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# STUDY OF DUAL CHANNEL INFRARED SPECTRORADIOMETER SYSTEMS

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## FOREWORD

This interim report was prepared in partial fulfillment of the requirements of Contract NAS 8-21144 with NASA, George C. Marshall Space Flight Center, Alabama. The contract monitor is Mr. Terry Greenwood of the Aero-Astrodynamics Laboratory.

## ABSTRACT

A dual channel infrared spectroradiometer system has been developed to furnish the spectroscopic data necessary for determination of temperature and partial pressure distributions of certain species within the exhaust of large rocket engines. The system includes an internal blackbody intensity calibration source, external radiation sources for absorption measurements, spatial and spectral scanning mechanisms, power supplies and recording apparatus.

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## INTRODUCTION AND SUMMARY

In zone radiometry, high-resolution spectral absorption and emission measurements are made along a set of predetermined lines of sight through the exhaust plume. From such data it is possible to calculate temperature and species concentration profiles for certain species in the exhaust plume. By comparing experimentally determined profiles with those determined analytically, the accuracy of analytical exhaust plume models may be evaluated and improved.

In the work to date, which has been supported primarily by the Aero-Astrodynamics Laboratory, NASA/MSFC, Huntsville, Alabama, spectroscopic instrumentation has been developed (Ref. 1, Contract NAS8-11261) and used (Ref. 2, Contract NASw-16) to study the exhausts of small rocket engines (1000-pound-thrust, 4- to 8-inch nozzle exit diameters) firing liquid propellants such as $LO_2$/RP-1 and $LO_2/C_2H_5OH$. In these studies temperature profiles and concentration profiles for the species $CO_2$ and carbon particles have been experimentally determined. In conjunction with theoretical analyses, mixture ratio profiles within the rocket nozzle have been deduced from the experimental data.

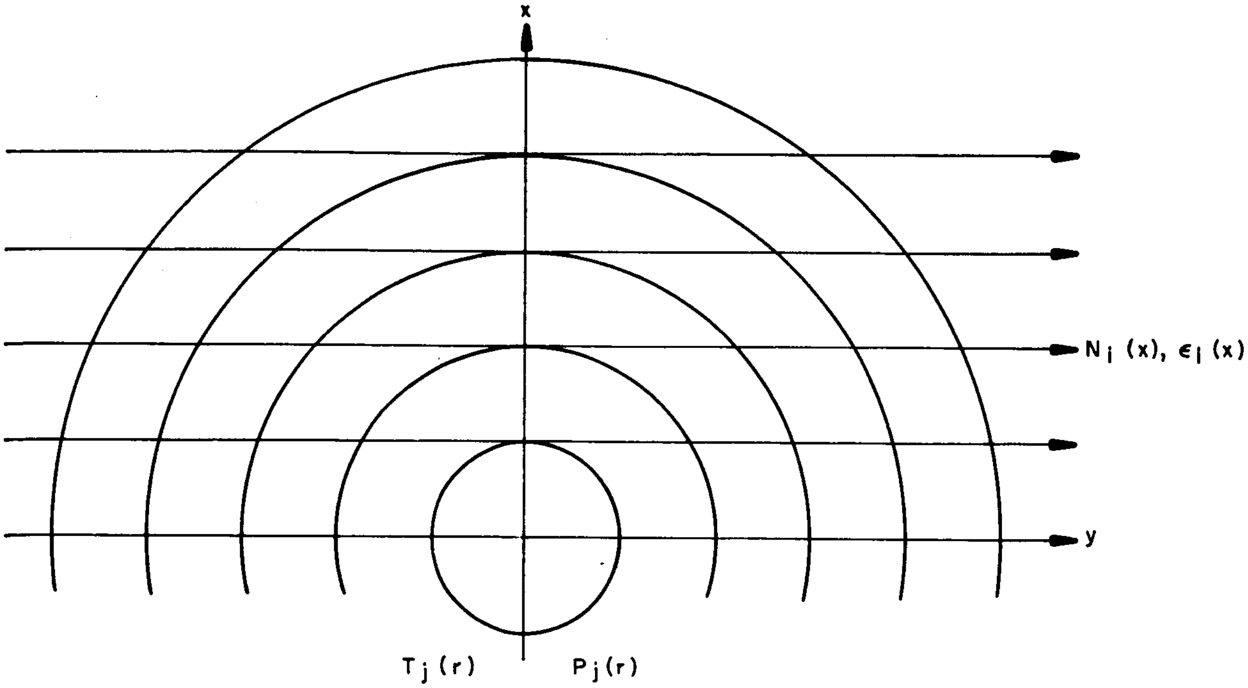
Logically, the next step in the use of the spectroscopic techniques perfected during the course of the programs described in Ref. 1 and 2 is to investigate the exhausts of "full-size" rocket engines. This report describes the spectroscopic instrumentation system developed under Contract NAS8-21144 to perform zone radiometry on large rocket engine exhausts during static tests of these engines. The system consists of an internal blackbody calibration source, external radiation sources for absorption measurements, spectral and spatial scanning mechanisms, power supplies, and recording equipment. All components used during engine firings, with the exception of the power supplies and recording equipment, can be operated in a vacuum environment. Thus, the exhausts of engines operated at altitude simulation facilities can be studied.

The spectroradiometer is presently equipped to operate in the 0.8 to 3.5 micron spectral range with one channel of low spectral resolution and one channel having the moderately high resolution afforded by a quarter-meter grating monochromator. Additional gratings and detectors can extend the spectral range of the instrument through the visible and ultraviolet to 0.3 microns or further into the infrared.

The spectroradiometer system is described in detail in this report. Suggested programs for use of the instrument are presented.

## DESIGN CRITERIA

The basic requirement of the spectroradiometer system developed in this program is that it be able to carry out zone radiometry experiments on large engine exhausts. The principles of zone radiometry are described in considerable detail in Ref. 1 and 2, and are reviewed briefly here. Because of the geometric shape of the rocket motor combustion chamber and nozzle, the exhaust plume may be assumed to be radially symmetric. The plume can therefore be divided into a series of concentric zones (Fig. 1). The partial pressure and temperature (and therefore the spectral radiance and spectral emissivity) of a particular species is assumed to be constant in each zone. The line-of-sight values of spectral radiance and spectral emissivity may be expressed in terms of the zonal values by equations of radiative transfer which take into account the absorptance of each zone. The important equations are listed in Fig. 1.



$P_j(r)$ = partial pressure of a particular species in the $j^{th}$ zone
$T_j(r)$ = temperature in the $j^{th}$ zone
$K_j(r)$ = spectral absorption coefficient of a particular species in the $j^{th}$ zone
$N_j(r)$ = spectral radiance per unit path length in the $j^{th}$ zone
$\epsilon_j(r)$ = spectral emissivity in the $j^{th}$ zone
$N_i(x)$ = measured spectral radiance along $i^{th}$ line of sight
$\epsilon_i(x)$ = measured spectral emissivity along $i^{th}$ line of sight

$$N(x) = \int_{-y_0}^{y_0} N(r) \exp \left[ - \int_{y}^{y_0} K(r)\ P(r)\ dy \right] dy$$

$$1 - \epsilon(x) = \exp \left[ - \int_{-y_0}^{y_0} K(r)\ P(r) \right] dy$$

Figure 1. Division of Plume Cross-Section into Zones of Uniform Temperature and Species Partial Pressure; Basic Equations for Radiative Transfer of Energy Through the Plume.

If the line-of-sight spectral radiance and spectral emissivity are each measured along N lines of sight for a division of the plume into N zones, then the 2N equations of radiative transfer may be solved for the zonal values of spectral radiance and spectral emissivity. The zonal values of temperature and species partial pressure may then be calculated. A computer program has been developed to carry out the necessary calculations.

An important requirement for meaningful zone radiometry measurements is that the spectral band pass of the instrument must be sufficiently small to ensure that fluctuations of spectral emissivity are negligible within the wavelength region encompassed by the band pass. If this requirement is not met, the concentration determination can be meaningless.

The practical implications of the necessity for a narrow band pass are as follows: If the radiation being measured is primarily continuum in nature, such as is found with incandescent carbon particles or in the central region of the 4.3-micron $CO_2$ band, then the spectral band pass (0.05 micron) furnished by a narrow band interference filter is sufficient for meaningful concentration determinations. Also, relative concentration distributions for such species as OH and CH may be determined under low spectral resolution. If, however, radiating species possessing spectral fine structure, such as $H_2O$, CO, HF, etc., are being studied, the spectral resolution afforded by a grating monochromator (0.00025 micron) is required. The grating monochromator is also suitable for making spectral scans of exhaust radiation along a fixed line of sight for species identifications.

From the above general considerations it can be stated that a zone radiometry system must provide for absorption and emission measurements along a series of coplanar lines of sight, and for maximum data collection, should contain channels of high and low spectral resolution. A particular requirement of the subject instrument is that it be suitable for studying rocket engines that are operated in altitude simulation facilities.

The basic difference in the zone radiometry system developed to study small engine exhausts (Ref. 1) and the system needed to meet the above requirements is in the method of achieving spatial scanning (variation of line-of-sight).

Two altitude simulation facilities were considered in the design of the system: the J-4 test cell at AEDC, Tullahoma, Tennessee, where test durations can be several hundreds of seconds and all spectroscopic components are inside the test cell; and the B-3 test cell at the Rocketdyne Nevada Field Laboratory where the test duration is two to three seconds and part of the spectroscopic apparatus is outside the test cell.

## ZONE RADIOMETRY SYSTEM

Figure 2 shows schematically how the major system components will be arranged at the two candidate engine test facilities. The location of the spectroradiometer with respect to the test cell is dictated primarily by space considerations at the two facilities.

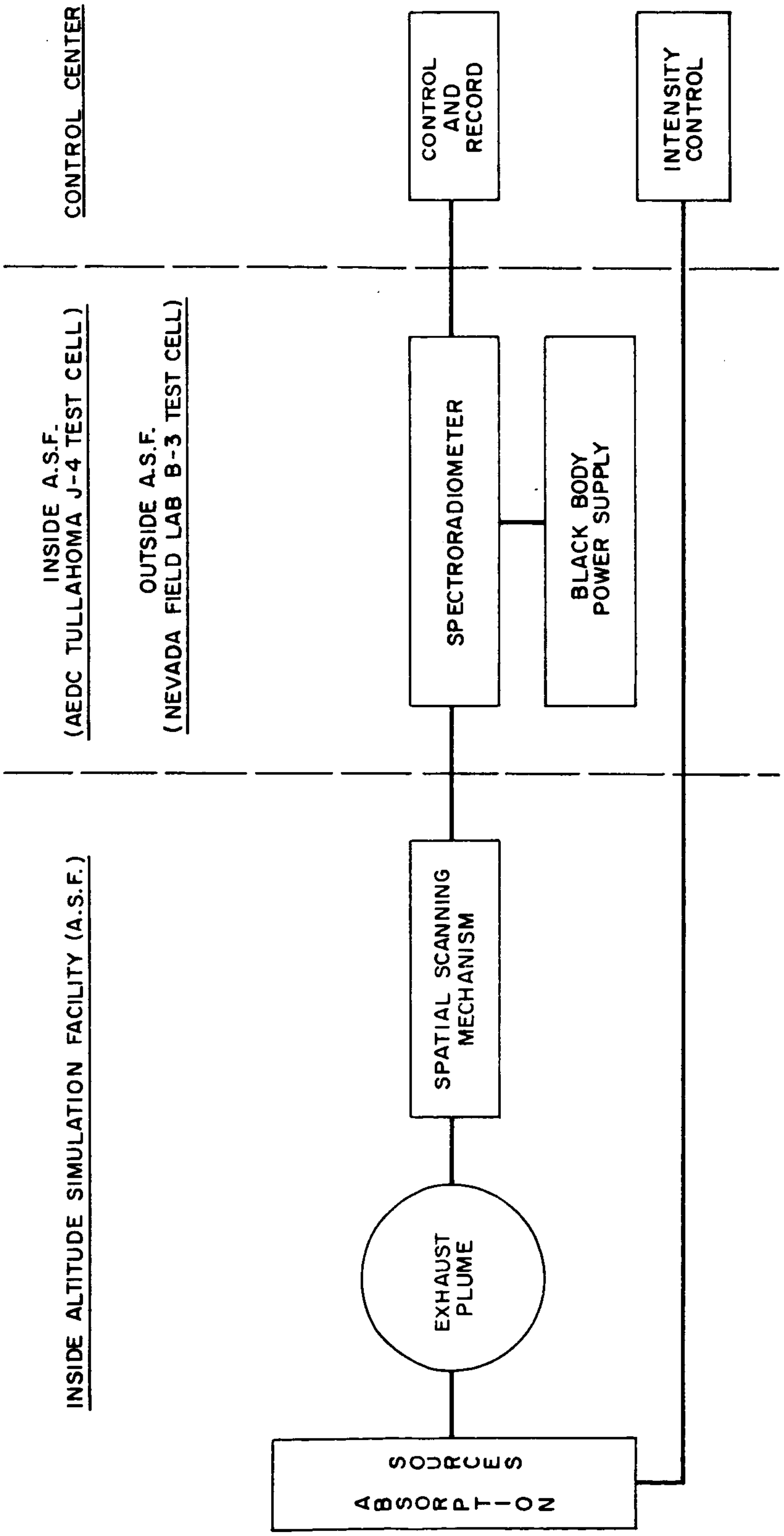


Figure 2. Block Diagram of Dual Channel Infrared Spectroradiometer System.

## SPECTRORADIOMETER

Figure 3 is an optical diagram of the spectroradiometer. Figure 4 is a photograph of the spectroradiometer and also the major recording and control consoles. Radiation from the exhaust and/or absorption sources is directed by the tracking flat, $M_1$, to an 18 degree off-axis parabola, $M_2$. Flat $M_3$ directs the converging light rays from the parabola to a focus on the monochromator entrance slit. The monochromator is a Perkin-Elmer Model 98-G equipped with a 240 grooves/mm grating and a PbS detector. A wide band germanium filter, $F_1$, is used to filter out unwanted short wavelength radiation. An optical chopper with reflective surfaces allows radiation to be time shared between the monochromator (high resolution channel) and a low resolution channel. In the low resolution channel, radiation transmitted by an aperture, A, and narrow band interference filter, $F_2$, is focused onto a PbS detector by elliptical mirror $M_4$. Blackbody radiation is brought into the two channels for an intensity calibration by mirrors $M_3'$ and $M_2'$; $M_1$ is moved to position $M_1'$ during the calibration. All mirrors are first surface, aluminized, and overcoated with silicon monoxide.

During zone radiometry experiments, the monochromator will transmit a fixed wavelength to the detector. If desired, spectral scans of the exhaust plume emission or transmittance may also be made. The maximum resolution of the monochromator is approximately 0.3 $cm^{-1}$ at 2.5 microns. However, the brightness temperature of exhaust plumes at simulated altitudes is probably not sufficient to allow use of slits narrow enough to achieve 0.3 $cm^{-1}$ resolution and maintain a good signal-to-noise ratio. It should be possible to achieve a working resolution of about 1 $cm^{-1}$.

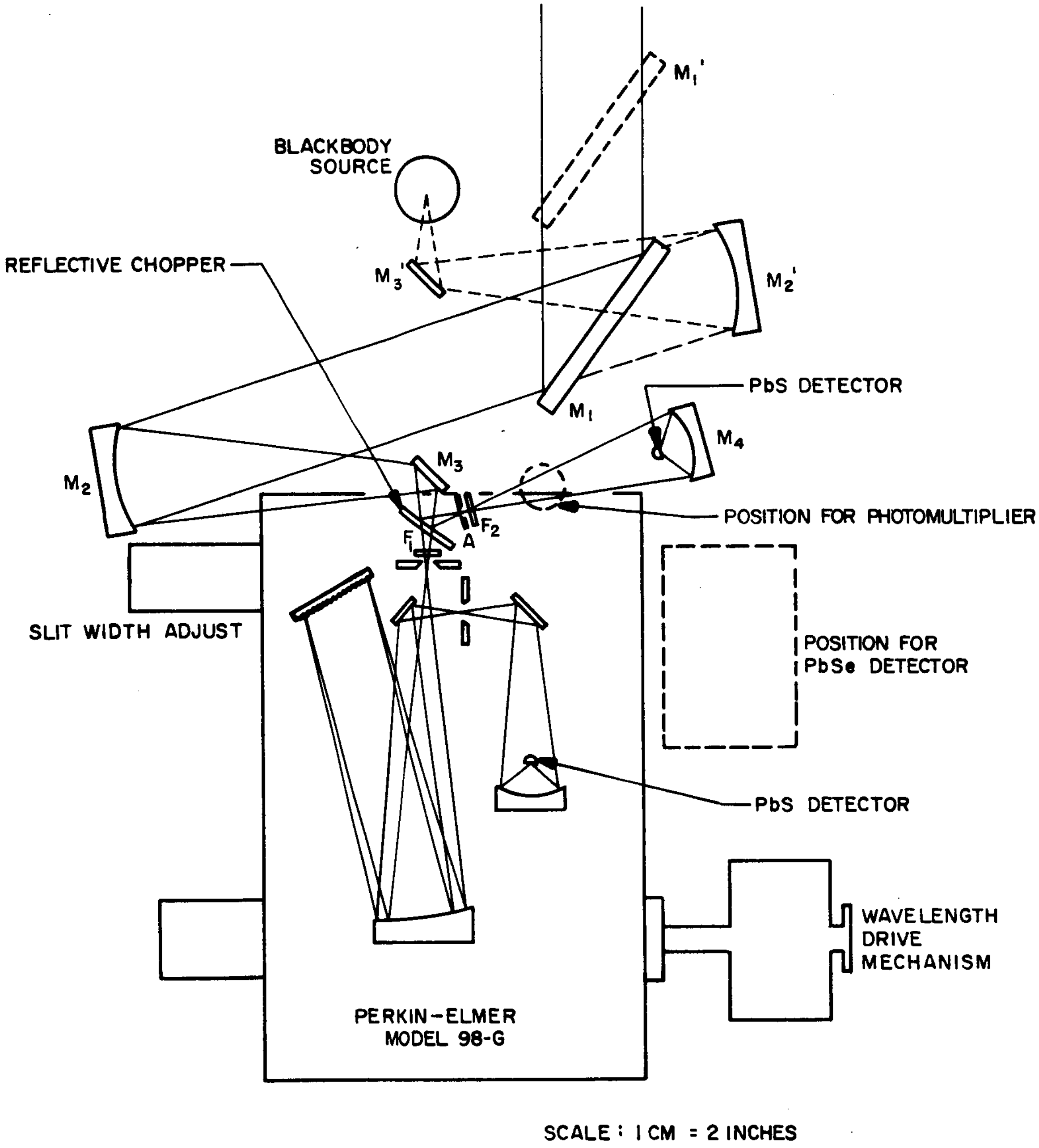


Figure 3. Optical Diagram of the Spectroradiometer.

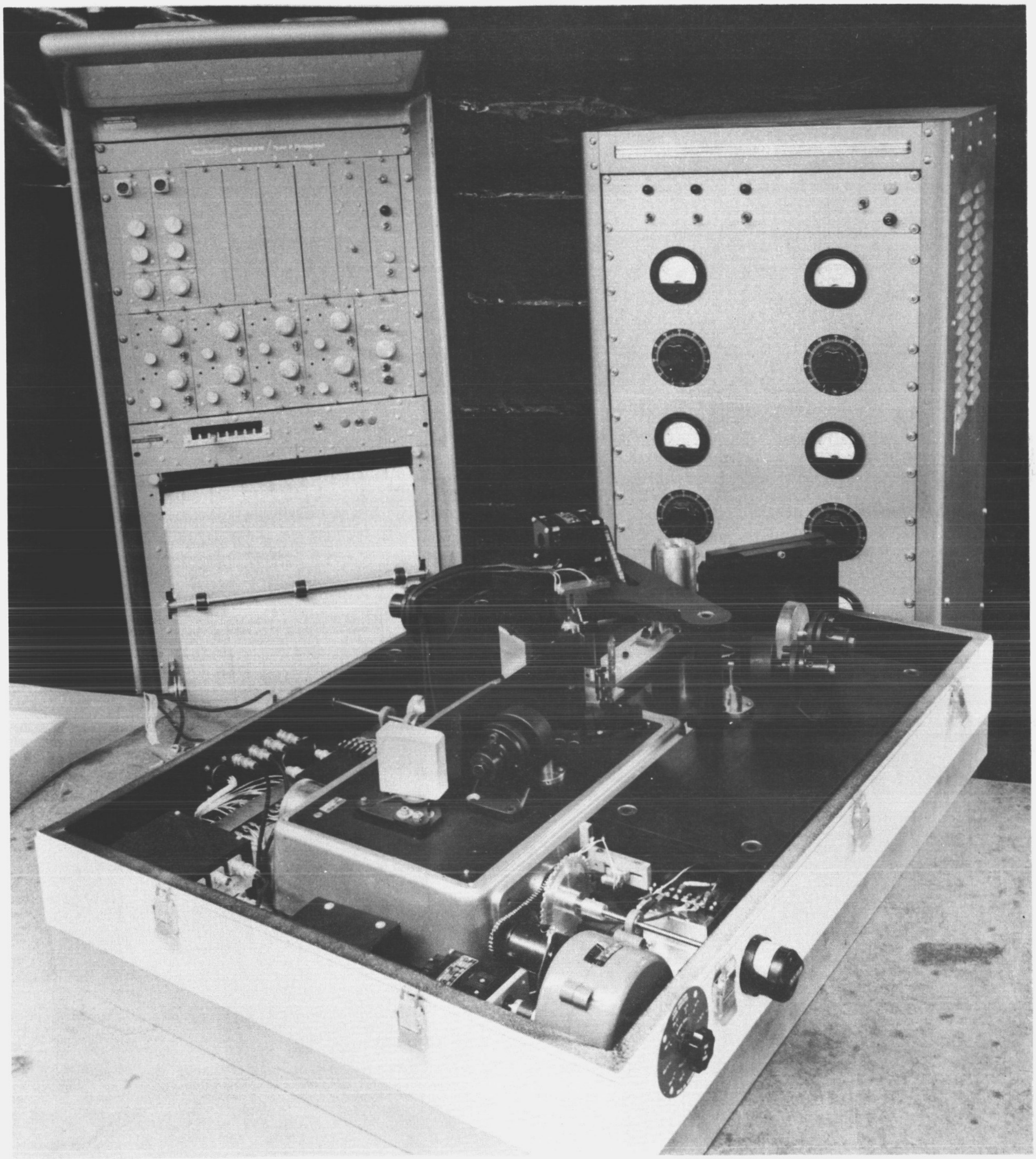


Figure 4. Photograph of the Spectroradiometer and Recording and Control Consoles.

The PbS detector allows coverage of the approximate spectral range 0.8 to 3.5 microns by the high resolution channel. Sufficient space has been preserved for addition of a photomultiplier (to extend coverage down to 3000 Angstroms) or a liquid nitrogen cooled PbSe detector (to extend coverage up to 7.5 microns).

The spectroradiometer has been assembled on a 28 x 38 inch ribbed aluminum baseplate. The instrument has been designed so that the internal pressure will be equal to ambient pressure (working range from one atmosphere to one millimeter of mercury). When operated at atmospheric pressure, the instrument will be purged with dry nitrogen to eliminate the effects of atmospheric water vapor absorption in the 2.5 micron spectral region (where the exhaust species HF and $H_2O$ radiate). Electrical power, cooling water, and purge argon are brought in to the blackbody through the baseplate. All other electrical and mechanical connections are made through an apron that is permanently attached to the baseplate. The tracking flat is moved manually through a port provided in the removable spectroradiometer cover.

## SPATIAL SCANNING AND ABSORPTION SOURCE SYSTEM

The spatial scanning and absorption source system has been designed with two particular rocket engine test facilities in mind: The J-2 nozzle exit is 80 inches in diameter and the test duration is as long as 150 seconds; the NFL site can accommodate engines with nozzle exit diameters as large as 40 inches and tests typically consist of three or four three-second firings over a period of about 100 seconds. The J-2 is fired vertically while engines at NFL are fired horizontally. In spite of these differences, the system is equally adaptable to either facility.

The spatial scanning and absorption source system arrangement as envisioned for the Nevada Field Laboratory is shown schematically in Figure 5. The absorption sources consist of ten individually housed tungsten ribbon filament lamps. For either test site the lamps will be equally spaced across the primary scan angle which encompasses lines of sight from a diameter to the exhaust plume edge. The scanning mirrors, $S_1$ and $S_2$, are different for each test facility, but are used with the same scanning mirror motor and mount, relay mirror, and housing.

## Absorption Sources

Each absorption source package consists of a tungsten lamp and transformer housed in a vacuum tight cylindrical can. A lens, mounted in a snout attached to the can, provides optical access.

Tungsten lamps with glass envelopes rather than quartz were chosen for the absorption sources. The glass envelope transmits a minimum of 50 percent of the filament radiation from 0.31 to 3.4 microns. Lamps with quartz windows transmit over a somewhat wider wavelength range, but cost six times as much as the glass envelope lamp. A glass lens will be used with each lamp to form a five times enlarged image of the lamp filament in the region of the exhaust plume. At NFL a thin sapphire window will be mounted in front of each lens to prevent exposure of the lens to hydrogen fluoride or other corrosive exhaust products.

The intensity of each lamp is individually adjustable to insure the most advantageous conditions (see data reduction section) for the absorption-emission measurements. The lamps operate at 3.5 volts and 30 amps maximum. A transformer mounted in each lamp housing converts

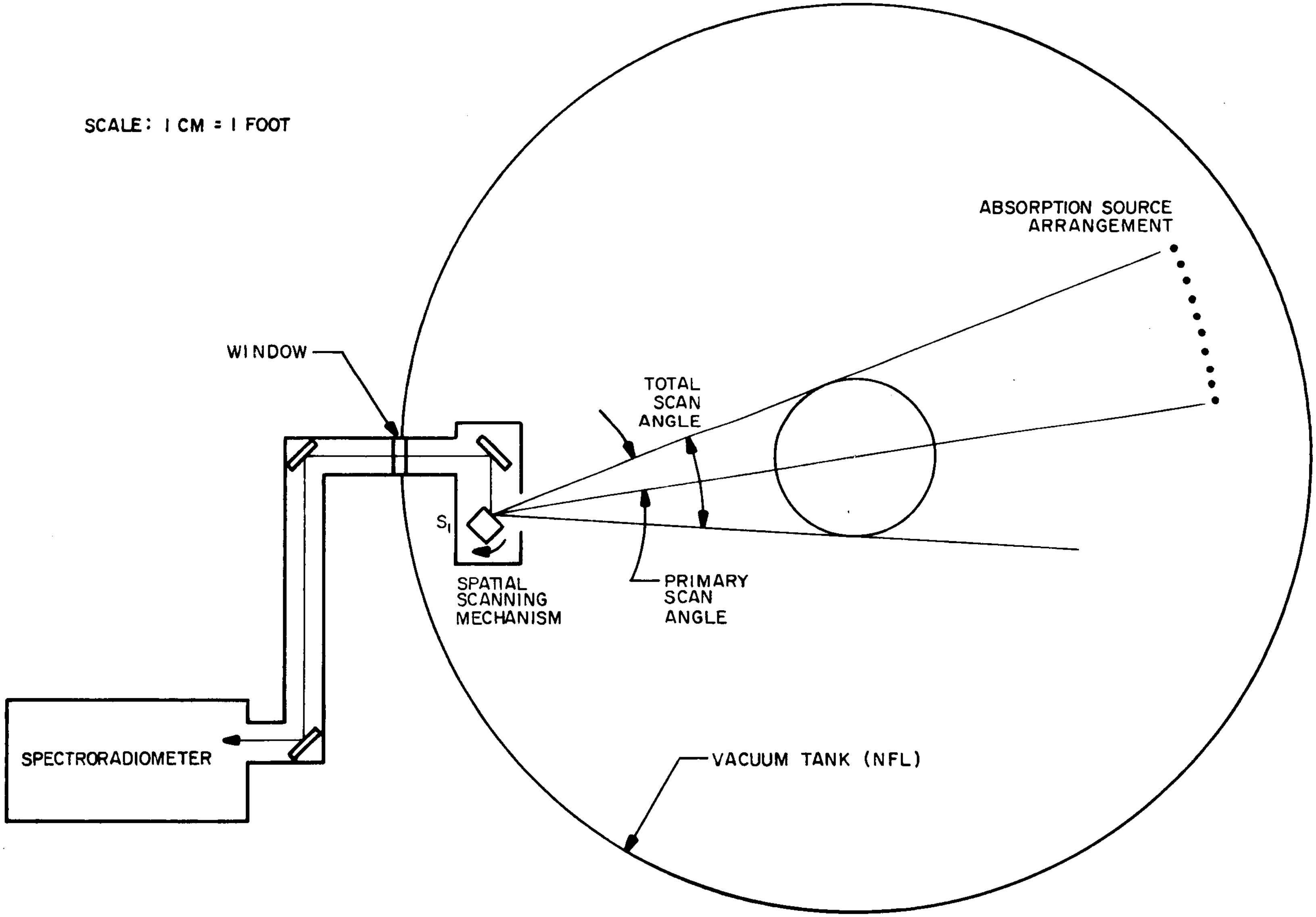


Figure 5. Arrangement of Spatial Scanning Mechanism and Absorption Sources at Nevada Field Laboratory.

110 volts at 1 amp (maximum) to the desired values; lamp intensity is remotely adjustable from the test site control center. The lamp housings will be vacuum tight with atmospheric pressure being maintained in the housings at all times. The lamp windows will be purged with nitrogen and covered by shutters during ignition and shutdown of the rocket engine. A single lamp, housing and control circuit are shown schematically in Figure 6a.

### Spatial Scanning Mechanism

The spatial scanning mechanism provides the variation in line-of-sight necessary for zone radiometry measurements. The instrument is shown schematically in Fig. 6b. The design of the spatial scanning mechanism was based on three primary considerations: Test duration, scan angle, and width of light beam at the scan mirror. The scan mirror for NFL ($S_1$, Figure 6b) was fabricated from a two-inch pyrex cube with four reflective surfaces; either four or eight scans of the plume can be made in one second. The J-2 scan mirror has two reflective surfaces (5 x 3 inches) and will scan the plume at rates of one per second or one per four seconds. In Figure 5 it can be seen that the primary scan angle covers one-half of the exhaust plume, i.e., from a diametrical line-of-sight out to the plume edge. Across this primary scan angle both emission and absorption measurements will be made (as discussed in the data reduction section). The remaining half of the plume will also be scanned in emission only. Comparison of the line-of-sight radiance profiles of the two halves of the exhaust plume will serve as a check on the radial symmetry of the plume.

The scan mirror is driven by a 50 rpm synchronous motor through pulleys and a drive belt. Different scan speeds than those mentioned above can be obtained by substituting various pulley combinations. A coded wheel mounted on the scan mirror drive shaft produces a signal at the

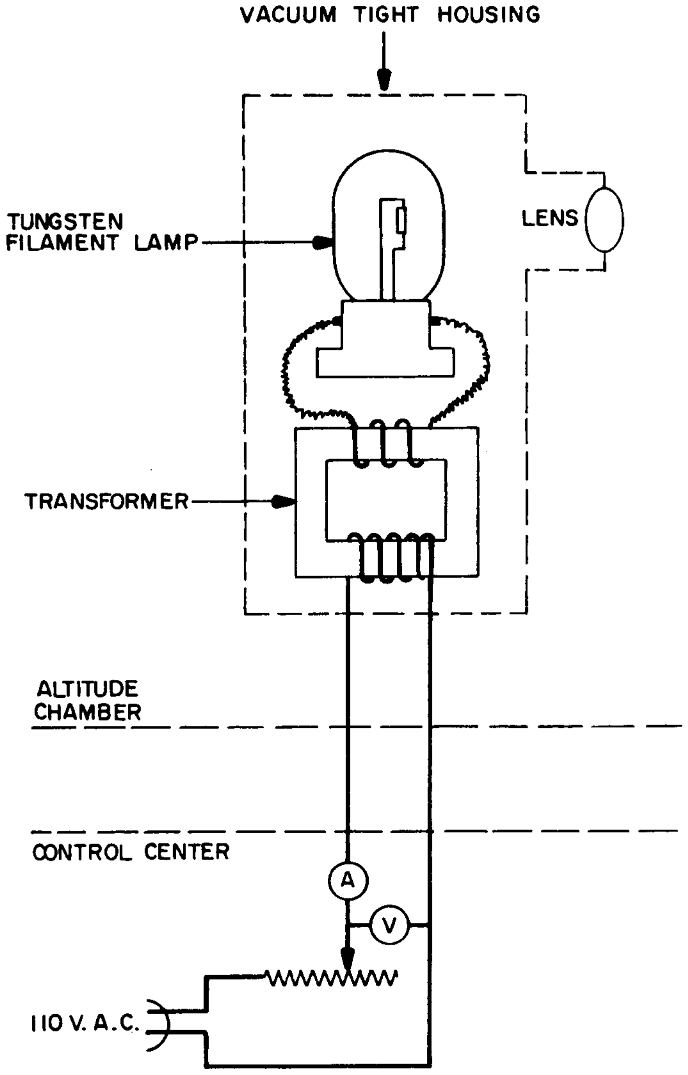


Fig. 6a. Absorption Source Housing and Control Circuit.

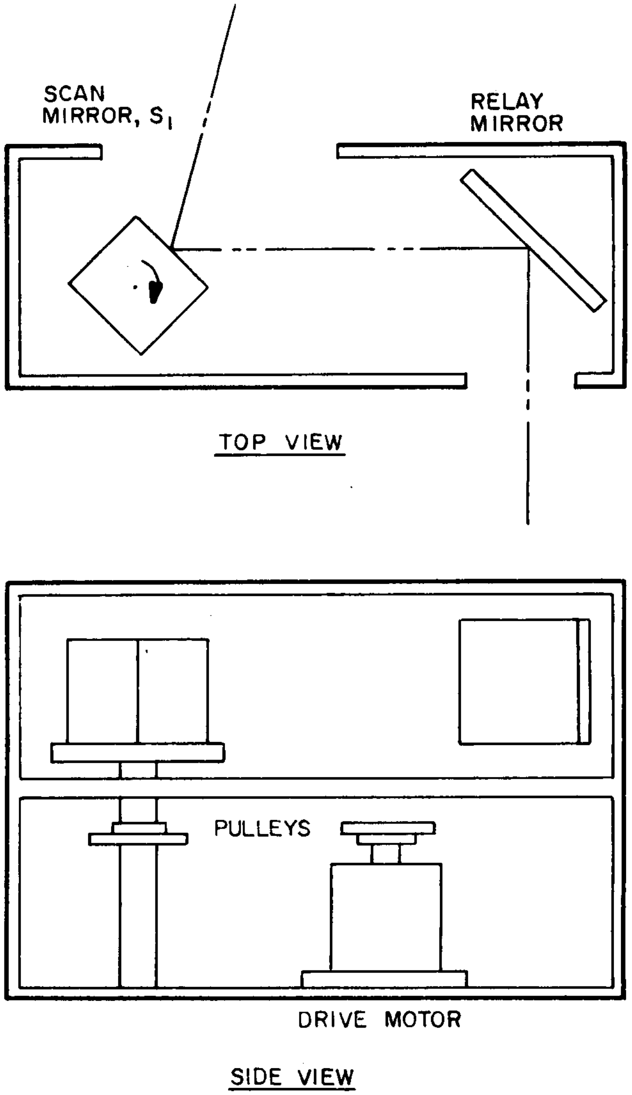


Fig. 6b. Spatial Scanning Mechanism.

recorder for positive identification of scan angle. The spatial scanning mechanism is housed as indicated in Figure 6b. The opening in the side of housing through which the plume is scanned will be covered by a remotely operated shutter during motor ignition and shutdown.

## ELECTRONIC, RECORDING, AND CONTROL SYSTEMS

The electronic and recording system assembled for the spectroradiometer is basically identical with that used in previous zone radiometry programs. Data will be recorded on an eight-channel strip chart recorder. Six channels will be used to record detector output - three channels at different amplifications for each detector. One channel will record a timing signal from the spatial scan system to indicate accurately the scan angle. The remaining channel will record a wavelength calibration signal during spectral scans. Provision is made to operate the entire spectroradiometer system either at the recorder location or at a remote location if the recorder is not located in the test site control center. All signal processing and recording electronics are mounted in a single relay rack. The power supplies for the ten absorption sources, the power switch for the spatial scan mechanism, and the shutter controls for the above are mounted in a separate relay rack. These two consoles were shown in Figure 4.

A third console houses the blackbody power supplies and controls. These controls include two flow switches installed in the argon purge line and the water cooling line, respectively. Should the argon or water flow rates drop to levels which could endanger the life of the blackbody, power is automatically shut down. Figure 7 shows schematically the recording and control systems and their relationship to other system components.

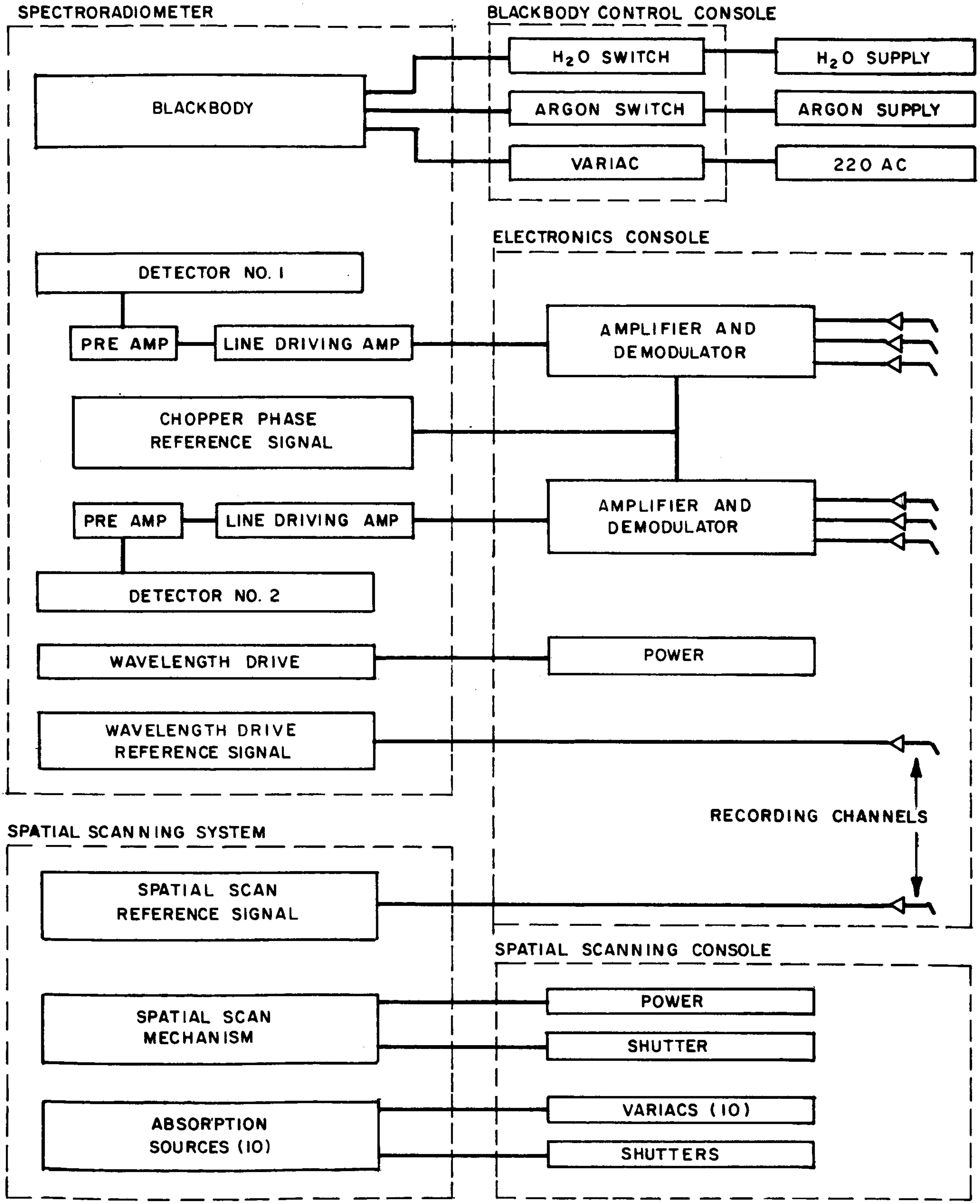


Figure 7. Schematic of Electronic, Recording, and Control Systems.

## DATA REDUCTION

Previously developed zone radiometry systems employed two optical choppers, one located between the absorption source and the exhaust plume, and the other between the plume and the detector. Emission and absorption were measured on successive scans of the plume with only the appropriate chopper being activated for each scan. In this double-chopper method, plume spectral radiance and spectral emissivity are measured independently. The double-chopper method is not suitable for use in this present system because of the use of multiple absorption sources, relatively short test durations, and the desire to time share incoming radiation with two detectors.

As was seen in Figure 3, the present system uses a single optical chopper. In this case, as the scanning mirror rotates through the primary scan angle during a firing, the recorder pen deflections alternately represent first line-of-sight (LOS) plume spectral radiance and then LOS plume spectral radiance plus the absorption source radiation transmitted along that LOS. A typical recorder trace would appear as shown in Figure 8. Note that to obtain $D_n$ and $D_{n+\tau}$ for identical lines of sight, a value of $D_n$ must be interpolated from values obtained for adjacent lines of sight. Pen deflections are proportional to spectral radiance, and the above deflections may be converted to radiance values by comparison with pen deflections produced by the blackbody calibration source at known temperature. The LOS spectral emissivity is obtained from $D_n$, $D_{n+\tau}$ and from the pen deflection produced by scanning the absorption sources when unattenuated by plume radiation ($D_\tau$) in the following manner: Since radiance is proportional to pen deflection,

$$D_{n+\tau} = D_n + D_\tau (1-\epsilon_{los})$$

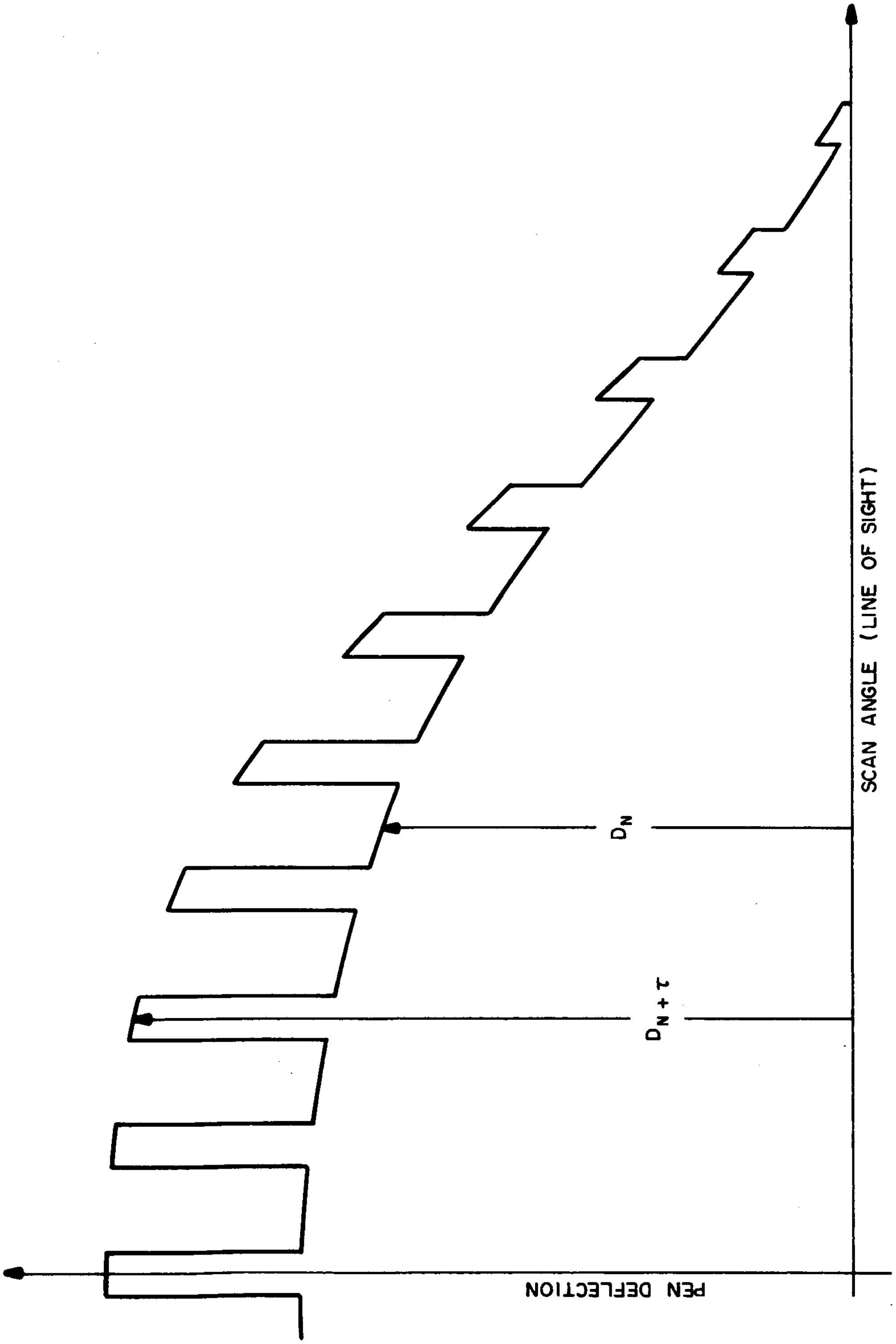


Figure 8. Typical Recorder Trace That Would Be Obtained During Zone Radiometry Measurement.

from which

$$\epsilon_{los} = 1 - \frac{D_{n+\tau} - D_n}{D_\tau}$$

If $D_n \gg D_\tau$ or $D_\tau \gg D_n$, the above expression becomes inaccurate; thus provision has been made to adjust the intensity of the various absorption sources so that their brightness temperature is the same order of magnitude as the corresponding LOS radiance.

The required experimental data (line of sight values of plume spectral radiance and spectral emissivity) are now ready for input to an existing computer program which calculates the radial distributions of temperature and the product of absorption coefficient and partial pressure. This computer program has recently been revised to allow the use of band model parameters if desired.

## CHECKOUT AND EVALUATION

The primary objectives of a checkout and evaluation of any spectroradiometer are determination of the following:

(1) Stray light level
(2) Wavelength calibration
(3) Spectral resolution
(4) Intensity calibration.

The spectroradiometer has been used in a brief study of the well-known atmospheric absorption lines of $H_2O$ as part of the evaluation procedure. The final intensity calibration of the spectroradiometer must be made when installed at a test site, so that the effect of all mirrors and windows in the optical path may be taken into account. The checkouts and evaluations already completed and those still to be performed are described below.

The determination of stray light levels, wavelength calibration and spectral resolution are straightforward and are carried out by studying the absorption spectrum of a known gas. The results of this determination are shown in the spectrum reproduced in Figure 9. This spectrum is a portion of the 2.7 micron absorption band of atmospheric $H_2O$ recorded with a slit width of .05 mm. The internal blackbody source operated at a temperature of 1800 degrees Kelvin was used in this experiment; the resulting path length was 2.2 meters.

## Stray Light.

Stray light evidences itself as radiation of unwanted wavelengths reaching the detector simultaneously with desired radiation. The principal effect of stray light is to cause erroneous transmittance measurements if it is not eliminated or taken into account in data reduction procedures. The stronger absorption lines in the 2.7 micron atmospheric $H_2O$ band absorb essentially 100 percent at their line centers at a path length of 2 meters. Thus, any difference between pen deflection at the center of these lines as compared with the pen deflection obtained when an opaque card is inserted in the light beam indicates the presence of stray light. It is seen that essentially no stray light is present in Figure 9a.

## Wavelength Calibration.

Wavelength calibration is obtained by comparison of known spectral line positions, such as those in atmospheric $H_2O$, with the drum turn calibration signal seen in Figure 9b. The wavelength drive is linear in drum turns and microns, and a wavelength calibration curve can be drawn up.

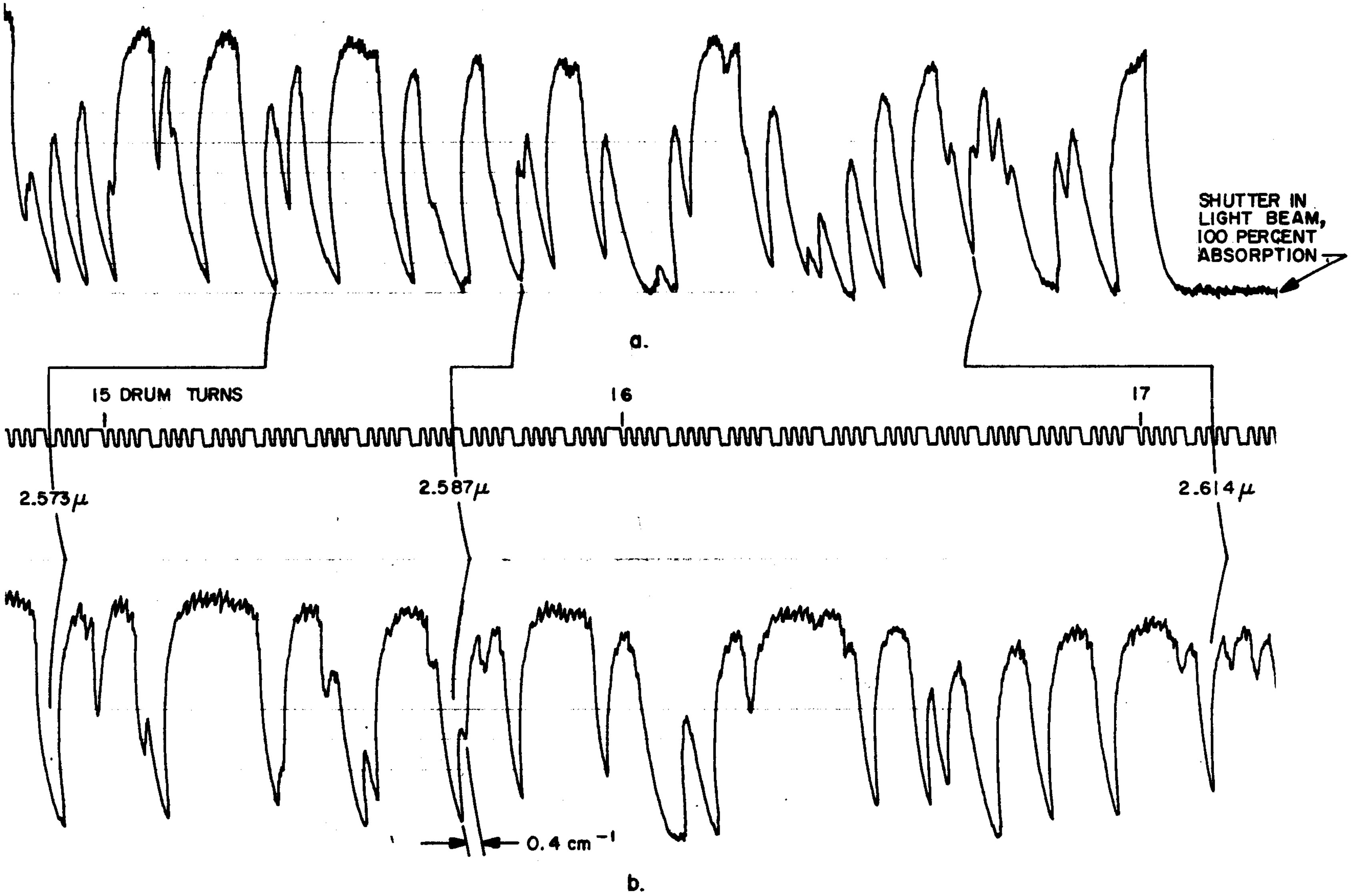


Figure 9: Atmospheric $H_2O$ Absorption: a. Humid Air Recorded to Show Maximum Absorption;
b. Dry Air Recorded to Show Maximum Resolution.

Spectral Resolution.

The spectral resolution of the spectroradiometer is indicated by the 0.4 $cm^{-1}$ separation of the spectral lines at 2.58 microns. This resolution, obtained at a signal-to-noise ratio of approximately 13, is consistent with that stated by the manufacturer of the monochrometer.

Intensity Calibration.

An intensity calibration of the spectroradiometer requires the measurement of the radiation intensity as a function of wavelength of an external source of known spectral radiance using the internal blackbody calibration source. This is done by obtaining the emission spectrum of both sources over the wavelength region of interest. Since spectral radiance is proportional to pen deflection, the spectral radiance of the external source can be determined at any wavelength by multiplying the ratio of pen deflections of external source to blackbody source by the blackbody spectral radiance at that wavelength. Prior to performing this measurement, it must be verified that both sources fill the field of view of the monochromator, as determined by the grating and entrance slit aperture.

The difference between the measured spectral radiance and known spectral radiance of the external source is used to calculate an intensity correction curve for the spectroradiometer. In a properly aligned instrument this difference is due to a difference in transmission or reflectivity of the various optical components in the blackbody and external source optical paths. Therefore, the final intensity calibration must be carried at the test site with the source of known intensity located in the region of the rocket exhaust plume.

A preliminary intensity calibration can be carried out in the laboratory to determine if the intensity correction curve is significantly wavelength dependent and if the angle of incidence onto the scanning mirror affects intensity measurements. Unfortunately, the scanning mirrors are approximately one and one-half months late in delivery, and the laboratory intensity calibration has not been carried out.

## RECOMMENDATIONS

It is recommended that this newly developed instrumentation system be used to study the exhausts of "full size" rocket engines. Two particular rocket engine firing programs have been considered as subjects for study by zone radiometry: the J-2, $LO_2/LH_2$ tests being conducted in the J-4 altitude simulation test cell at AEDC, Tullahoma, Tennessee; and the 2000-pound-thrust engine tests using space storable propellants such as $FLOX/CH_4$, $FLOX/B_2H_6$, and $OF_2/B_2H_6$ which are expected to be conducted in an altitude simulation facility at the Rocketdyne Nevada Field Laboratory.

The J-2 exhaust is of interest because this engine is operational and the data obtained would be of value in confirming the calculated radiative heat transfer to the components of vehicles using this engine. Studies of the exhausts of engines using the space storable fluorine containing oxidizers are of interest since these engines are still in developmental stages, and the information learned in the zone radiometry studies will be useful in the design of such engines. The information obtained will also be of value in heat transfer calculations for exhausts containing fluorine compounds.

It is felt that zone radiometry data should be taken on both the J-2 and the space storable exhausts. Because little is known about the exhausts of engines using space storable propellants, the main emphasis, from the standpoint of the number of tests monitored under various engine operating conditions, should be placed on studies of these propellants.

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