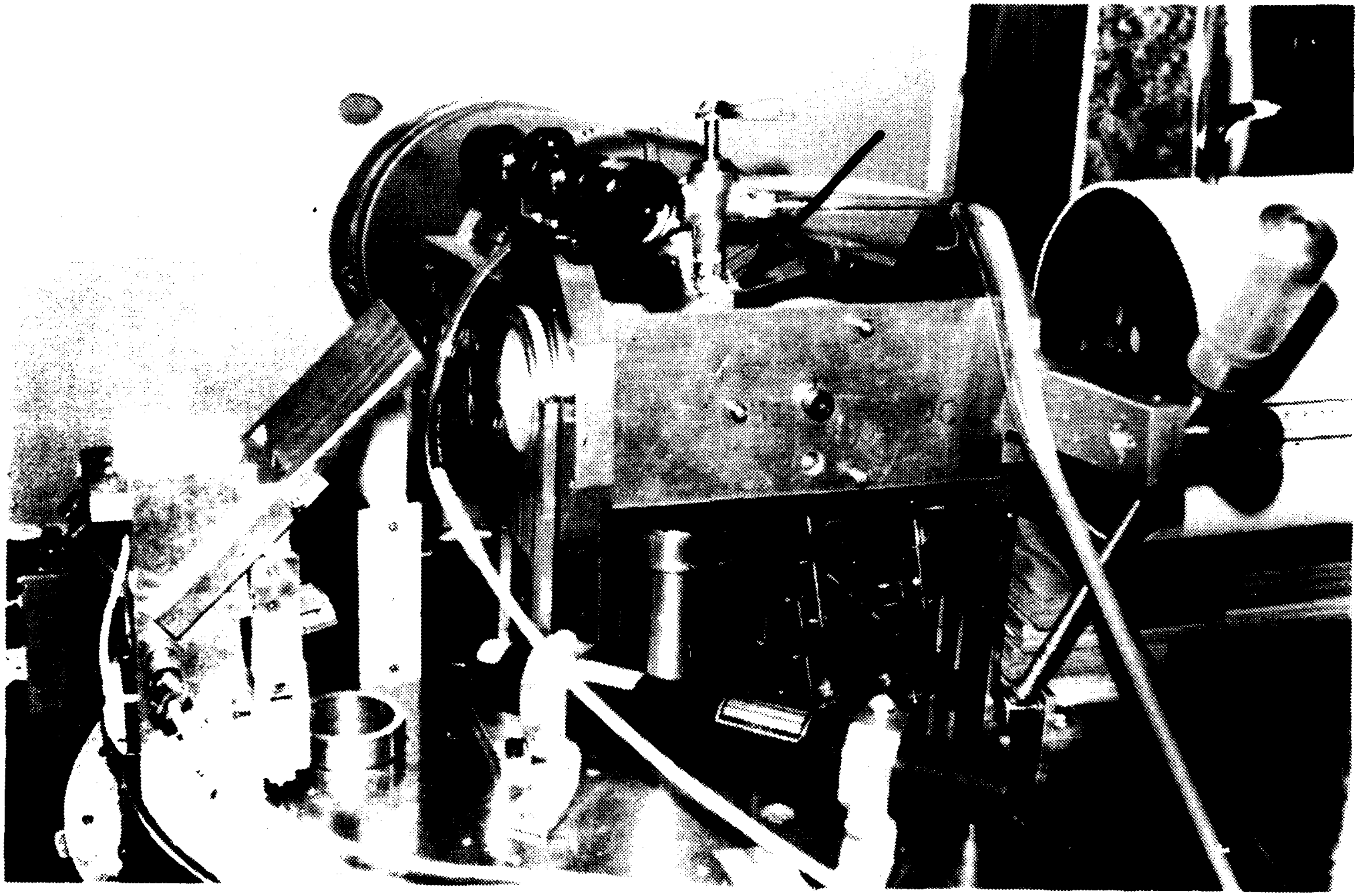


Figure B.2 N_2O Cell Inserted in Optical Path

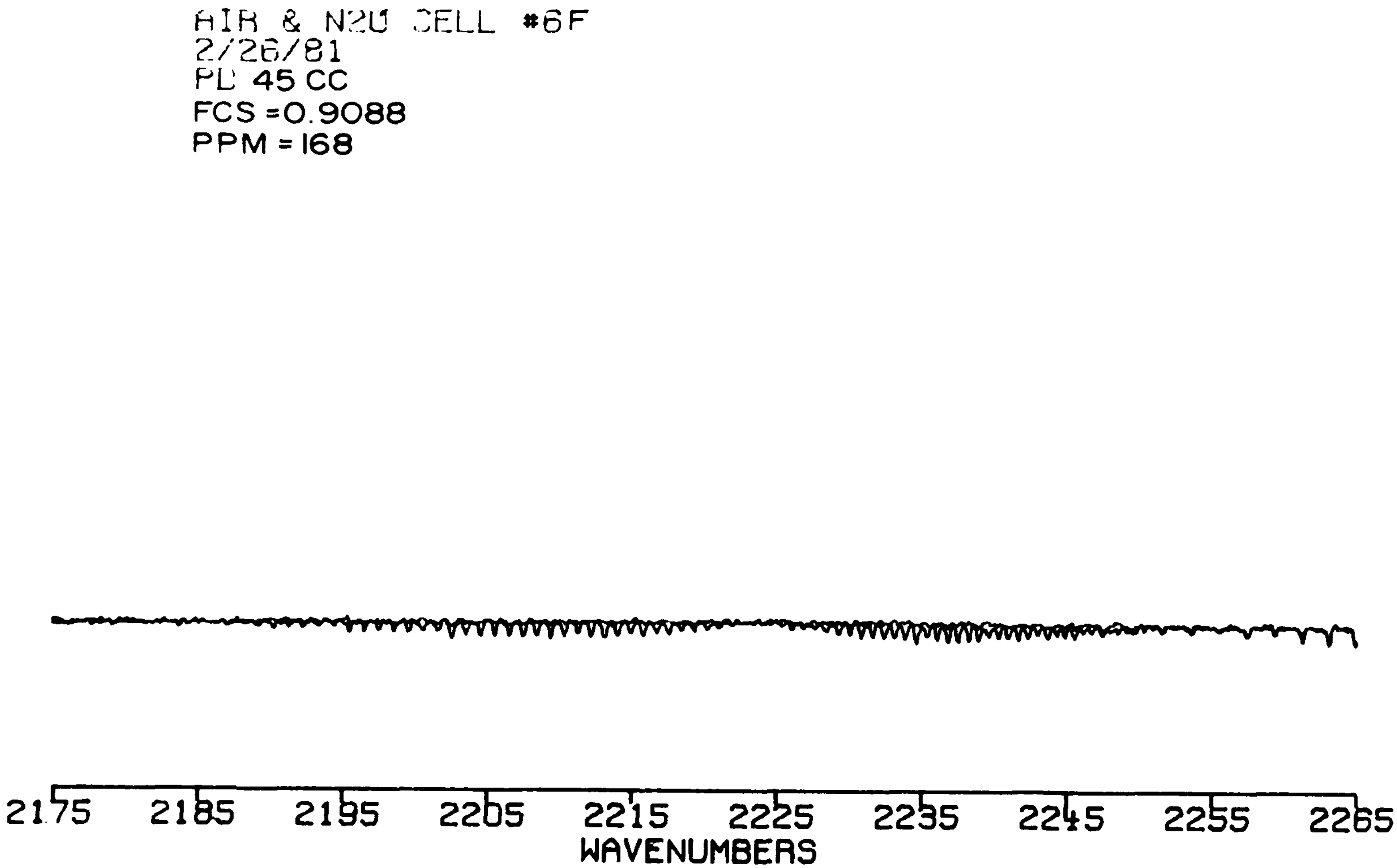


Figure B.3 168 PPM N_2O

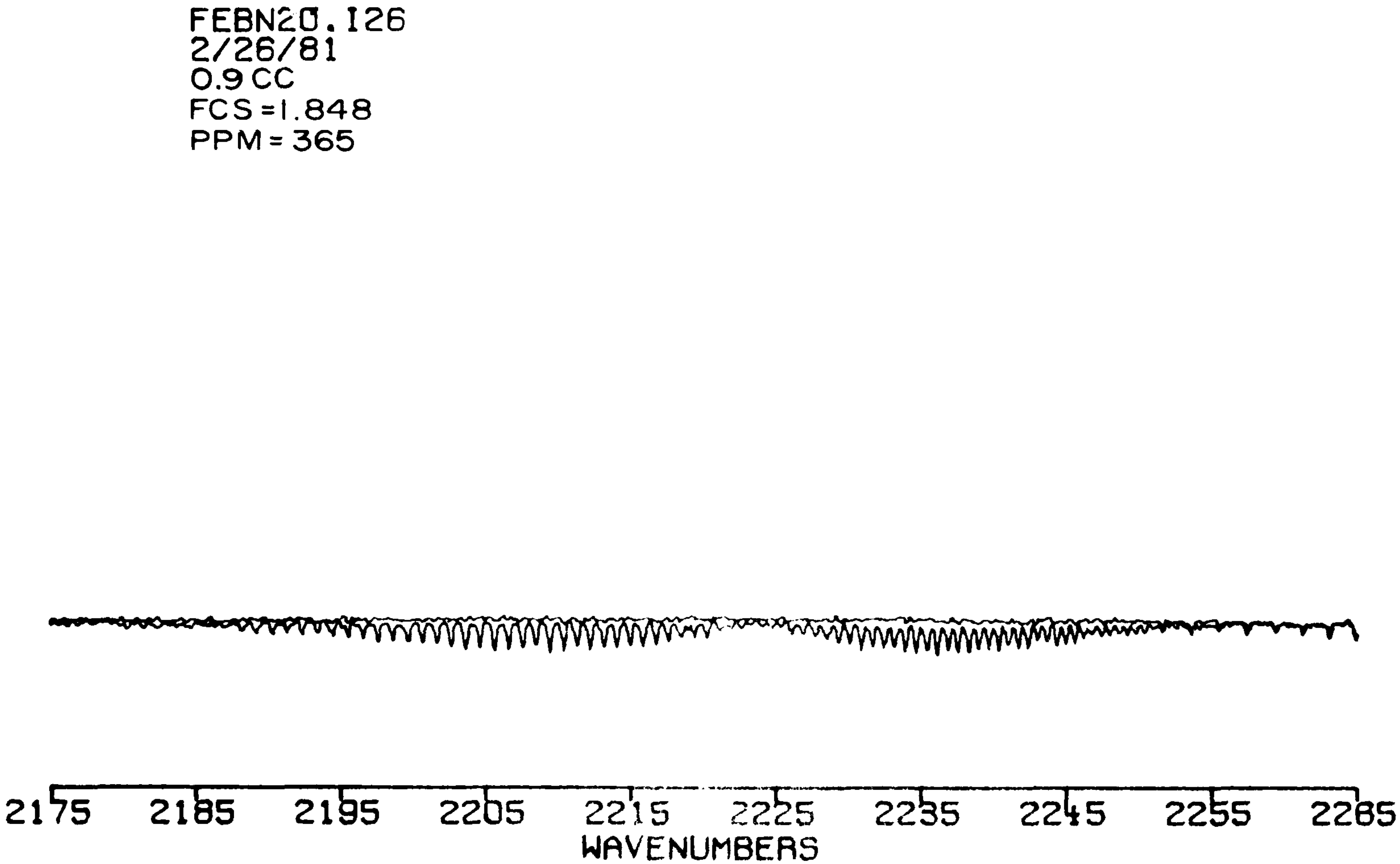


Figure B.4 365 PPM N_2O

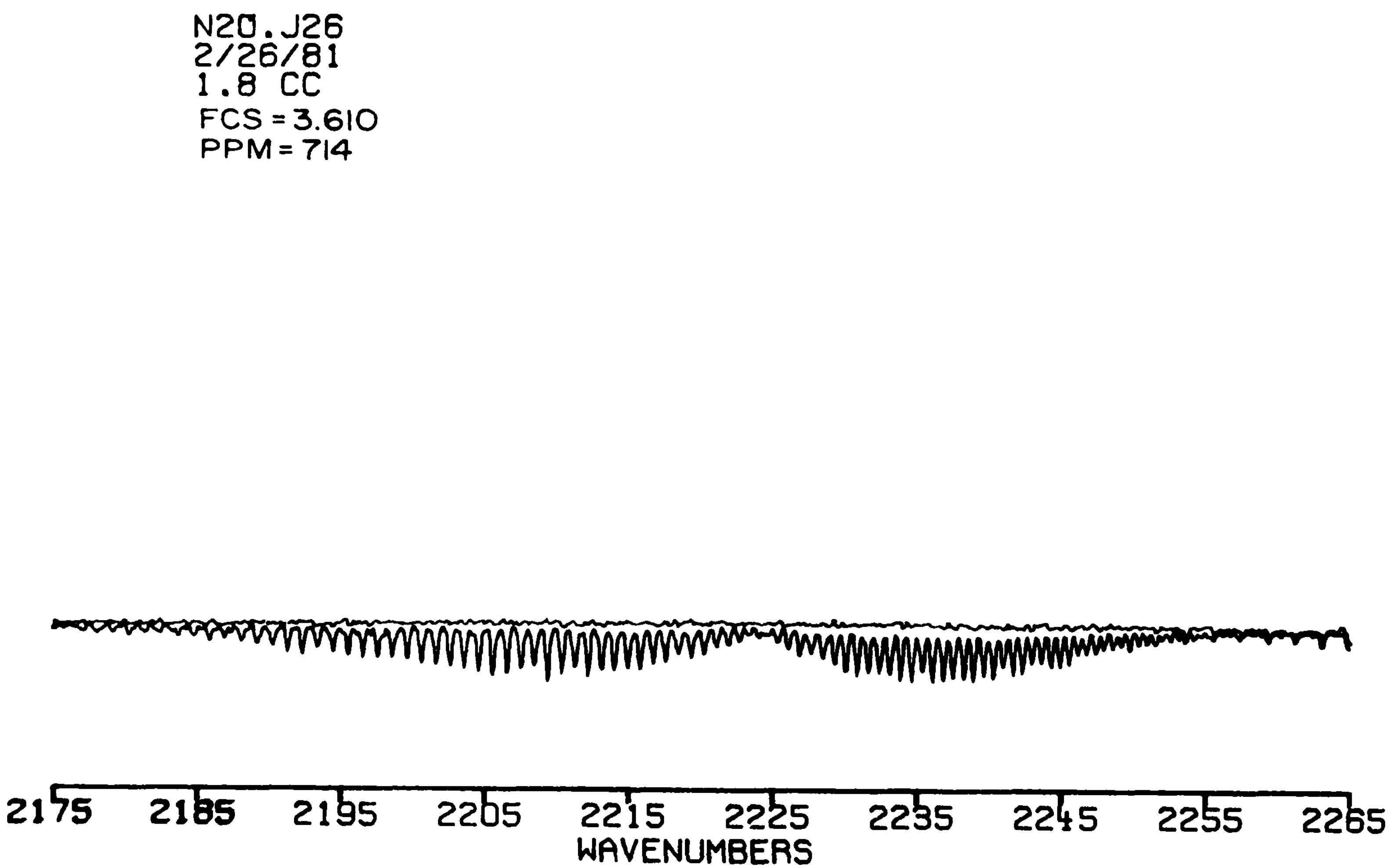


Figure B.5 714 PPM N_2O

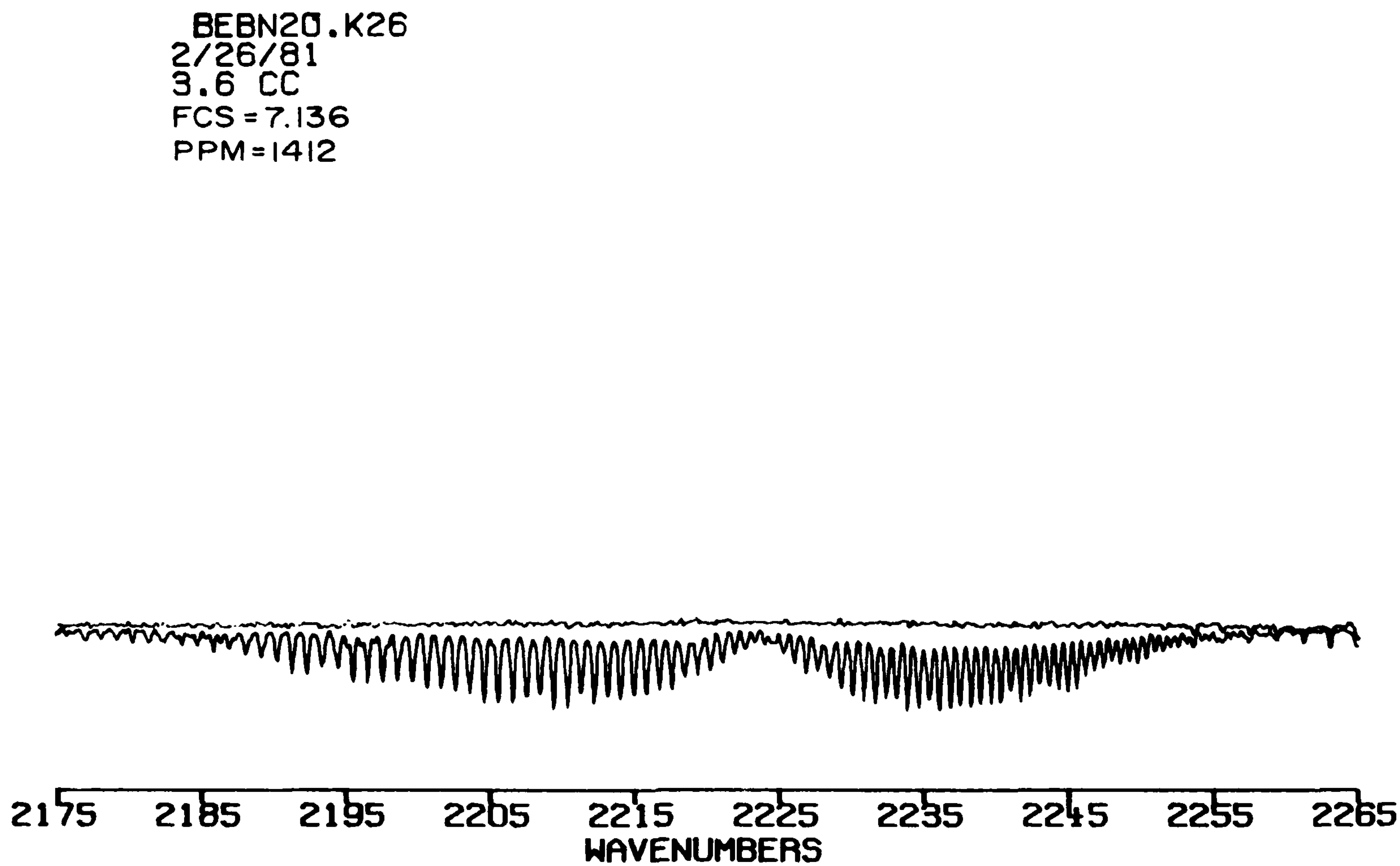


Figure B.6 1412 PPM N_2O

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