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Potential Spin-Offs of the Carbon Dioxide Observational Platform System (CO-OPS) for Remote Sensing Opportunities

J. Briscoe Stephens

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

National Aeronautics
and Space Administration

**Scientific and Technical
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POTENTIAL SPIN-OFFS
OF THE
CARBON DIOXIDE OBSERVATIONAL PLATFORM SYSTEM
(CO-OPS)
FOR
REMOTE SENSING OPPORTUNITIES

by

J. Briscoe Stephens
CO-OPS Study Scientist
Atmospheric Sciences Division
NASA/Marshall Space Flight Center
Huntsville, Alabama 35812

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I. INTRODUCTION

Remote sensing techniques that could utilize the slight losses of energy from the microwave beam which powers the NASA/MSFC Carbon Dioxide Observational Platform System (CO-OPS) to achieve the objectives of the U.S. Department of Energy (DOE) Carbon Dioxide Research Program's regional observational data requirements (ODRs) (Appendix A) will be heuristically addressed. The analytical justification for these techniques and applications will be left to the literature where it exists in voluminous detail.

The opportunity for regional remote sensing of the carbon dioxide and water vapor constituents in the atmosphere will be discussed as a potential spin-off of the CO-OPS. The CO-OPS is envisioned as a high altitude (~25 km) observational platform system powered by microwave energy for regional observational use by the DOE in their Carbon Dioxide Research Program. Figure 1 is a preliminary candidate concept for the CO-OPS as one might envision based on earlier NASA studies [1,2].

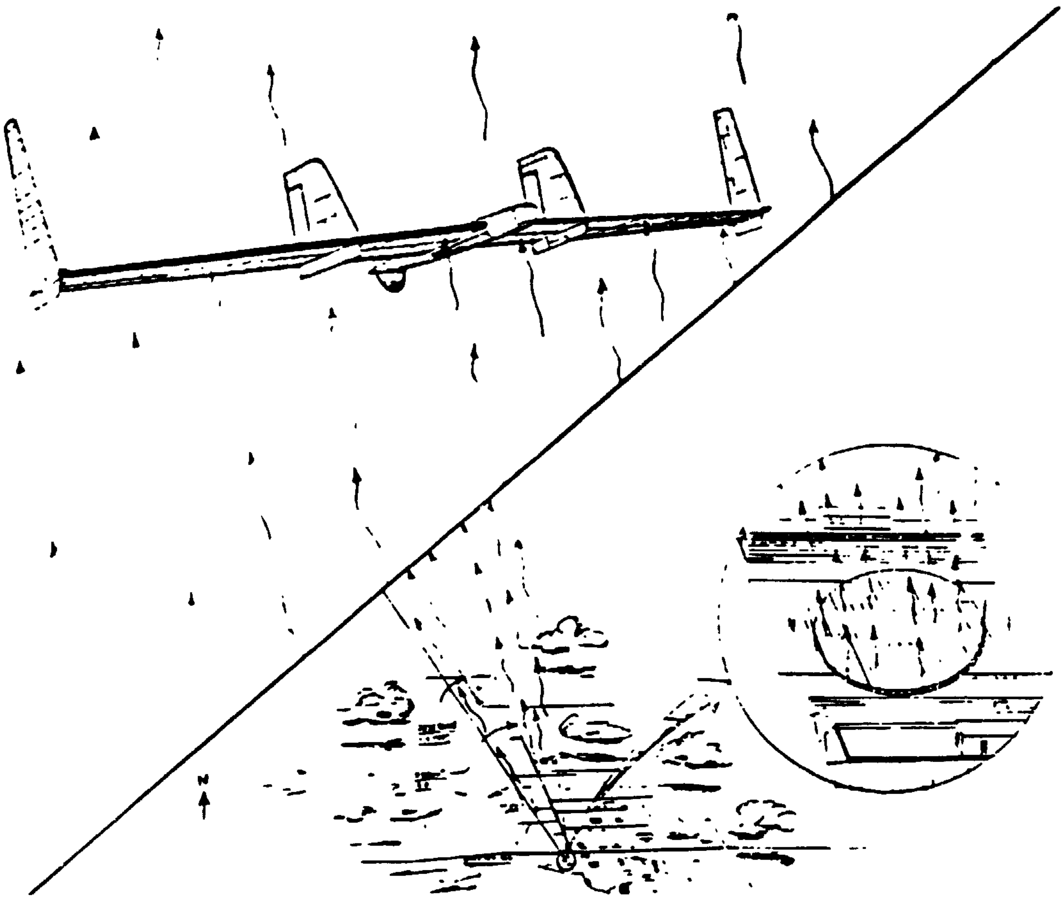

Figure 1. A preliminary candidate concept for the NASA/MSFC CO-OPS.

The slight losses in microwave energy in the microwave beam employed to power this candidate concept for the CO-OPS are manifested in the heating of the column of atmosphere between the ground-based microwave antenna and the observational platform. This heated atmospheric column can be envisioned as a fixed infrared searchlight (2000 watts or more in power). This provides a source which with remote sensing techniques affords an opportunity to retrieve information concerning the kinematic and thermodynamic parameters of atmospheric carbon dioxide and water vapor [3-7]. Since the microwave beam already exits as a function of the CO-OPS operations, remote sensing investigations employing this microwave beam can be conducted at a relatively low additional cost.

II. BACKGROUND

Prior to consideration of the opportunities for potential scientific data that could be obtained by employing remote sensing techniques in conjunction with the CO-OPS microwave beam losses, the NASA/MSFC CO-OPS purpose and concept will be summarized. Research and development activities appropriate to spectroscopic remote sensing of atmospheric kinematics and thermodynamics will also be summarized.

Currently, NASA's Marshall Space Flight Center is conducting a system study for the U.S. Department of Energy's Carbon Dioxide Research Program to determine the feasibility for the concept of a Carbon Dioxide Observational Platform System (CO-OPS) that can meet the observational data requirements of the DOE carbon dioxide research activities. A candidate concept for the design of NASA/MSFC CO-OPS is a microwave-powered platform that operates at an altitude of about 25 km above the surface and will maintain an appropriate quasi-fixed position relative to the ground (Figure 1). This platform will carry an observational data package of sensors to achieve the DOE observational data requirements for their carbon dioxide research activities (Appendix A). This candidate CO-OPS receives it power for operation from a ground based microwave antenna about 100 meters in diameter. This antenna will radiate about 250 kW of microwave energy at 2.45 GHz vertically upward in a truncate cone geometry to the CO-OPS vehicle. At the CO-OPS operations altitude (25 km) the cone of microwave energy will have a diameter of about 10 km. The microwave beam is expected to be attenuated by about 2 percent in clear weather and less than 10 to 15 percent during severe rain storms [2]. Since in clear weather almost all the atmospheric water vapor is contained in the troposphere, this implies that 5,000 watts of energy from the microwave beam or about 200 watts per kilometer of the beam will be available as a source for atmospheric investigations as a by-product of CO-OPS operations. During periods of high humidity and inclement weather, this source strength will be even greater. In the next section, it will be conceptually shown how these microwave beam losses due to basically atmospheric water content can potentially provide valuable information on the atmosphere for use in the DOE Carbon Dioxide Research Program.

The second facet in this paper is a summary of the atmospheric statistical optical spectroscopy remote sensing techniques *depending on clear air turbulence* that were developed at NASA/MSFC during the late sixties and early seventies [3-9]. Feasibility studies for the passive retrieval of localized atmospheric kinematic information were conducted at MSFC, Colorado State University, and NOAA Boulder, CO during the period between 1967 to 1973 [5,6]. The passive (natural radiation source) atmospheric remote sensing of atmospheric kinematics and thermodynamics was attempted with limited success. The primary difficulty encountered was the signal-to-noise ratio. As used here, the signal is localized information associated with the phenomenon of interest -- the remainder is noise. Since the desired signal relative to the atmospheric noise is small, the length of integration time required to suppress the noise is of relatively long duration (1 to 2 hours). Since the atmospheric turbulents are not statistically stationary for long periods of time, it is difficult to acquire the necessary length of data records for this technique. To overcome this difficulty, it is necessary to reduce the noise so that the integration time can be reduced. Two alternatives to this passive atmospheric remote sensing which reduce the noise are active (manmade radiation source) atmospheric remote sensing and spectroscopic remote sensing, both of which reduce the background noise.

Active atmospheric remote sensing of atmospheric kinematics and thermodynamics *depending on clear air turbulence* has been attempted with limited success. While the manmade source reduced the signal-to-noise ratio, the difficulty was the location of the source relative to the phenomenon of interest. These active remote sensing techniques do afford useful scientific information when the source can be effectively deployed.

Spectroscopy affords the potential to reduce background noise. The potential of optical spectroscopic remote sensing, coupled with correlation statistical techniques for the retrieval of localized kinematic and thermodynamic atmospheric information concerning specific atmospheric species such as water vapor and carbon dioxide, was studied at MSFC [3-6]. In support of this MSFC activity, laboratory experiments and analysis were performed by Drs. S. Bruersma, D. J. Lysobey, et al. at the University of Oklahoma in carbon dioxide correlation spectroscopy. These laboratory experiments clearly demonstrated that carbon dioxide concentrations and thermodynamics could be retrieved employing correlation spectroscopy [7-9].

In 1973, Dr. J. B. Stephens performed a primitive field test in the atmosphere to demonstrate the feasibility and applicability for the concept of correlation spectroscopy (Appendix B). The atmospheric temperature measured was in accord with standard meteorological practice. The results obtained from this field test for the short-term (10 minutes) concentrations of carbon dioxide contained significant variations in carbon dioxide concentrations coupled with supporting changes in observable phenomena (Figure 2). Specifically, the three peaks represent the peak traffic in the morning, noon, and evening on the highway (Rideout Road) at MSFC that was 342 meters west and parallel to the optical line-of-sight of the infrared radiometer. This preliminary field test indicated that correlation spectroscopy had potential for active remote sensing applications.

The losses in the microwave beam utilized in the CO-OPS -- which acts as a infrared searchlight in the atmosphere illuminating the region of investigation -- may be used as a source for active remote sensing. When coupled with carbon dioxide and water vapor spectroscopy, which also improves the signal-to-noise ratio, the microwave beam from this candidate CO-OPS should provide an opportunity for the application of remote sensing techniques to acquire information on the atmospheric behavior to satisfy the DOE observational data requirements (ODR) at a relatively low cost.

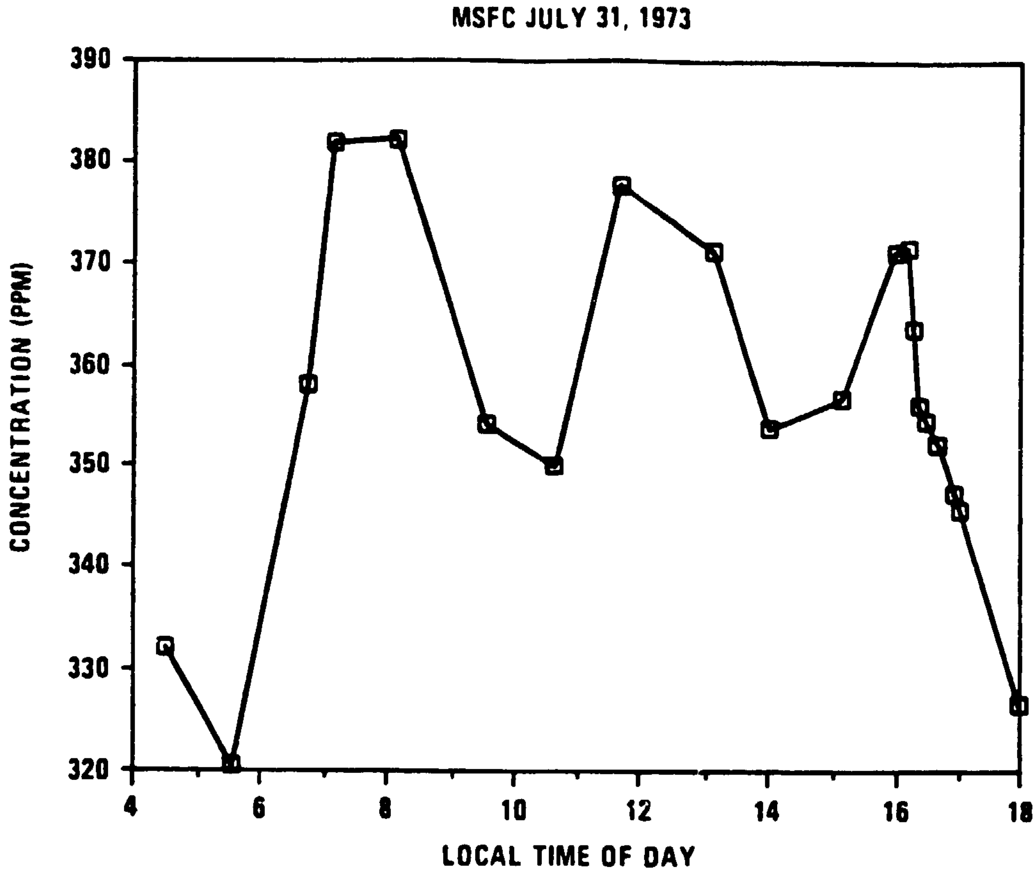

Figure 2. Temporal history of carbon dioxide concentrations.

III. APPLICATIONS CONCEPTS

A. Atmospheric Column Concentrations of Water Vapor

1. Background

The microwave beam affords a radiation source that may be employed with remote sensing techniques to meet some of the DOE observational data requirements (ODR) (Appendix A) for categories A, B, and C which are for atmospheric profiles, atmospheric species, and clouds, respectively.

The key feature to be utilized to retrieve atmospheric information is the attenuation of the microwave beam (2.45 GHz). Basically this attenuation is due to the absorption of the microwave energy by water vapor. This is physically manifested by an atmospheric warming in the microwave beam. This causes the water vapor to radiate infrared energy at the water vapor vibrational bands at 2.68, 2.72 and 6.30 microns since the water vapor is above the ambient atmospheric temperature. The 2.68 and 2.72 micron vibrational bands of water vapor transfer this radiative energy to the 2.70 micron vibrational band of carbon dioxide. This results in a rise in carbon dioxide temperature. Thus, the 2.7, 4.2 and 15.0 micron vibrational bands of carbon dioxide radiate energy as a result of the microwave beam.

Therefore, the microwave beam produces what could be referred to as noise, in some applications, (1) by slightly reducing the atmospheric density in this beam, and (2) by increasing the infrared radiation in the water vapor and carbon dioxide vibrational bands. If one employs some basic infrared spectroscopic techniques coupled with some basic statistical techniques, this noise could be utilized as an infrared signal that affords significant information concerning the atmospheric thermodynamics and kinematics. The remaining discussion will be directed toward examining concepts appropriate to the retrieval of this atmospheric information.

2. Concept for First Order Water Vapor Column Density Estimates

The atmospheric water vapor causes the microwave beam to be attenuated. Hence, when the amount of microwave attenuation is calibrated with the water vapor column density, operational estimates of this density, which is essentially in the troposphere, are potentially possible by measuring this attenuation. While this concept is not physically absolute, it does afford a simple approach to a first order estimate that supports one of the DOE Observational Objectives (Appendix A.)

B. Classical Carbon Dioxide and Water Vapor Spectroscopy

1. Background.

Water vapor concentrations in the atmosphere can be estimated based on the attenuation of the microwave beam utilized to power this candidate CO-OPS. This attenuation of the microwave beam amounts to about 5,000 to 38,000 watts of power being injected into the infrared spectrum as a searchlight beam passing through the troposphere. If the methods of classical spectroscopy are employed, additional remotely sensed atmospheric information may be available from this energy source. These concepts are applicable either from a ground based radiometer, without a loss in the CO-OPS sensor payload, or from a CO-OPS-based radiometer. Both approaches have interesting advantages.

Ground operations would eliminate the background black body radiation from the Earth and allow for the development of new spectroscopic techniques. An infrared radiometer on the airborne CO-OPS using infrared spectroscopic techniques could be employed for regional carbon dioxide and water vapor data retrieval. This would parallel the VAS [VISSAR (Visible, Infrared Spin Scan Radiometer) Atmospheric Sounder] system on meteorological satellites. A cross-correlation, in terms of carbon dioxide research activities, between the data sets could be made. This would enable a better utilization of the existing VAS satellite data as inputs to the global circulation models used by the DOE Carbon Dioxide Research Program.

Some of the radiation from the 2.68 and 2.72 vibrational bands of water vapor is absorpted by carbon dioxide; thus these water vapor vibrational bands are screened. Consequently, these vibrational bands do not afford a simple potential for spectroscopic water vapor data retrieval. Hence, the 4.2 and 15 micron vibrational bands of carbon dioxide and the 6.3 micron vibrational band of water vapor are normally employed for atmospheric infrared spectroscopic data retrieval involving these species. Since Hg Cd Te detectors, which are commonly used in this spectral window, perform best in the spectral region between 4 and 7 microns, this discussion is directed toward primarily the use of 4.2 and 6.3 micron bands of carbon dioxide and water vapor, respectively.

2. Tropospheric Kinematics Utilizing Carbon Dioxide Spectroscopy

Estimates of the atmospheric carbon dioxide kinematics above the microwave antenna are possible from either the ground or from on board the CO-OPS by employing single scanning infrared radiometers. This concept is rather straightforward. It could afford a relatively low-cost source of atmospheric information given that the microwave beam already exists to power the CO-OPS.

The sampling procedure is straightforward. One would scan, in the 4.2 or 15 micron vibrational bands of carbon dioxide, the circumference of the microwave beam -- looking for the sector of the beam where the microwave energy is being transported downsteam by the tropospheric wind. This is not necessarily the mean wind direction (height weighted average) for the troposphere; rather, this represents the mean transport direction (mass weighted average) for the carbon dioxide. Since the carbon dioxide is usually considered by the carbon dioxide scientific community to be uniformly distributed with altitude in the troposphere, this result should closely approximate the mean wind direction in the troposphere. Conceptually, the mean transport speed can also be estimated by the relative displacement of the half power point of this vibrational band.

While this approach may not be exact in all cases because of some of the simplifying assumptions that are necessary in the concept, it does afford a relatively easy method of continuously remotely monitoring atmosphere kinematic. When coupled with conventional sounding techniques like radiosondes, it can afford some information for the detailed small-scale kinematic data on atmosphere transport that is normally not available.

3. Tropospheric Kinematics Utilizing Water Vapor Spectroscopy

The sampling procedure is similar to that employed for carbon dioxide, except that one would scan in the 6.3 micron vibrational band of water vapor the circumference of the microwave beam -- looking for the sector of the beam where the microwave energy is being transported downsteam by the tropospheric wind. However, this is not normally the mean wind direction for the troposphere -- rather, this represents the mean mass transport direction for the water vapor, since the water vapor is usually not uniformly distributed in the troposphere. Conceptually, the transport speed could also be estimated by the relative displacement of the half-power point of this vibrational band.

This approach does afford a relatively easy method of continuously remotely monitoring the atmosphere water vapor kinematics since this candidate CO-OPS concept requires a microwave beam. When coupled with conventional sounding techniques like radiosondes, this technique can afford some information for the detailed small-scale kinematic data on atmosphere transport that is normally not available.

C. Carbon Dioxide and Water Vapor Perturbation Spectroscopy.

1. Background

Spectroscopic concepts designed to utilize the turbulent fluctuations in the atmosphere to retrieve thermodynamic data will be discussed. This spectroscopy will be defined as perturbation spectroscopy.

In the last section, concepts for the retrieval of atmospheric kinematics using the mean spectroscopic radiation of the vibrational bands of carbon dioxide and water vapor were presented. This section expands the discussion to the variance about these means and defines it as perturbation spectroscopy. Consideration of the vibrational bands is limited in this section to the 4.2 micron band of carbon dioxide and the 6.3 micron band of water vapor.

2. Tropospheric Thermodynamics Utilizing Carbon Dioxide Perturbation Spectroscopy

Retrieval of the atmospheric carbon dioxide related thermodynamics parameters -- concentration and temperature -- in the region above the microwave antenna are potentially possible from either the ground or from the CO-OPS by employing a single scanning infrared radiometer and ascertaining the variance of the temporal history of the data. This assertion is based on theoretical analyses, laboratory experiments, and feasibility field tests of carbon dioxide perturbation spectroscopy [4, 6-9].

Classical infrared spectroscopic techniques could be applied utilizing the 4.2 micron vibrational band of carbon dioxide to determine the thermodynamic properties of the carbon dioxide in the microwave beam if either the temperature or the concentration are purely (absolutely) known. Generally, neither of these parameters are purely known without making working assumptions -- in fact, they are both desired outputs to test these working assumptions, since investigators are often forced to assume their way around the problem.

The solution to this problem is perturbation spectroscopy, which provides the first derivative of the infrared carbon dioxide vibrational band spectrum. In practice the atmospheric turbulents cause a small fluctuation in the temporal history of the infrared radiation from a small bandwidth in the wing of the carbon dioxide vibrational band. The variance of this signal is the first derivative of the spectrum. This perturbation spectrum has a cross-over point where the carbon dioxide concentration is temperature independent; hence, one of the two unknowns is found and the temperature follows using classical spectroscopy.

Field testing of the feasibility of perturbation spectroscopic techniques for carbon dioxide thermodynamic tropospheric data retrieval could be performed as a precursor to future carbon dioxide remote sensing space activities.

3. Tropospheric Thermodynamics Utilizing Water Vapor Perturbation Spectroscopy

Estimates of the atmospheric water vapor thermodynamics region above the microwave antenna are also possible from either the ground or from the CO-OPS by employing single scanning infrared radiometers. While the estimates are theoretically feasible, they are currently only of research interest.

While the theory for water vapor perturbation spectroscopy has been developed, this theory in not supported with empirical data. Laboratory experiments with water vapor in a perturbation calibration cell were attempted at both MSFC and the University of

Oklahoma with questionable results. The problem encountered was with varying amounts of water vapor adhering to the walls of this cell, which made calibration virtually impossible to the degree of accuracy required for the validation of the theory. Therefore, water vapor perturbation spectroscopy calibration tests will probably need to be accomplished with well instrumented field tests.

Classical infrared spectroscopic techniques coupled with perturbation spectroscopy could be applied utilizing the 6.3 micron vibrational band of water vapor to estimate the thermodynamic properties of the water vapor in the microwave beam. Since the same radiometric system that is used for carbon dioxide perturbation spectroscopy is also appropriate for water vapor perturbation spectroscopy, the concept and calibration for the water vapor perturbation spectroscopy could be done in conjunction with the carbon dioxide perturbation spectroscopy field tests at very little additional cost.

D. Cross-Correlation Spectroscopy for Localized Atmospheric Kinematic and Thermodynamic Information

1. Background

The use of the CO-OPS microwave beam to obtain localized information will be addressed here. Up to this point, the information retrieval system has been a single radiometer looking along the microwave beam, that is, column information. This variance analysis used with perturbation spectroscopy is effectively the auto-correlation at a zero time delay. When this is transformed into the time domain, we obtain the temporal correlation of the signal with itself. When two radiometers with crossing fields of view provide time histories concerning the same phenomenon, Cross-correlation spectroscopy can afford localized information.

Thus, if a second radiometer is added to the CO-OPS remote sensing system, located about one kilometer from the radiometer at the microwave beam antenna (Figure 3), localized information can theoretically be obtained using cross-correlation statistical techniques [4]. The cross-correlation technique is a statistical technique that compares the temporal time series of the atmospheric turbulence fluctuations from two radiometers (Figure 4). The result is a cross-correlation curve plotted as a function of the delay times in the two time series (Figure 5). This cross-correlation curve affords a temporal comparison of the degree of relative correlation between the two signals. At zero delay, the degree of correlation represents the amount of information common to the fields of view for the two radiometers. The cross-correlation curve can be Fourier transformed to the frequency domain from which one obtains the power spectra.

When the radiometers are viewing specific wavelengths, one obtains cross-correlation spectroscopy as was discussed in the last section. That is, by restricting the spectral bandpass to a wavelength unique to a specific constituent in the atmosphere, the information retrieved is unique to that constituent; hence, the kinematic and thermodynamic properties of carbon dioxide and water vapor in a specific region can be detected under certain conditions which will be considered next.

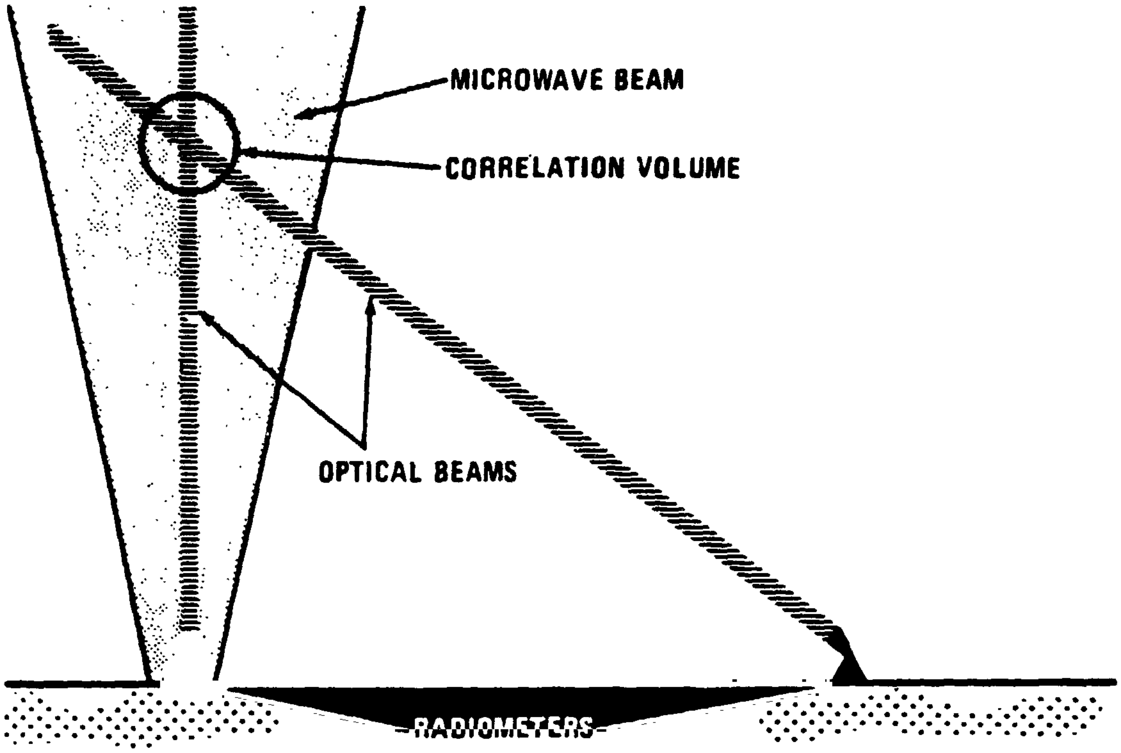

Figure 3. Cross-beam correlation system.

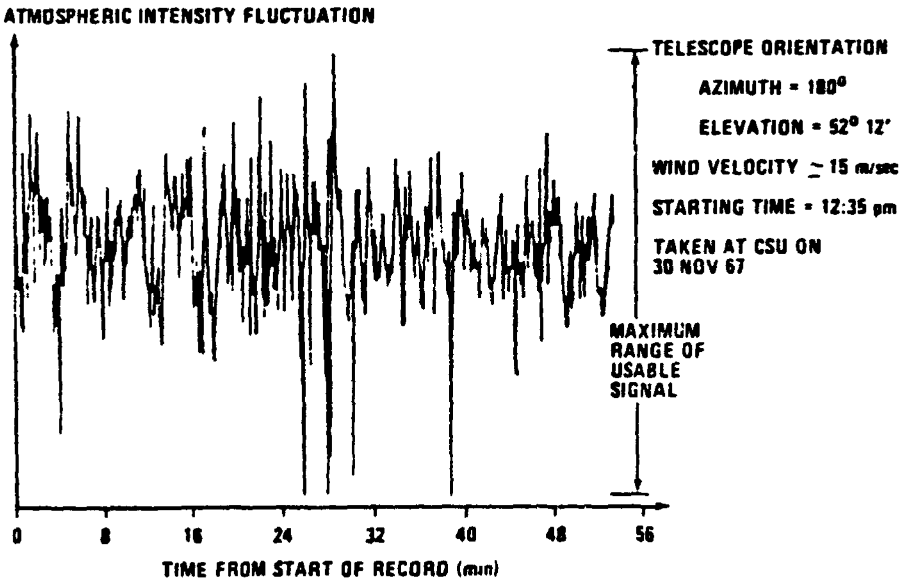

Figure 4. Temporal fluctuations from two radiometers.

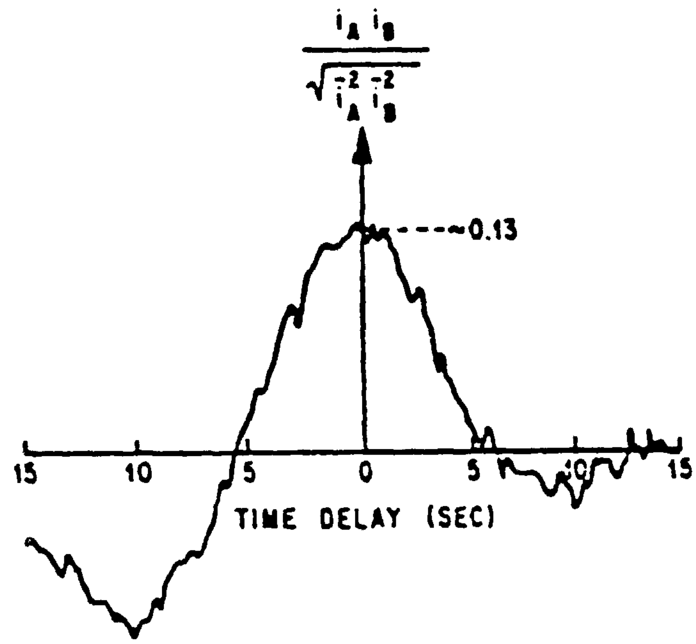

Figure 5. Cross-correlation curve.

2. Cross-Correlation Spectroscopy for Carbon Dioxide

Conceptually the cross-correlation spectroscopy utilizing the 4.2 micron carbon dioxide band as a signal source can both afford results to carbon dioxide modeling questions and afford data for analyses of the long-term carbon dioxide greenhouse effects. This can be achieved through the retrieval of atmospheric profiles for the carbon dioxide concentrations and temperatures.

These results can be achieved in two ways: (1) the simple way, for research operations and concept verification, is to scan up and down along the beam of the radiometer at the base of the microwave antenna with the off-antenna radiometer, or (2) the off-antenna radiometer can also be a fan of beams for operational data collection. This discussion will focus on option 1, because it affords an overview of the basic principles of concern.

A key issue that can be resolved with carbon dioxide cross-correlation spectroscopy is exactly how uniformly mixed is carbon dioxide in the atmosphere. If carbon dioxide is uniformly mixed, as it is commonly assumed and modeled, the peak in the cross-correlation curve will occur at zero time delay and the carbon dioxide temperature profile will fall out directly. However, if the carbon dioxide is not uniformly mixed, then nonzero time delay peaks in the cross-correlation curve will occur. This would mean that clouds of carbon dioxide are being transported around the atmosphere. The data in the field test, Appendix B, suggest that this is the case, at least in the surface mixing layer. If these upper layers are also nonhomogeneous, then the atmospheric carbon dioxide concentration and temperature profiles could only be retrieved at the selected layers where the higher densities of carbon dioxide exist. Because the 4.2 micron carbon dioxide band in the microwave beam is the radiation source, the altitude region of uncertainty is limited by the volume of the optical beam from the off-antenna radiometer in the microwave beam (Figure 3). The exact altitude can then be ascertained by slightly changing the off-antenna radiometer's beam elevation to obtain the maximum cross-correlation at the zero time delay. Thus because the system is quasi active, we are able to restrict the correlation volume to a relatively small volume in the atmosphere and consequently retrieve a quasi-discrete profile (no greater than the length of the off-antenna radiometer beam in the microwave beam) for the carbon dioxide concentrations and temperatures in the atmosphere directly above the CO-OPS microwave antenna.

It is desirable to simultaneously collect data at more than one altitude for temporal simultaneity profiles. This temporal simultaneity can be achieved using the second option, an off-antenna fan radiometer with multiple optical beams.

3. Cross-Correlation Spectroscopy for Water Vapor

Conceptually, the cross-correlation spectroscopy for water vapor utilizing the 6.3 micron water vapor band in the NASA/MSFC CO-OPS microwave beam as a signal source can, like in the case of carbon dioxide, both afford results applicable to water vapor modeling questions and afford data for analyses of the long-term carbon dioxide greenhouse effects. This can be achieved through the retrieval of atmospheric profiles for the water vapor concentrations and temperatures. This technique is basically the same, except that the water vapor infrared band is utilized.

The water vapor cross-correlation spectroscopy cloud provides a valuable data base on cirrus clouds. The energy absorbed from the microwave beam by the cirrus cloud should provide a clean signature for microwave radiation albedo analyses. The relative concentrations and temperatures of these clouds should be retrievable. The theory for water vapor perturbation spectroscopy is identical to the theory for carbon dioxide perturbation spectroscopy.

IV. CONCLUSION.

The remote sensing of the carbon dioxide and water vapor constituents in the atmosphere has been conceptualized as a potential spin-off of the microwave powered candidate concept for the Carbon Dioxide Observational Platform System (CO-OPS). The slight overall losses in microwave energy from the beam utilized by the CO-OPS are a strong (5,000 kW) infrared searchlight that can be employed as a source with remote sensing techniques for information concerning the kinematic and thermodynamic parameters of atmospheric carbon dioxide and water vapor. Some qualitative and quantitative approaches have been proposed to stimulate thinking about the potential for effective utilization of this powerful infrared searchlight associated with the microwave beam of the CO-OPS.

It appears that a wide variety of options exist for investigations that can effective utilize this infrared source to achieve objectives set forth in the DOE observational data requirements (ODR) (Appendix A). Specifically, this microwave beam can be a source to achieve the DOE ODRs for Category A, atmospheric profiles; Category B, atmospheric species; and Category C, clouds.

The microwave beam affords an active source for remote sensing techniques using instrumentation that are either ground- based or flown on the CO-OPS. Hence, some data to satisfy the DOE ODRs can be obtained without affecting the payload capacity of the CO-OPS.

The range of candidate investigations also varies from simple, low-cost experiments, like measurements of the attenuation of the microwave beam as an indicator of the column density of the atmospheric water vapor, to rather complex experiments involving cross-correlation spectroscopy to retrieve the kinematic and thermodynamic properties of the atmosphere.

A number of applicable remote sensing techniques have been discussed. They have only been proposed as candidate remote sensing techniques -- not to preclude any of the many other potential candidate remote sensing techniques or configurations.

Thus it appears that CO-OPS microwave beam has potential as an infrared source to provide remote sensing information to meet the DOE ODRs set forth for the CO-OPS missions. It further appears that these are relatively low-cost experiments that can be done as a direct spin-off of the mainline CO-OPS activities.

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Appendix A

CO-OPS OBSERVATIONAL DATA REQUIREMENTS

1. Background

The preliminary guidelines for the DOE CO-OPS observational data measurement requirements will be summarized in terms of: (1) the candidate categories of CO-OPS observational data requirements, and (2) a list of candidate geographical CO-OPS operation sites. The basis for these requirements is taken from the NASA/MSFC system study of the utilization of space for carbon dioxide research conducted in support of the DOE Carbon Dioxide Research Program. It was prepared under contact and documented in the following final report:

Glaser, P. E.; and R. Vranka: **System Study of the Utilization of Space for Carbon Dioxide Research.** Prepared for NASA/Marshall Space Flight Center by Arthur D. Little, Inc. in association with Ball Aerospace Systems Division and Boeing Aerospace Company, Contract NAS8-35357, April 1984.

This referenced study report addresses the global observational data objectives and requirements of the DOE Carbon Dioxide Research Program. The NASA/MSFC CO-OPS Prephase A System Study will address the regional observational data objectives and requirements of the DOE Carbon Dioxide Research Program. The global observational data requirements were defined in terms of the *modeling data base* for global circulation models utilized in the DOE Carbon Dioxide Research Program. Based on DOE requirements, the "modeling data base" refined by DOE to reflect the CO-OPS preliminary "observational data requirements." DOE also provided a list of candidate geographical CO-OPS operation sites with the observational data requirements for each site.

Table I, summarizes the space-observable data requirements that the above referenced contract study identified.

Table I: Scientific Data Requirements Identified by ADL Study.

SDR NO.	SPACE DATA REQUIREMENTS	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY
1.	AEROSOL CONCENTRATION.	1000	30	10%
2.	ATMOSPHERIC CONCENTRATIONS, CARBON DIOXIDE.	500	3	1 ppm
3.	ATMOSPHERIC CONCENTRATIONS. TRACE GASES.	1000	30	0.5 ppm
4.	BIOSPHERE, VEGETATION INDEX.	200	30	-
5.	CLOUDS, CIRRUS.	200	1	-
6.	CLOUDS, FRACTIONAL COVERAGE.	200	0.5 HOUR	5%
7.	CLOUDS, VERTICAL STRUCTURE.	200	0.5 HOUR	0.5
8.	LAND ICE.	—	365	1 mel
9.	PRECIPITATION.	200	1	10%
10.	RADIANCE AT THE TOP OF THE ATMOSPHERE	1000	1	0.1–5%
11.	SEA CURRENTS.	200	30	2–5 cm
12.	SEA ICE.	200	5	1%
13.	SEA LEVEL.	200	30	10 cm
14.	SEA SURFACE TEMPERATURE.	200	5	0.2° C
15.	SEA SURFACE WINDS.	100	30	2 m/sec
16.	SNOW COVER.	200	5	5%
17.	SURFACE ALBEDO.	200	30	2%
18.	SURFACE ATMOSPHERIC PRESSURE.	500	30	1.5 mb
19.	SURFACE MOISTURE, SOIL.	500	30	10%
20.	SURFACE TEMPERATURE, SOIL.	500	30	1° C
21.	VERTICAL TEMPERATURE PROFILE.	500	5	1–2° C
22.	VERTICAL WATER VAPOR PROFILE.	200	2	10%
23.	WIND FIELD.	500	0.5	0.3 m/sec

2. Candidate Categories of CO-OPS Observational Data Requirements

As stated previously, the objective of the NASA/MSFC CO-OPS system study is the conceptual design of a high altitude observational platform system that can meet the guidelines for the data measurement requirements for the DOE Carbon Dioxide Research Program. To achieve this objective, it is necessary to determine as many of the DOE requirements as possible for: (1) the categories of CO-OPS observational data requirements in terms of the scientific data requirements, and (2) a list of geographical CO-OPS operation sites with the appropriate categories of CO-OPS observational data requirements. These categories are given in Tables II through VII.

TABLE II: CATEGORY A - Atmospheric profiles

SDR NO.	OBSERVATIONAL DATA REQUIREMENTS	MODELING DATA BASE: GRID SIZE (km)	MODELING DATA BASE: TEMPORAL SAMPLING (DAYS)	MODELING DATA BASE: ACCURACY	OBSERVATIONAL DATA BASE: GRID SIZE (km)	OBSERVATIONAL DATA BASE: TEMPORAL SAMPLING (DAYS)	OBSERVATIONAL DATA BASE: ACCURACY
21.	VERTICAL TEMPERATURE PROFILE.	500	5	1–2° C	~ 150	4 HRS	~ 0.2° C
22.	VERTICAL WATER VAPOR PROFILE.	500	5	10%	~ 150	4 HRS	5 – 10%
23.	WIND FIELD	500	0.5	0.3 m/sec	~ 150	4 HRS	0.1 m/sec

TABLE III: CATEGORY B - Atmospheric species

OBSERVATIONAL DATA REQUIREMENTS (ODR) SDR NO.	MODELING DATA BASE			OBSERVATIONAL DATA BASE		
	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY
1. AEROSOL CONCENTRATION.	500	30	10%	~150	6 HRS	5%
2. ATMOSPHERIC CONCENTRATIONS, CARBON DIOXIDE.	500	3	1 ppm*	10–100	LOCAL NOON & MIDNIGHT	0.3 ppm
3. ATMOSPHERIC CONCENTRATIONS. TRACE GASES.	500	30	0.5 ppb	10–100	LOCAL NOON & MIDNIGHT	0.3 ppb
ODR ON PLATFORM MEASUREMENTS: A. TEMPERATURE, PRESSURE, & WIND VELOCITY GAS & AEROSOL SAMPLING				LOCAL	HOURLY	STATE-OF-THE-ART
B. PARTICLE CONCENTRATIONS.				LOCAL	HOURLY	STATE-OF-THE-ART

TABLE IV: CATEGORY C - Clouds

SDR NO.	OBSERVATIONAL DATA REQUIREMENTS	MODELING DATA BASE			OBSERVATIONAL DATA BASE		
		GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY
5.	CLOUDS, CIRRUS. COMMENTS: CLOUD TOP & BUTTOM TEMPERATURES AND ALTITUDES ARE DESIRED.	200	1 HR	—	1.0	MIN	0.5° C
6.	CLOUDS, FRACTIONAL COVERAGE.	200	0.5 HOUR	5%	200	20 MIN	5%
7.	CLOUDS, VERTICAL STRUCTURE. COMMENTS: MEASUREMENTS SHOULD INCLUDE: A. ICE CONTENT; B. WATER CONTENT. C. PRECIPITATION D. RATE PRECIPITATION (mm/hour) E. ALTITUDE OF TOP & BOTTOM OF CLOUDS F. TEMPERATURE STRUCTURE OF CLOUDS.	200	1.0 HOUR	5%	0.5	10 MIN	TBD
10.	RADIANCE AT TOP OF THE ATMOSPHERE.	500	1	0.1–5%	TBD	TBD	TBD

TABLE V: CATEGORY D - Sea/ocean

SOR NO.	OBSERVATIONAL DATA REQUIREMENTS	MODELING DATA BASE			OBSERVATIONAL DATA BASE		
		GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY
11.	SEA CURRENTS.	200	30	2–5 cm	10	0.[illegible]	TBD
12.	SEA ICE.	200	5	1%	10	0.5	TBD
13.	SEA LEVEL.	200	30	1 cm	10	0.5	TBD
14.	SEA SURFACE TEMPERATURE.	200	5	0.2° C	10	0.5	TBD
15.	SEA SURFACE WINDS.	100	30	2 m/sec	10	0.5	TBD

TABLE VI: CATEGORY E - Snow/ice

SOE NO.	OBSERVATIONAL DATA REQUIREMENTS	MODELING DATA BASE			OBSERVATIONAL DATA BASE		
		GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY
9.	PRECIPITATION. COMMENTS: WHICH CLOUDS, AT WHAT RATE AND TOTAL AMOUNT.	200	1	10%	10	0.25	5%
17.	SURFACE ALBEDO.	200	30	2%	100	1	1%
18.	SURFACE ATMOSPHERIC PRESSURE.	500	30	1.5 mb	500	1	1 mb
19.	SURFACE MOISTURE, SOIL.	500	30	10%	100	7	5%
20.	SURFACE TEMPERATURE, SOIL.	500	30	1° C	100	7	0.5° C

TABLE VII: CATEGORY F - Surface conditions

SOR NO. OBSERVATIONAL DATA REQUIREMENTS	MODELING DATA BASE			OBSERVATIONAL DATA BASE		
	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY	GRID SIZE (km)	TEMPORAL SAMPLING (DAYS)	ACCURACY
8. LAND ICE.	—	365	1 m elev	100	7	TBD
16. SNOW COVER.	200	5	5%	100	1	TBD

3. Candidate Geographical CO-OPS Operation Sites

The preliminary guidelines for the DOE CO-OPS observational data measurement sites will be summarized. It must be emphasized that CO-OPS should be designed to be a quasi mobile system that can be moved to new sites as the DOE Carbon Dioxide Research Program requires.

TABLE VIII: CO-OPS OPERATIONAL SITE No. 1: NASA/MSFC

The initial CO-OPS operational site will be at NASA/MSFC.

OBSERVATIONAL REQUIREMENTS		
Observational Categories	Altitude (km)	Observation Time
A, B, C, & F	20	TO BE DETERMINED
Comments: NONE		

TABLE IX: CO-OPS OPERATIONAL SITE No. 2: VAFB/EAFB

The next site of operation probably will be Vandenberg/Edwards Air Force Base.

OBSERVATIONAL REQUIREMENTS		
Observational Categories	Altitude (km)	Observation Time
A, B, C, D, & F	20	TO BE DETERMINED
Comments: NONE		

TABLE X: CO-OPS OPERATIONAL SITE No. 3: East Coast

East coast site in the New Jersey area.

OBSERVATIONAL REQUIREMENTS		
Observational Categories	Altitude (km)	Observation Time
A, B, C, D, & F	20	TO BE DETERMINED
Comments: NONE		

TABLE XI: CO-OPS OPERATIONAL SITE No. 4: Other Sites

Other potential site for long-term CO-OPS include, but not limited to, the West Antartic, the Intertropical Zone (e.g. Panama) and an east coast site at about 60^{0} North latitude.

OBSERVATIONAL REQUIREMENTS		
Observational Categories	Altitude (km)	Observation Time
A, B, C, D, E, & F	20	TO BE DETERMINED
Comments: NONE		

TABLE XII: CO-OPS OPERATIONAL SITE No. 5: Target of Opportunities

Other operation sites will include targets of opportunities such a areas associated with volcanic activity.

OBSERVATIONAL REQUIREMENTS		
Observational Categories	Altitude (km)	Observation Time
A, B, C, & F	6 to 40	Hourly

Comments:

a. Emphasis should be placed on ODR A in Category B.

b. Explore the feasibility of the use of drop and up sondes.

Appendix B
CARBON DIOXIDE PERTURBATION SPECTROSCOPY MEASUREMENTS

1. Background

A scientific experiment was conducted in the atmosphere to ascertain the feasibility of the concept of carbon dioxide perturbation spectroscopy as an atmospheric remote sensing technique and to define the requirements for future engineering field tests of the concept. More specifically, the objective of this experiment was to determine whether perturbation spectroscopy could be utilized to detect manmade and natural variations of carbon dioxide in the atmosphere.

Based on a theoretical analysis[4], laboratory tests were conducted at the University of Oklahoma to demonstrate and to provide calibration data for the concept of carbon dioxide perturbation spectroscopy[7-9]. These systematic tests were conducted in a highly idealized simulated turbulent environment in the laboratory and verified the theory of perturbation spectroscopy in the case of carbon dioxide. The scientific experiment to be discussed was designed to determine whether these idealized laboratory results could be applied to the hostile environment of the atmosphere for the remote sensing of kinematic and thermodynamic carbon dioxide parameters.

This appendix will afford a general description of the NASA/MSFC Atmospheric Infrared Sensing System and the carbon dioxide perturbation spectroscopy experiment in support of the results presented in Section III.C.

2. NASA/MSFC Atmospheric Infrared Sensing System

The NASA/MSFC Atmospheric Infrared Sensing System was employed in the carbon dioxide perturbation spectroscopy field experiment that will be discussed in the next part of this appendix. This infrared sensing system was composed of three subsystems: (1) the infrared radiometer, (2) the remote monitoring console, and (3) the information processing and analysis center (Figure 6).

The optics in the infrared radiometer was a 25 cm diameter Cassegrainian telescope. The incoming infrared radiation was filtered with a variable filter wheel whose spectral range was from 3.5 m to 6.8 m with a bandpass of 0.10 m. The Hg Cd Te detector that was cryogenically cooled with nitrogen Joules cooling.

The signal from the Hg Cd Te detection was amplified and filtered in the remote monitoring console near the radiometer (within 2 meters). The low pass filter filtered out frequencies below 0.01 Hz and the high pass filter filtered out frequencies above 10.0 Hz. The remote monitoring console also contained an oscilloscope to monitor the signal prior to transmission to the information processing and analysis center.

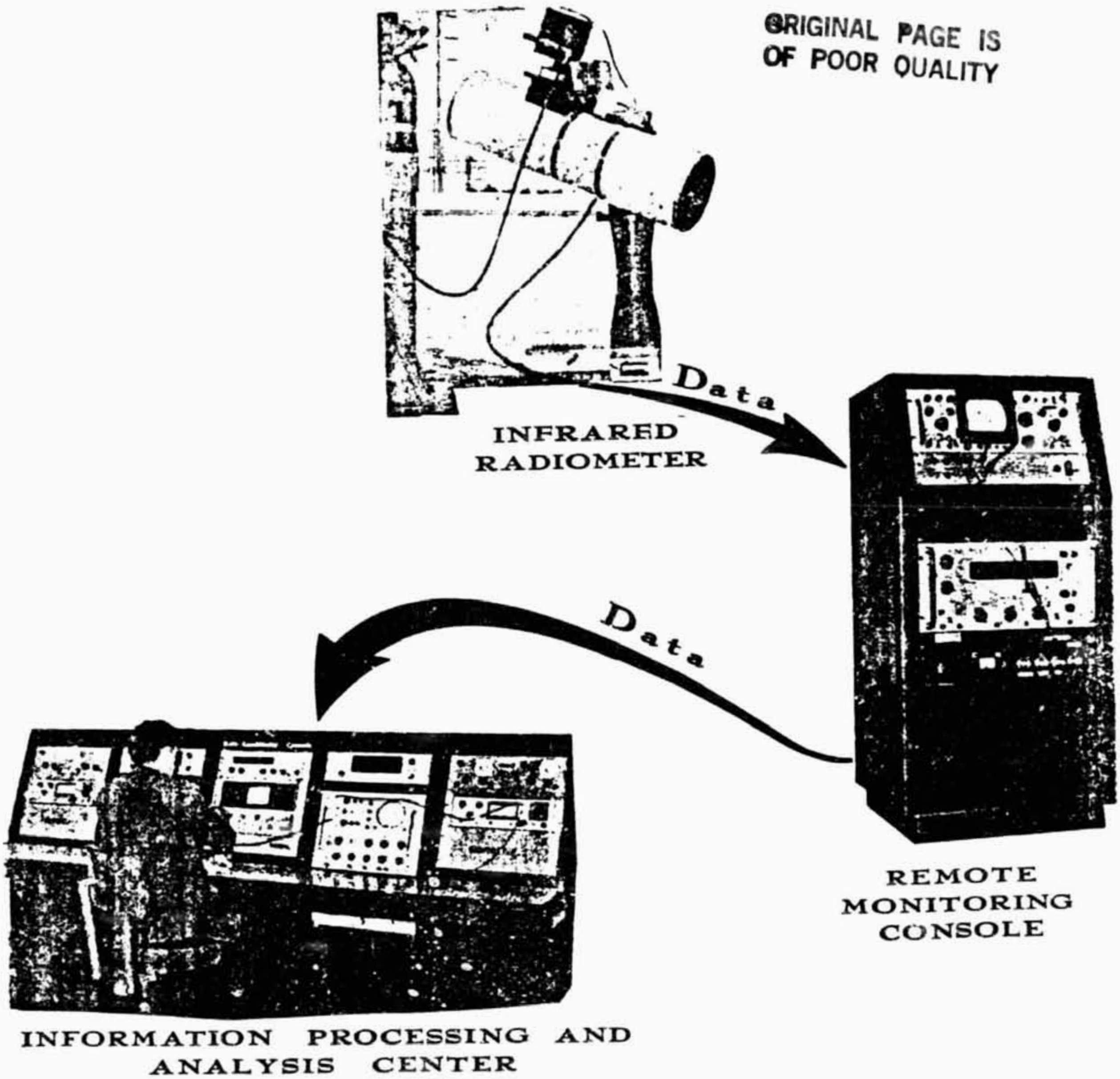

Figure 6. NASA/MSFC atmospheric infrared sensing facility

The information processing and analysis center contained an analog correlator, digital voltmeters, FM tape recorder, and standard electronic test equipment. The incoming signal from the remote monitoring console was split at the information processing and analysis center. One part of the signal was recorded on the FM tape recorder, while the other part was auto-correlated with the analog correlator. The results were read on the digital voltmeters.

3. Description of the NASA/MSFC Carbon Dioxide Perturbation Spectroscopy Experiment

A description of the carbon dioxide perturbation spectroscopy experiment that was conducted in the atmosphere at NASA/Marshall Space Flight Center will be provided. The objective was to ascertain the feasibility of the concept of carbon dioxide perturbation spectroscopy as an atmospheric remote sensing technique and to define the requirements for future engineering field tests of the concept.

The infrared radiometer was placed on the rear deck of building 4311 and boar sighted in a northern direction over a grassy field on building 4200, 1.22 km away. The optical beam was maintained approximately parallel to the ground and 12.43 meters above the surface. Rideout Road, a main traffic artery, was 231 meters west and running parallel to the radiometer's line-of-sight. During the course of the experiment, the wind was approximately from the west. That is, the carbon dioxide emitted by the traffic along Rideout Road was transported by the wind directly into the line-of-sight of the infrared radiometer. It was the objective of the experiment to determine if an increase in the carbon dioxide concentrations could be detected during peak traffic periods.

The infrared filter was set to 4.0 micron before and after each test to establish the radiation level. To obtain the carbon dioxide concentrations, the infrared filter was set to 4.21 . The data records were auto-correlated over 10-minute intervals.

The resulting carbon dioxide concentrations measured employing perturbation spectroscopy (Figure 2) showed three peaks in the carbon dioxide concentrations corresponding to the incoming traffic, 7 to 7:30 am; the noon traffic, 11:30 am to 1 pm; and the exiting traffic, 3:45 pm to 4:15 pm. These measurements also showed that the ambient level of carbon dioxide during the workday from the service vehicles was of higher concentrations than during the nonworking periods of observation.

The partly cloudy conditions during the day afforded observations of the changes in the carbon dioxide concentrations that could be closely correlated with photosynthesis. That is, when the clouds cast a shadow over the grassy field over which the measurements were made, the rate of change in the carbon dioxide concentrations decreased.

In summary, this experiment showed the feasibility of the concept of carbon dioxide perturbation spectroscopy as an atmospheric remote sensing technique. It demonstrated that perturbation spectroscopy could be utilized to detect manmade and natural variations of carbon dioxide in the atmosphere.

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16. ABSTRACT

Alternate remote sensing techniques that could utilize the slight losses of energy from the microwave beam which powers the NASA/MSFC Carbon Dioxide Observational Platform System (CO-OPS) to achieve the objectives of the U.S. Department of Energy (DOE) Carbon Dioxide Research Program's regional observational data requirements, ODRs, are addressed heuristically.

The opportunity for regional remote sensing of the carbon dioxide and water vapor constituents in the atmosphere are discussed as a potential spin-off of the CO-OPS. The CO-OPS is envisioned as a high altitude ($\sim$25km) observational platform system powered by microwave energy for regional observational use by the DOE in their Carbon Dioxide Research Program.

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