**MONITORING THE RESPONSE OF THE
UPPER TROPOSPHERE/LOWER STRATOSPHERE TO A
GREENHOUSE GAS SCENARIO**

PROGRESS REPORT

~~BUDGET PERIOD~~
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Research Accomplishments

The initial design of the interferometer's calibration system was evaluated by comparison of concurrent spectra collected with the CSU (Colorado State University) system and the UW (University of Wisconsin) system during the WISP (Winter Storms Project) in February and March, 1991 at Platteville, Colorado. Results of the comparison indicated that the thermoelectrically cooled black body calibration sources required further evaluation. An alternate calibration methodology consisting of a liquid nitrogen source and an ambient temperature black body was adopted. The modified instrumentation was deployed at a mountain site in order to collect spectra free from the effects of lower level water vapor and man made pollution. Atmospheric soundings were also collected. Measured and modeled results compared well for clear sky cases. The sensitivity of the spectra to changing observation zenith indicate spectral regions most sensitive to changes in optical path variation. The ability to detect even nearly sub-visual cirrus clouds was demonstrated. The $60^\circ/0^\circ$ ratios of CO_2 emitted radiances for clear sky cases were constant to within 1.0%, indicating that the basic ratio method for tracking changes in CO_2 concentration to within 5% even without relying on inversion algorithms. Various inversion techniques have been reviewed, and a physically correct, simultaneous scheme has been acquired to examine the accuracy to which temperature and water vapor concentration profiles and concentrations of the uniformly mixed gases may be retrieved. A high speed computer work station has been acquired to perform these computations. The interferometer system was deployed in the FIRE II (First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment) in an intense observation exercise to study the radiative properties of cirrus clouds. Data from this deployment will enhance our understanding of the information content of the spectral data pertaining to cirrus cloudiness.

1.0 Introduction.

The primary goal of this project is to demonstrate the feasibility of monitoring the response of the atmosphere to the increases in concentration of the greenhouse gases. The proposed methodology consists of collecting emission spectra at different zenith angles and examining the data for evidence of predicted climate change. The primary signals of interest consist of: a) increases in upper tropospheric temperature and decreases in lower stratospheric temperature; b) changes in the amount or type of cloud cover; and, c) changes in the amount of H_2O vapor loading. This report covers progress achieved during the six month period from February 2, 1991 to November 2, 1991 and the anticipated progress during the six months following that period. A separate mini proposal outlines the effort planned for the period May 1, 1992 through April 30, 1993.

2.0 WISP Participation

The first opportunity to evaluate the design of the calibration of the interferometer system was provided during WISP, which took place in February and March of 1991. During the experiment the UW interferometer collected spectra nearly continuously. The CSU interferometer was deployed from a school bus which had been converted into a field laboratory unit. The calibration unit for the CSU system consisted of two copper disks whose temperatures were controlled thermoelectrically. Several concurrent spectra were collected in clear and cloudy sky conditions. Even though the interferometer design was basically the same, the systems differed in some respects. First, and most important, the UW system utilized a calibration system consisting of a liquid nitrogen filled dewar as the cold target and a conical black body at ambient temperature as the hot source. The UW interferometer had a maximum resolution of 2.0 cm^{-1} compared to 1.0 cm^{-1} for the CSU system. Also, the mirrors of the systems had different coatings. Fig. 1 shows a comparison of the equivalent brightness temperatures derived from the two systems.

The traces appear to agree quite well on the scale used in figure; however, a closer inspection reveals errors of several degrees in some portions of the spectrum. The discrepancies are to some extent artifacts of different types of data processing. For example, besides the differing resolutions of the interferometers, the UW spectra were transformed unapodized; i.e., the interferograms were processed solely by performing a fast Fourier transform, while the CSU spectra were triangularly apodized and phase corrected. The differing processing procedures can introduce emission peaks whose shapes differ substantially. Nevertheless, the comparison of many spectra indicated substantial disagreement between the systems. The discrepancies may be attributable to deviation from true black (grey) body behavior of the calibration black body disks in the CSU system. In addition, deposition of frost on the disks was deemed to be a possible factor contributing to the uncertainty of the emissivity of the disks. As a result it was decided to construct a calibration system similar to that of the UW system against which the thermoelectrically cooled unit could eventually be further evaluated. Also, new software was written so that the CSU interferograms could be processed without phase correction or apodization.

3.0 Mountain deployment

In order to observe signals of climate change, measurements of the natural atmosphere are needed; i.e., the atmosphere free of daily changes introduced by human activity. Also, because it is the upper portion of the troposphere and the lower portion of the stratosphere which is of prime interest, a high elevation site was dictated. The planned site for long term deployment was Mauna Loa Observatory. Preliminary discussions were held with Mr. Elmer Robinson, the director of the observatory, who indicated that current staffing levels at the observatory would not be sufficient to routinely operate the instrument. Due in part to the time required to hire part time staffing to assist in our effort, and because of the

Figure 1 Comparison of equivalent brightness temperatures derived from UW and CSU spectra.

initial delay in the project caused by late delivery of the instrument, deployment at Mauna Loa was not deemed feasible in the current budget period. As an alternative, the instrument was deployed at the Pingree Park Campus of CSU which is located 50 miles southwest of the main campus at an approximate elevation of 9000 feet. This deployment was originally proposed prior to that at Mauna Loa as a checkout of the systems capabilities.

The interferometer was taken to the mountain site in August, 1991 in the field laboratory bus. A radio theodolite sounding system was also taken to the site. The system remained at the site until early October, 1991. Spectra were collected every few days under a variety of sky conditions; however, it wasn't until early fall that frequent clear sky conditions prevailed.

3.1 Spectra at different observation zenith

As a general rule spectra were collected as a function of observation zenith, usually starting at 0° and proceeding at each 15° of zenith to 75° . An atmospheric sounding was taken during the period of the zenith angle scans. Figure 2 is an example of a sequence of spectra taken at different observation zenith angles under clear sky conditions.

Figure 2 Spectra collected at observation zenith angles of 0° , 15° , 30° , 45° , 60° and 75° under clear sky conditions.

Several interesting features pertaining to temperature retrieval are evident in the figure. First, the plot indicates those regions (generally the less opaque regions) which are most sensitive to changes in observation zenith. The CO_2 emission region between 732 and 740 cm^{-1} shows a marked dependence on zenith angle. This is the region in which the original sensitivity to ratios of radiances was noted. Other portions of the spectrum, such as the near opaque region near 720 cm^{-1} , indicate very little sensitivity to the change in observation zenith. In these regions the radiance has been emitted from the lower atmosphere and increases in the optical path result in a less dramatic increase in radiance. While the ratio of emitted radiances has been shown to contain information on the concentration of CO_2 , and to a lesser extent information about the mean temperature of

the atmosphere, retrievals may or may not benefit from data collected at the greater zenith angles. The bulk of the information for retrieving temperature lies in the spectral resolution with which the data are collected. For example, currently at a resolution of 1.0 cm^{-1} , over 1500 measured spectral radiances are available for the inversion algorithm. From Fig. 2 it is apparent that, especially in the 75° case, some spectral smoothing is evident compared to the 0° case. On the other hand, it may be that in other spectral regions, the emission from weak lines is enhanced at the higher elevation angles to a point above the noise level so that they add information content to the retrieval process. This aspect of the retrieval requires further investigation. At this point it appears that spectra collected at different zenith angles will be most useful in providing information on concentration. If the concentration of CO_2 can be acquired (using the ratio method) independently from the retrieval algorithm, a more accurate temperature profile should result, since the first guess state of the atmosphere for the inversion is an assumption of the concentration of the uniformly mixed gases.

3.2 Consistency of the radiance ratios

Since the $60^\circ/0^\circ$ radiance ratios are sensitive to changes in the concentration of CO_2 , it is important to establish the precision at which the ratio can be measured for constant concentration of the gas. Eight cases were examined to establish the baseline precision for measurement of the ratios. Fig. 3 is a plot of the ratios for these cases in the region initially found to be most sensitive to the CO_2 concentration.

Figure 3 Ratios of $60^\circ/0^\circ$ observed radiances under clear sky and thin cloud conditions.

First, it should be noted that the top two curves in the figure resulted from data collected under thin cirrus overcast conditions. In the top curve a thin cirrus deck was obvious and for the second curve, nearly sub-visual cirrus conditions prevailed. Actually, the top two curves resulted from sequential spectra collection under a dissipating cirrus layer, and it was only by observing the portion of the sky near the solar disk that any indication of cloud particles could be visually detected for the second curve. The spectra for the dissipating cirrus deck is discussed further below. In addition, examination of the ratios in this portion of the spectrum may mislead one into the conclusion that the ratios track each other throughout the spectrum. This was found to definitely not be the case. The ratios for the truly clear sky cases are remarkably constant. Table 1 displays the value of the ratios at a wavenumber of 745.846 cm^{-1} for all eight cases of Fig. 3.

Date	Sky condition	Ratio Value
9/03/91	clear	1.431
9/05/91	near sub-vis cirrus	1.533
9/16/91	cirrus	1.624
9/16/91	clear	1.431
9/16/91	clear	1.435
9/25/91	clear	1.425
9/25/91	clear	1.443
9/25/91	clear	1.435

Table 1. Values of the $60^\circ/0^\circ$ radiances at 745.846 cm^{-1} for clear or nearly clear conditions.

The consistency of the ratio, even though the data set is small, is encouraging. The standard deviation of the clear sky value is less than 0.5% of its mean. This type of ratioing is, of course, sensitive in part to temperature structure. The range of surface temperature deviation amongst the clear sky cases in the Table was only 3.7 C and the deviations in upper air temperatures were even smaller. Thus, further evaluation of the dependence on temperature structure is indicated. Also this preliminary data indicates that the ratio may be sensitive to the presence of even extremely thin clouds. Clearly, more observations are necessary to establish the usefulness of these ratios. An excellent opportunity will present itself during the second FIRE cirrus intensive field observation period in the fall of 1991.

3.3 Cloud detection and characterization.

One of the primary signals of climate change would be a change in the amount or type of cloud cover. This topic is at the core of the warming scenario. Although the ratio method above seems to be sensitive to the presence of even the thinnest clouds, it is not viewed as the method with the most potential to diagnose cloud properties. Rather the radiometric signal in the atmospheric window region is seen as containing the most information about the cloud type.

An interesting opportunity to observe the effect of upper level clouds on the window spectra presented itself on September 5, a day which began with moderately thick cirrocumulus overcast. By late morning the clouds had thinned considerably to what could be termed thin cirrus. Early in the afternoon the clouds could almost be termed sub-visual cirrus, and it was only by looking near the solar disk that some cloud was evident. Fig. 4 depicts the spectra at 0° observation angle for each of these cases. The downward slope of the spectra from low to higher wavenumbers is evident in the figure. The two bottom curves are portions of the spectra from which the ratios for the two cloudy cases of Table 1 were extracted.

Figure 4. Downwelling spectral radiance in the atmospheric window during conditions of dissipating cirrus overcast.

A close examination of the bottom trace, for the near sub-visual cirrus, indicates that some slight slope remains. Even this small sloping spectra could be contrasted with that of a clear atmosphere in which this portion of the spectra would be more nearly horizontal, especially in the 800 to 1000 cm^{-1} portion of the spectrum.

Of course, in addition to the mere presence of clouds, their physical characteristics are subject to change as well in any climate change scenario. The primary cloud parameter of interest is the cloud optical depth. Also important is the microphysical makeup of the cloud in determining the role the clouds play in any feedback loop. The upcoming FIRE II cirrus intensive field observation phase will provide an opportunity to collect spectra under cirrus overcast in a data rich collaborative effort. It is hoped that information learned during the experiment will allow additional information to be retrieved from the spectral and ratioed signals.

4.0 Temperature Retrieval Algorithm

As indicated in the original proposal, the ratio of 60° to 0° radiances shows sensitivity mainly to the concentration of the greenhouse gases and a smaller sensitivity to temperature structure. The alternative method of detecting changes in the temperature structure is the more conventional temperature retrieval or inversion approach. The basic question about the effectiveness of conventional temperature retrieval in this application is the height to which the temperature structure can be retrieved from ground based interferometric measurements. Initial retrieval from interferometric measurements by Smith et. al. (1988), indicates that temperature retrieval may be achieved to an altitude of 500 mb and water vapor to 700 mb, based on comparisons with satellite data. These results were reported for data collected at Madison, WI. It is our intention to apply a similar algorithm to the data collected at the Pingree Park site to see if the high altitude collection site extends the height to regions where the 2CO_2 atmosphere temperature structure change is predicted to be most prominent.

Selection of an appropriate retrieval algorithm was, of course, the first step into this phase of the research. There are various approaches to the problem, and the selection of a particular algorithm was based on the following attributes of such algorithms in general. First, the algorithm should be based on physical modeling rather than statistical correlation. In the latter category we also cast the "neural network" or "artificial intelligence" approach. It is important to use a physically correct model since in a climate change scenario, past statistical data bases would not necessarily be representative of current conditions. Also, the need for a large statistical database is avoided. Second, the approach should solve the true nonlinear system of equations. Linearization of the equations is less accurate and thus, less preferable. Third, the algorithm's solution should not be sensitive to the order in which parameters are considered. For example, if the algorithm's solution is dependent upon the order in which clouds and H_2O vapor are treated, then past experiences with the model, which are almost certainly tuned to the downward looking problem, will not necessarily

provide optimal results for this application. Fourth, the model should be generally compatible with FASCOD3. We have based all of our modeling effort on the FASCOD3 code. As mentioned section 3.0, some discrepancies may be introduced in any comparative process as artifacts of data processing. For example, apodization, slit functions, filter functions and even interpolations may introduce apparent errors. We have become familiar with the output options of the FASCOD3 model and have developed software to access its various output options. For example, Fig. 5 is a comparison of equivalent brightness temperatures from the phase corrected, triangularly apodized, interferometric measurement and the triangular slit function of the FASCOD3 calculation, using the atmospheric sounding from the period of measurement. Although the basic calibration appears to be excellent, marked disagreement is still apparent near the peaks and valleys of the curve. We have developed the capability to access the monochromatic output of the FASCOD3 model and are in the process of developing software which should eliminate discrepancies due to data processing procedures. The basic process will involve performing a transformation from spectral to interferogram space by performing a fast Fourier transform on the monochromatic FASCOD3 data, and subsequently performing a transformation to spectral space using the same apodization function as applied to the measured data. This matching of measured to modeled output is essential to performing accurate temperature and gaseous concentration retrievals.

Thus, a retrieval algorithm not compatible with the features of FASCOD3 would require an additional investment of resources. Finally, the question of availability was considered. Creation of a new retrieval algorithm was not one of the research goals of this effort. Thus, a code which was available received high consideration. With all of this in mind we have requested and received from Phillips Laboratory (formerly AFGL) the Path Characterization Algorithm for FASCOD3. CSU will be a pre-beta test site for the code. This code will be applied to spectra collected at the mountain deployment and future spectral collections to explore its capabilities.

Since the code interacts with FASCOD3, which is a fairly CPU-time intensive code, (running the model on our SPARC station I for a 500 cm^{-1} portion of the spectrum requires over an hour of computation) we have acquired one of the fastest workstations currently available, an HP730, which will greatly facilitate investigation of the applicability of conventional retrieval codes to the problem at hand. This phase of the research will begin in early 1992.

Figure 5. Equivalent brightness temperature comparison from measured and FASCOD3 modeled spectra.

5.0 Summary

The initial calibration design of the emission interferometer system was evaluated in comparisons with the University of Wisconsin system during the Winter Storm project in February and March of 1991. The tests indicated the further evaluation and refinement of the thermoelectrically controlled system is necessary. A more basic calibration system was constructed and the system deployed at a high elevation site in the foothills of the Rocky Mountains. Spectra and atmospheric soundings were collected under various sky conditions. The results show favorable comparisons with the FASCOD3 model. Spectra were collected at different observation zenith angles to investigate those portions of the spectrum most sensitive to changes in atmospheric path. The stability of the $60^\circ/0^\circ$ radiance ratios have been evaluated for the small number of clear sky spectra collected to date. Initial results indicate that the ratio is constant to about 0.5%, (excluding large variations in the temperature structure) for clear sky cases. The ratio also shows sensitivity even to thin cloudiness. Examination of the spectra in the atmospheric window region shows that the slope of the floor of the spectra is sensitive even to near sub-visual cirrus conditions. A temperature and

gaseous concentration retrieval algorithm has been acquired to investigate the more conventional inversion to the current problem. A high speed computer workstation has been acquired to facilitate this phase of the research. The interferometer will be deployed in the second FIRE cirrus intensive field observations to investigate the information content of spectral measurements concerning the microphysical makeup of cirrus clouds.

6.0 Reference

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