TECHNICAL PROGRESS REPORT

For the period

November 1, 1993 through October 31, 1994

For the grant

HIGH SPECTRAL RESOLUTION FTIR OBSERVATIONS FOR THE ARM PROGRAM: CONTINUED DEVELOPMENT, EVALUATION AND ANALYSIS

Henry E. Revercomb, Principal Investigator (608) 263-6758

Fred A. Best, Program Manager (608) 263-6777

Prepared for the

DEPARTMENT OF ENERGY
OFFICE OF ENERGY RESEARCH

Prepared by the

UNIVERSITY OF WISCONSIN
SPACE SCIENCE AND ENGINEERING CENTER

JULY 25, 1994

1.0 INTRODUCTION

The DOE grant to the University of Wisconsin (UW) teamed with the University of Denver (UD) for the design and fabrication of high spectral resolution FTIR (Fourier Transform Infrared) instrumentation for the CART sites of the Atmospheric Radiation Measurement (ARM) Program began on September 15, 1990 with a three year grant that funded the development of prototype instrumentation. In October 1993 we were granted funding for an additional three years under the same contract. This report outlines the progress that has been made to date during the reporting period from November 1993 through October 1994. Significant progress has been made during this reporting period and the project is currently on schedule to achieve the primary objectives of the first year.

The objective of the first three years of this grant was to develop three different types of instruments, named the AERI, AERI-X, and SORTI. The major portion of these instrument developments has been completed. The Atmospheric Emitted Radiance Interferometer (AERI) is the simplest and a prototype was deployed at the Southern Great Plains (SPG) Cloud and Radiation Test (CART) Site in March of 1993. The AERI instrument has a 0.5 cm^{-1} resolution (unapodized) and measures accurately calibrated radiance spectra for radiation studies and for remote sensing of atmospheric state variables. The AERI-X and the SORTI are higher spectral resolution instruments for obtaining the highest practical resolution for spectroscopy at the ARM central sites. The AERI-X, like the AERI, measures atmospheric emitted radiance, but with a resolution of 0.1 cm^{-1}. The AERI-X prototype instrument is in the final stage of development and is expected to be deployed at the CART Site by the end of this calendar year. The Solar Radiance Transmission Interferometer (SORTI) which has been deployed at the CART Site since December of 1993, measures the total transmission of the atmosphere by tracking the sun through changes in atmospheric air mass. The large solar signal makes it practical for this instrument to offer the ultimate in spectral resolution, about 0.003 cm^{-1}.

The continuing instrument development objectives of the follow-on grant (of which this is the first of three years) are to achieve an operational AERI-X and to continue with important general instrument developments that will improve remote operations and reliability of all three instruments by building on the significant operational experience gained with the deployed AERI and SORTI. These efforts will also concentrate on optimizing calibration and noise performance. New efforts will address spectroscopic issues and remote sensing from the combined data sets.

This report summarizes the progress of both the UW and the UD. The UW has the primary responsibility for the AERI and the UD for the higher resolution instruments. However, many of the considerations for data system design, data format, software design, and calibration hardware are common.

During the remainder of this fiscal year, emphasis will be placed on the following tasks: complete the hardware for the AERI-X prototype instrument; perform further detailed characterization testing of the AERI Blackbodies; and further development of enhanced instrument performance models. We will also perform analysis of the AERI data that was obtained in the summer of this year from the CART site, in order to help achieve an improved definition of the self broadened water continuum.

2.0 SUMMARY OF PROGRESS - UNIVERSITY OF WISCONSIN

The major thrust of the effort at the University of Wisconsin has been in the areas of support of the AERI prototype that is deployed at the CART Site, enhanced instrument developments that can be implemented in future AERI, AERI-X, or SORTI instruments, and in specrtroscopic analysis of the water vapor continuum. The principal instrument developments include: the use of a Stirling Cooler to maintain the detectors at 77 K; development of quality control criteria and controls; and development of the AERI-X operating system which evolved out of several AERI operating system upgrades. Significant refinements to the foreign broadened water vapor continuum were defined in our science team paper that was submitted in February 1994 and will not be repeated in this report. A paper on the AERI was also presented at the 1994 AMS meeting.

2.1 Support of the AERI at the SPG CART Site

The AERI prototype instrument was deployed to the Southern Great Plains (SGP) Cloud And Radiation Testbed (CART) central facility in March 1993. Data from this system has been made available to the experiment center (and all interested science team members) from the beginning and continues today. This data has supported the definition of the AERI/LBLRTM quality measurement experiment as well as several other research efforts. It is anticipated that the AERI prototype will continue to operate at SGP CART until the AERI-01 facility instrument is delivered in early fall 1994.

Though the AERI prototype is under the control of site operators, the current grant is supporting continued monitoring of the instrument performance by experienced personnel at the UW. Problems identified through remote monitoring of the instrument at Wisconsin (through the INTERNET) have been identified and corrected using remote (telnet and ftp) access to the AERI; often without the need for any site operator intervention. Personnel at Wisconsin have also responded to problems identified by site operators to effect a rapid return to normal data collection.

The AERI prototype at the SGP central facility was installed in the optical trailer in a temporary configuration viewing through an opening in the ceiling (see Table 1) in December 1993. This temporary configuration makes use of a motor driven hatch installed on the roof of the optical trailer which closes automatically in the presence of rain or snow, opening when the precipitation ceases. Since the optical trailer is air conditioned this configuration requires a "chimney" of insulated material between the ceiling and the AERI prototype fore optics. Since the chimney cannot really be maintained at ambient conditions it does present some difficulties for remote sensing with AERI prototype data. The final AERI-01 configuration will eliminate the need for this chimney by having the scene mirror protrude out the side wall of the trailer with an insulated barrier between the scene mirror and blackbodies (outside) and the interferometer/detector assembly (inside).

Table 1. ***Major Milestones of the AERI prototype at SGP CART***

7 Dec 93	Begin AERI operations from optical trailer using newly installed ceiling hatch
20 Jan - 11 Feb 94	AERI prototype supports Winter Single Column Model (SCM) IOP
6 Apr - 8 Apr 94	AERI prototype calibration validation tests performed on site
11 Apr - 1 May 94	AERI prototype supports Remote Cloud Sensing / Spring SCM IOP
July 94	AERI prototype supporting Summer SCM (in progress)

The AERI prototype system at CART in 1993-4 has followed an operational schedule which closely matches the availability of personnel on site, i.e. the AERI has collected data from 9 AM to about 5 PM Monday-Friday every day except during IOPs when the system has been run continuously (24 hours per day every day). All the mechanical and software systems of the AERI prototype actually run continuously, but data collection using the AERI prototype is dependent upon the filling of a liquid nitrogen detector dewar (by hand) every eight hours. This limitation will be lifted with the deployment of the AERI-01 facility instrument which will use a mechanical cooler in place of liquid nitrogen thus allowing truly continuous and unattended operation (even at remote sites).

In April 1994, after one year at the CART site, the AERI prototype system was brought down briefly for an assessment of radiometric performance issues. A series of tests were run on site in Oklahoma to check for potential drifts in sensor calibration. The system passed all tests thereby demonstrating the expected reliability and robustness we anticipate for the radiometric performance of all future units.

2.2 Stirling Cooler Implementation for the AERI

We have procured and recently integrated a Stirling cooler assembly into the first production AERI and have demonstrated that the radiometric performance of the AERI in this configuration is very close to that observed with liquid nitrogen cooled detectors as shown in Figures 1 and 2. The long wave MCT detector channel is particularly clean; and the shortwave InSb channel appears clean except for the region from 2600 to 3000 cm^{-1}. We have identified the source of this noise to be electrical in nature (as opposed to an artifact of mechanical vibration such as detector microphonic noise) and are highly optimistic that it can be reduced to negligible levels. It now appears that the Stirling cooler is a cost effective and technically viable option for cooling the AERI detectors.

It has long been desired to eliminate the need for liquid nitrogen as a means to cool the AERI detectors. The supply of liquid nitrogen presents logistical problems in the field because detector dewars with hold times longer that one day are not practical; thus, for continuous operation of an AERI instrument in the field, a dewar fill would be required at least once per day. Automated liquid nitrogen filling systems have proved to be unreliable in the highly variable field environment. In addition, even with a perfectly functioning auto-fill system, liquid nitrogen would be burned at the rate of one 160 liter tank every two weeks, which still puts a reasonably large servicing burden on an operational instrument. Just the liquid nitrogen alone could run near $3K for one year.

Recently, Stirling cooler technology has become a very attractive option for cooling detectors. Prices have come down to under $10 K per unit and lifetimes are now guaranteed for on the order of one year. In order to determine the most suitable Stirling cooler for the AERI we have investigated the performance specifications from several vendors and had extensive discussions with both Stirling cooler manufacturers and infrared detector manufacturers. We choose a Litton "split" type Stirling cooler in which the compressor is in a separate housing from the regenerator or cold finger section; both sections are connected by a thin walled stainless steel tube. This Stirling cooler has three principal advantages for use with the AERI:

1) *Low vibration.* The split configuration allows the relatively massive compressor piston to run in a dual opposed motion, which minimizes vibration. The cold finger section contains a relatively small mass that vibrates at the compressor drive frequency of 60 Hz. Integral Stirling coolers, in which the relatively massive compressor piston is mechanically linked with the regenerator, cannot be configured in a balanced mode and thus typically generate more vibration than integral coolers.

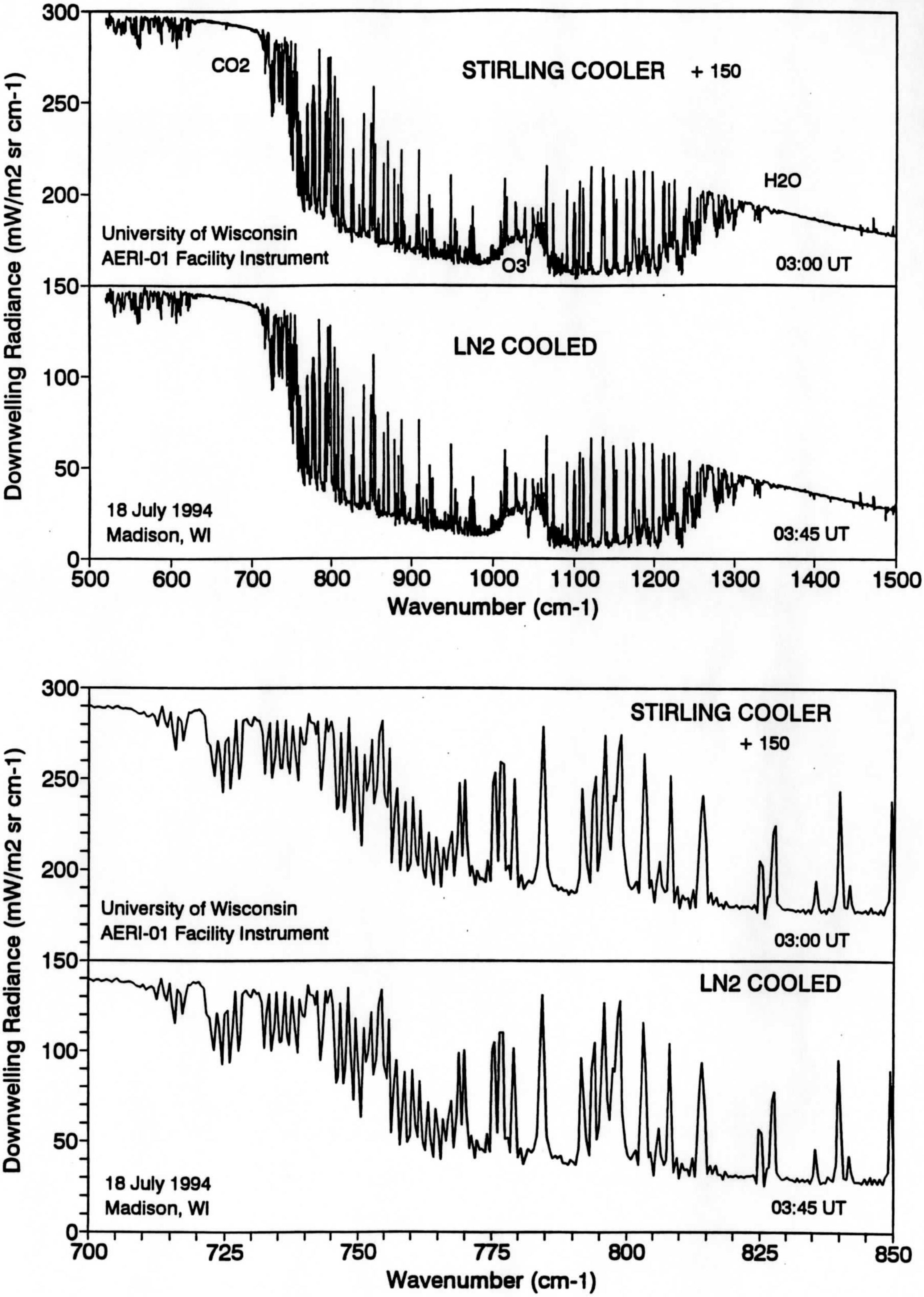

Figure 1. Comparison of longwave AERI spectra with and without Stirling cooler while observing clear skies. The bottom figure shows an expanded region in the AERI longwave band. Though the spectra were obtained 45 minutes apart, the agreement is remarkable.

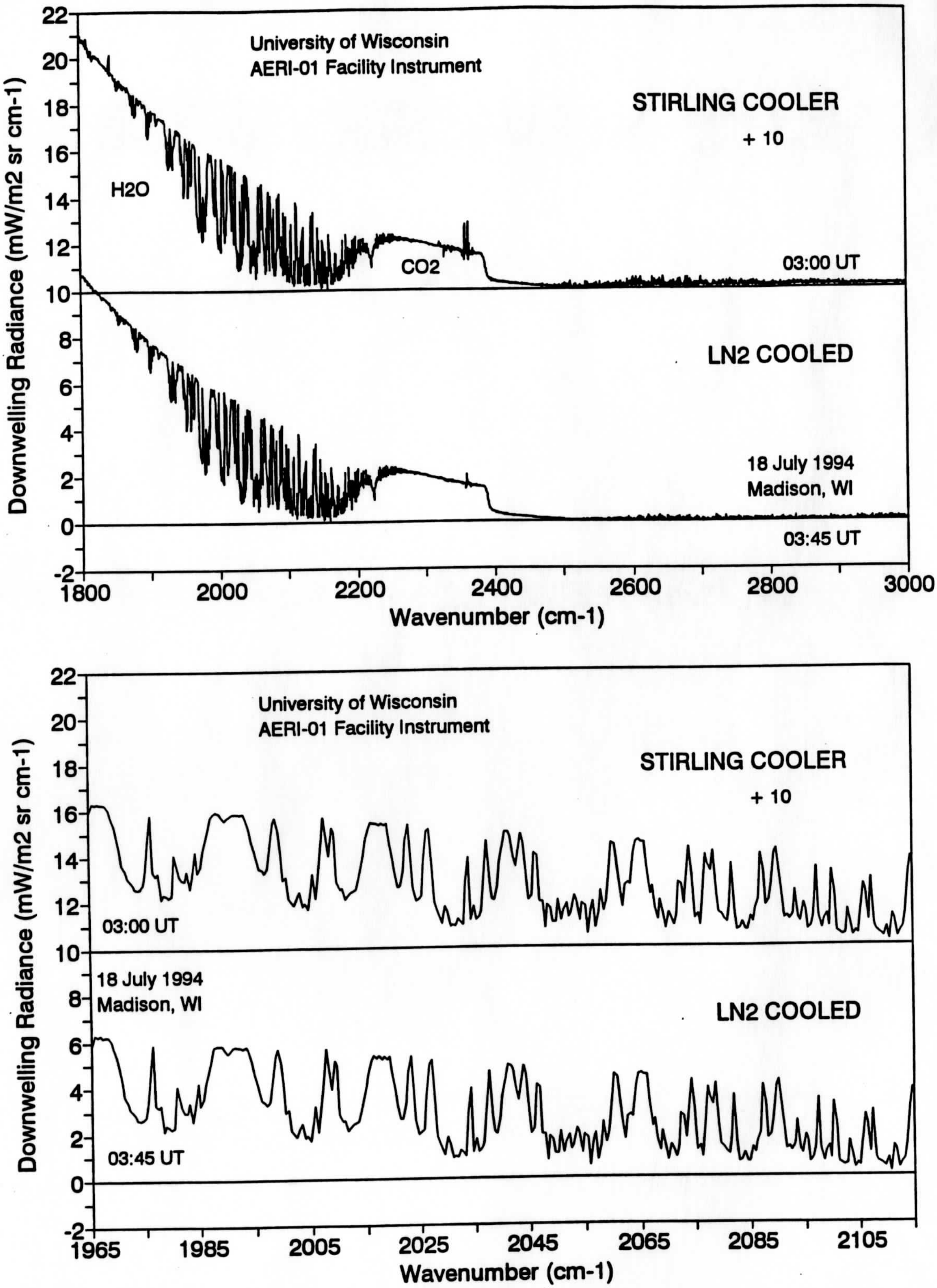

Figure 2. Comparison of shortwave AERI spectra with and without Stirling cooler while observing clear skies. The bottom figure shows an expanded region in the AERI shortwave band. The small additional noise in the 2500 to 3000 cm-1 range is an artifact of the test configuration. This noise has been shown to be due to EMI and we expect to eliminate it through proper shielding.

2) *Established vendor, good lifetime, good service record.* The Litton cooler has a lifetime guarantee of one calendar year. At the end of that time the unit must be sent back to Litton for refurbishment for piston replacement and cleaning, for an estimated cost of less that $2K (less than one year supply of liquid nitrogen). The Litton cooler is very popular and the company has set up an efficient servicing system that can turn-around a refurbishment job in one week. With Litton's track record it is very unlikely we will get caught in a bind in the future when servicing and spare parts replacement will become an issue.

3) *Easy serviceability in the field.* The split Stirling configuration has another distinct advantage over the integral coolers because the cold finger in the split type can be easily removed from the sealed dewar that houses the detectors, without violating the dewar vacuum. This arrangement allows a Stirling cooler to be replaced in the field without physically changing the detectors or without changing any optical alignments of the detectors to the interferometer system. In addition, the dewar well that accepts the split Stirling cooler cold finger can be filled with liquid nitrogen when the cold finger is removed. This greatly facilitates diagnostic testing because it allows the interferometer system to run with the Stirling cooler integrated detectors, but without the Stirling cooler mechanism being operated. This feature proved to be very useful in our evaluation testing of the Stirling cooler assembly that was installed on the AERI.

In summary, we have researched Stirling cooler technology, specified and procured a Litton cooler with detectors installed, integrated this cooler assembly into an AERI, performed several compatibility and performance tests, and have come to the conclusion that Stirling cooler technology is a viable technology for use in cooling the AERI detectors.

2.3 Development of Quality Control Criteria and Displays

Under previous support the AERI system was brought to the point of full unattended operation with the notable exception of an automated means to keep the infrared detector package at cryogenic temperatures. Though this exception is removed through the use of a mechanical cooler in the AERI-01 system, there is still a need to monitor important instrument parameters in order to provide warning flags both to the system operators and to users of the data stream. In order to facilitate this process, a set of new quality control summary products have been implemented that greatly simplify the monitoring of instrument performance.

These new summary products, which include detector noise levels, system responsivity, system nonlinearity, temperature sensor calibration and, blackbody stability, are in addition to the monitoring of important system temperatures and other indicators of system health that were previously available. The term summary product is valid here because not only are the quantities condensed in size to a small volume but all the relevant data is collected together in one set simplifying the display and use of the information. Criterion for instrument health (e.g. electronics temperatures) have been implemented into the AERI operational display which will raise warning flags to alert an operator within sight of the AERI display. These same criteria can be implemented on whatever computer system is used for monitoring the AERI operation.

At the time of writing the summary products have been included as part of the AERI data stream and several logical flags have been defined which apply conditional tests to the summary data in order to determine a true or false condition. The currently defined logical flags are for whether 1) hatch open (or not), 2) hot blackbody is stable (or not), and/or 3) detector noise in each channel meets specification (or not). A combination of these flags can be used to determine whether the data is usable for a particular application or not.

Future work in this area will emphasize details unique to the AERI-X system, though most of the same concepts will transfer without modification.

2.4 AERI-X Operating System Based on AERI Design

The AERI-X operating system is currently in the design phase with detailed implementation awaiting the integration of the AERI-X hardware subsystems into a fully functional instrument. However, a substantial portion of the required operating system details have been implemented as improvements to the AERI operating system. Some of these new features are a generalization of the SSEC native data format to allow for multiple data records for a single time instance, inclusion of complete data processing history information (program versions and parameters used), and a formal data abstraction through the use of c-language I/O modules. These changes to the AERI system software will make the transition to the AERI-X much simpler while maintaining the compatibility been AERI and AERI-X, an important consideration for system maintenance and further development. It should be noted that the use of an interface module to the data will greatly simplify the task of integration of the AERI and AERI-X data into the CART site data system software, since the details of the native instrument data format do not need to be known to access the data.

3.0 SUMMARY OF PROGRESS - UNIVERSITY OF DENVER

This section describes the work done by the University of Denver during the reporting period. The major activities involve the deployment and operation of the SORTI prototype at the CART site and the AERI-X prototype development.

3.1 SORTI Deployment at SGP CART SITE

The SORTI was installed at the SGP ARM site in November of 1993. The instrument was fully operational by February of 1994. The initial installation involved setting the instrument up and establishing communications with the instrument. A considerable investment of time and effort was put into the development of computer operations to develop a stand alone instrument.

The operational plan for the instrument calls for the acquisition of absorption spectra at various sun elevation angles throughout the day. This is accomplished with a minimum of ARM site personnel involvement. The spectral regions are analyzed in both low resolution (.015 cm^{-1} for comparison with AERI data) and high resolution. The spectral regions presently examined are 750 - 1350 cm^{-1}, 1500 - 2000 cm^{-1}, 2400 - 3000 cm^{-1}, and 4000 - 4260 cm^{-1}.

The SORTI is a fair weather, clear sky instrument. Presently ARM site personnel are charged with evaluating the weather and starting SORTI if the conditions are favorable for its operation. The instrument has been stable and operational for periods of months during the development processes. SORTI has been down several times since February for software upgrades, hardware upgrades, and for a period following the April IOP when the SORTI instrument was jostled by visiting personnel. SORTI has provided a base set of data during this time which is allowing the development of automatic quality control software, to be installed at the site to prepare the data for ingest at PNL. The instrument has provided the University of Denver with valuable data during the solar eclipse on 10 May 1994, this operation was coordinated with DU's instrument in Hawaii. The SORTI instrument has been involved in two Intensive Observational Periods (IOP's). The cloud cover during these periods was generally heavy and SORTI was not heavily involved in these operations.

Typical spectra obtained by the SORTI instrument at the SGP CART site are found in Figures 3 and 4.

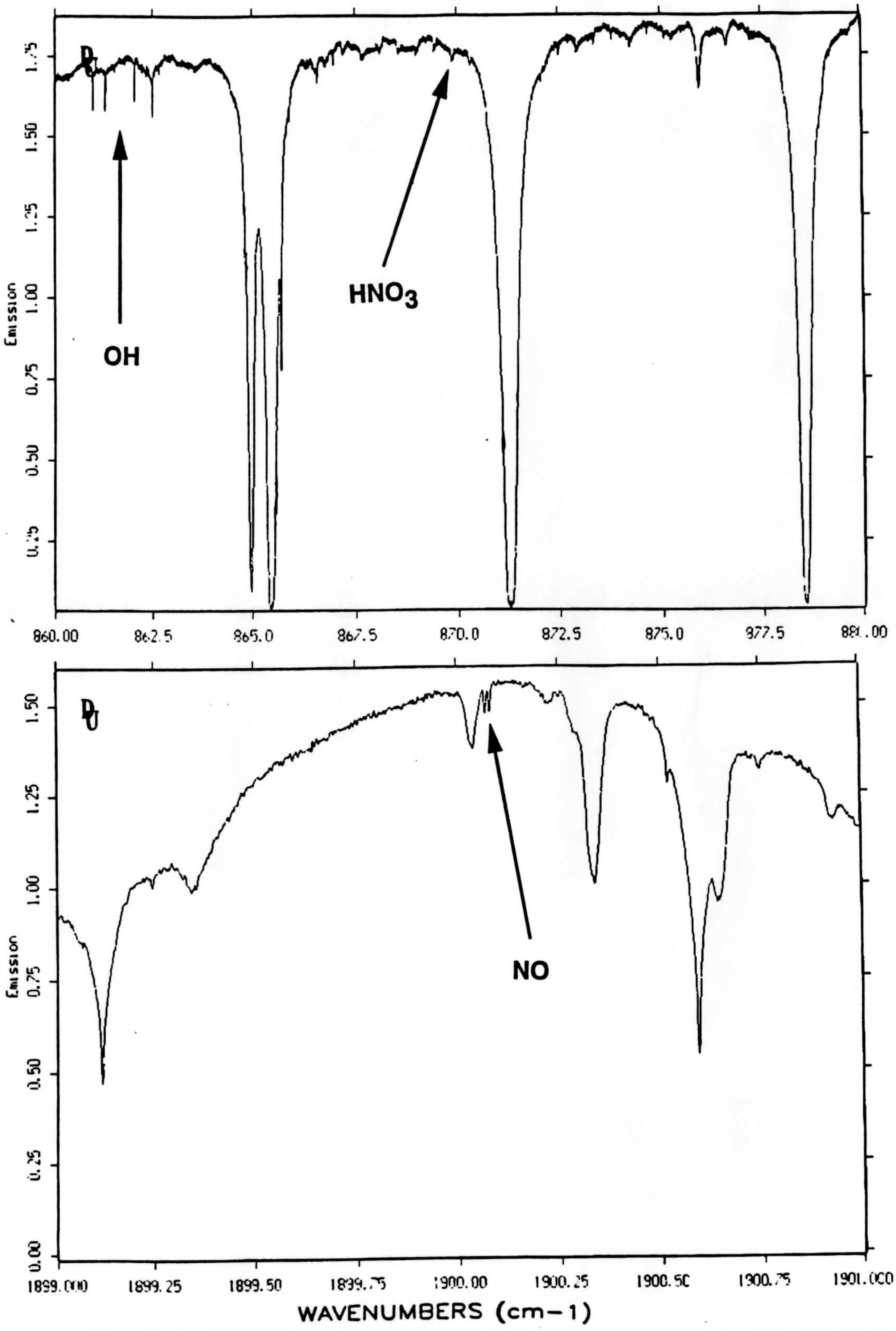

Figure 3. SORTI data obtained at the SGP CART site. The upper figure is a high sun angle spectra showing the HNO_3 region. The very sharp small features are solar OH. The lower figure illustrates the NO doublet at approximately 1900.1 cm^{-1}.

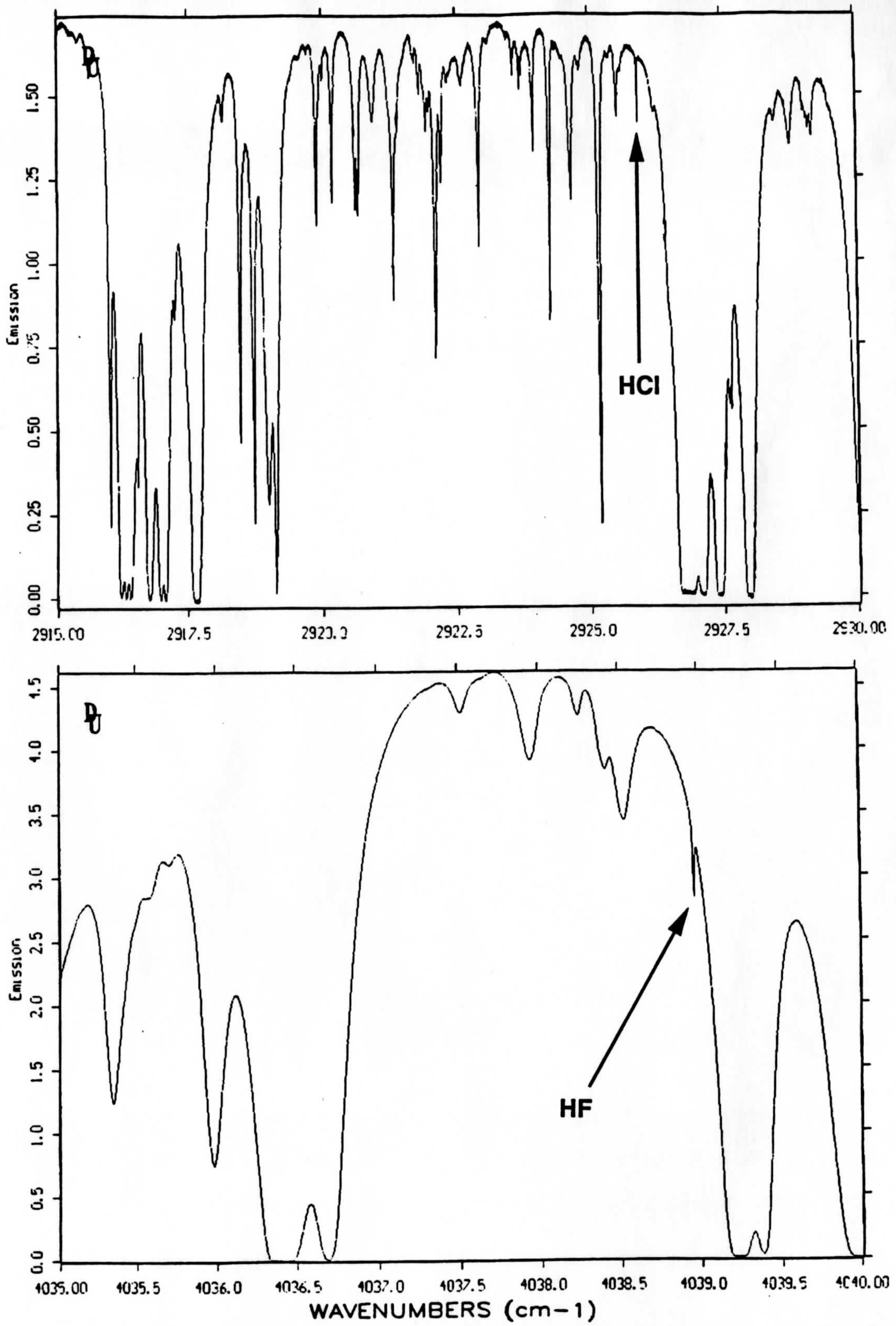

Figure 4. SORTI data obtained at the SGP CART site. The upper figure shows HCl features at approximately 2925.8 cm^{-1} (the sharp absorption feature on the low wave number side of the deep absorption centered at 2927 cm^{-1}). The lower figure shows HF features at approximately 4039 cm^{-1} (the sharp absorption feature on the side of the strong absorption between 4039 and 4039.5 cm^{-1}).

The SORTI should be developed into a fully functional instrument at the ARM site in a short period of time. Quality control software is being tested presently and data ingest parameters have been developed. Future plans include a new sunseeker. The present sunseeker arrangement does not allow for the use of low sun during the summer and requires site personnel to make determinations of the weather and activate the sunseeker. DU will develop a sunseeker that will activate itself during clear sky conditions.

3.2 AERI-X Prototype Development

Significant progress was made in the development of the AERI-X. Several modifications to the development instrument were implemented. The fixed cube corner reflector mount was changed to include an XY translation stage for easy and precise adjustment. We were able to improve the signal levels by about 30% over the best earlier adjustment. The problem of jitter in the starting sample of the interferogram was solved by installing a white light source, detector and electronics (this required some changes in the infrared optical arrangement). The white light channel provides a precise start of sampling indicator for data taking. The digital signal processing board and its software were modified to allow sampling of the interferogram at two different gains. It had been found that the dynamic range available with the 16 bit A/D converter was not sufficient to handle the signal to noise ratio in the interferograms. The beam scanning mechanism and calibration blackbodies were attached to the instrument, and collection of data under computer control was enabled. We now have a working AERI-X system that produces good signal to noise spectra at high resolution, as shown in Figures 5.

Further work on the AERI-X is underway. Specifically, calibration accuracy and stability need to be demonstrated. This will be easier when the software for automatic processing of the data is completed. In addition, the instrument will be run nearly continuously to study its reliability.

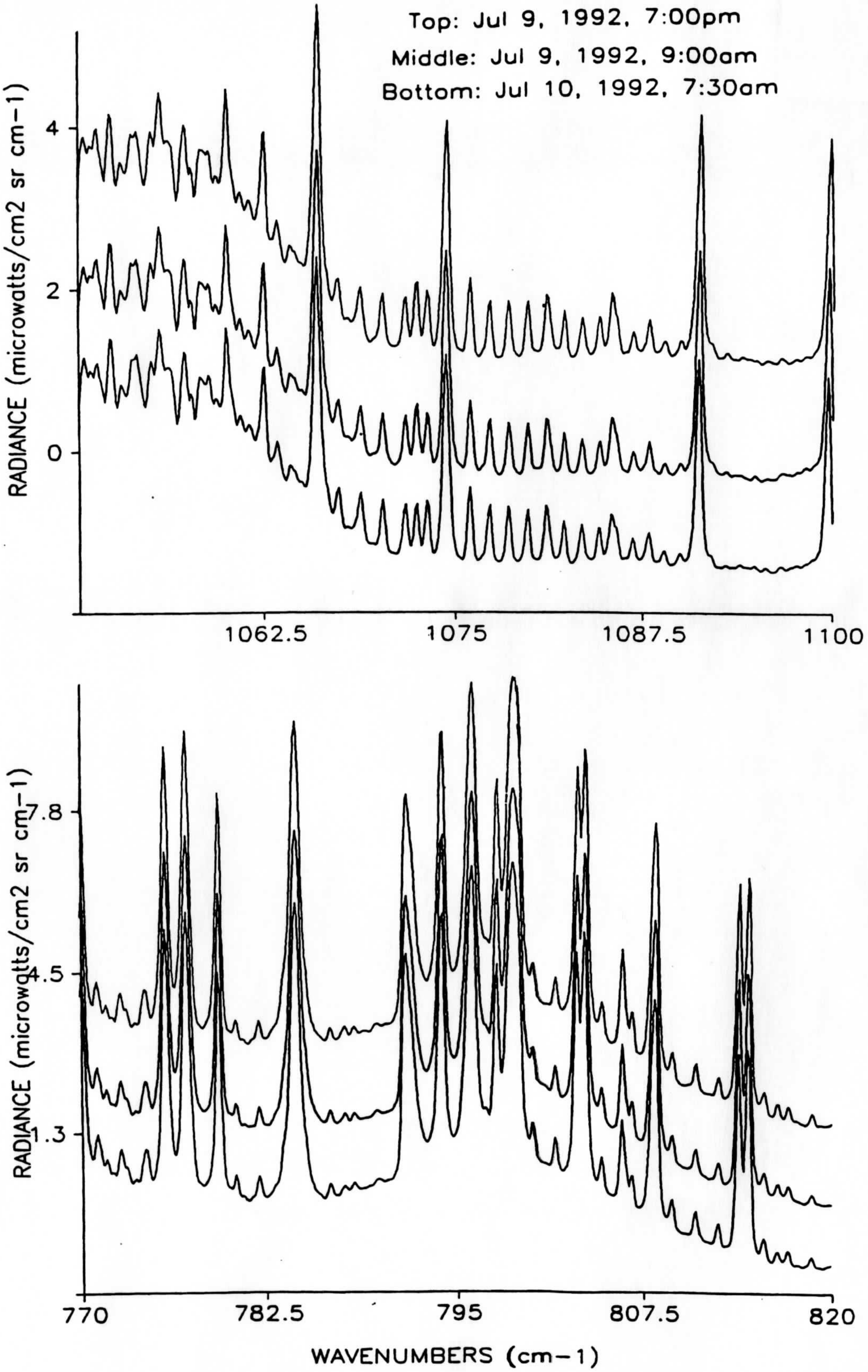

Figure 5. Sample data from the AERI-X prototype taken at 45° elevation in Denver on the dates shown. The spectral reproducibility and good noise performance are evident. Twenty minutes was used to collect 2 sky and 2 blackbody views.