A NEW FOUR-CHANNEL SCANNING SPECTROMETER FOR BALLISTIC-RANGE RADIOMETRY

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ABSTRACT

A new moving-source scanning spectrometer for use in ballistic-range radiometry is described. This instrument uses the radiating gas cap of ballistic-range models as the source and entrance slit and develops a scan across the spectrum from 2,000 to 10,000 Å by virtue of the model motion along its flight path. The spectral resolution for full spectral coverage varies between 10 and 100 Å, depending on gas-cap thickness and test-section window size. The instrument has been calibrated spectrally for both wavelength and intensity. Sample experimental results are shown.

INTRODUCTION

The ballistic range has been a valuable tool for experimental study of atmospheric entry aerodynamics and heating for several years. Recently, the utility of the ballistic range has been extended to the study of gas kinetics, molecular physics and gas radiation. In these latter applications it is necessary to observe spectrally the radiation emitted from the gas cap formed ahead of the model. Several spectrometric techniques have been used for this task; however, most of these have serious limitations. For example, a spectrograph gives excellent spectral resolution, but the time available for exposure, normally a microsecond or less, is not generally sufficient for exposure of photographic film. Narrow band-pass radiometers using phototubes have good response characteristics but give poor spectral coverage unless very large numbers of radiometers are used or large numbers of tests are performed with radiometers where wavelengths are variable. There is, however, one instrument for spectral data acquisition ideally suited to ballistic-range testing that has good response, good spectral coverage, and reasonable spectral resolution. This instrument is called a moving-source scanning spectrometer. The purpose of this paper is to discuss the essential features of this type instrument and describe a four-channel instrument in operation at Ames Research Center.

PRINCIPLE OF OPERATION

A moving-source scanning spectrometer is simply one that uses the source itself as the entrance slit and develops a scan across the spectrum by virtue of the motion of the source. In December of 1959, Messrs. Woodcock and Jones of the Perkin-Elmer Corporation suggested to St. Pierre of CARDE[1] that the luminous gas cap of blunt-nosed models at hypersonic speeds in ballistic-range tests would provide a good moving source for this type instrument. Proof of this observation is shown in Fig. 1, which is a self-luminous picture taken from the side of a blunt-nosed model flying at 7.9 km/sec into air at about 0.1 atmospheric pressure. This picture was taken by an image-converter camera with an exposure time of 0.1 μsec. Clearly, the gas cap, as viewed from the side, appears much like an illuminated curved slit, indicating the moving-source scanning principle is applicable. Spectral resolution in any spectrometer depends on the width of the entrance and exit slits. The width of the entrance slit in this case is the width of the gas cap; hence, spectral resolution will depend on model size. If other regions of the flow field, such as the wake, were luminous, the moving source would be extensive and the moving-source scanning concept would be of little, if any, value for spectral detail.

The principle of operation of a moving-source scanning spectrometer is illustrated in Fig. 2. The model is shown at a point in its flight past the window in the test section. At any instant the instrument acts as a normal monochromator; that is, the spectrum dispersed by the grating is focused, and a slit in the focal surface lets a small portion of the spectrum fall on the photocathode of a multiplier phototube. The scanning feature of the instrument is introduced by the model motion along the flight path. As the model moves, the spectrum moves and, consequently, is swept past the exit slit. The variation in intensity across the spectrum is sensed by the phototube and recorded directly on film via an oscilloscope.

PRIOR ART

The first known instrument of this type developed for ballistic-range radiometry was constructed in 1960 by Mr. St. Pierre of CARDE.[1] His instrument covered the spectrum from 4,000 to 6,000 Å with 40 Å resolution. A second instrument was made in 1962 at Ames Research Center of the NASA by Messrs. Victor Reis,[2] Roger Craig, and William Page, by modifying a Ferrand UV-VIS grating monochromator. This instrument covered the spectrum from 2,900 to 4,300 Å with 100 Å resolution. The present author has built instruments with 5 Å resolution, but with only 200 Å spectral coverage. Mr. David Cooper of Ames has built an instrument with 25 Å resolution and 1,000 Å spectral coverage.[3] The success of these instruments and the increasing demand for gas-cap spectra with reasonable resolution encouraged the design of the present instrument. The design goal for this instrument was to cover the spectrum from 2,000 to 10,000 Å and maintain reasonable spectral resolution. The design considerations that led to choosing a four-channel concept for the design are discussed in the next section.

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DESIGN CONSIDERATIONS

The principal factors affecting the design of a particular instrument are spectral resolution and spectral coverage, from an optical viewpoint, and signal-to-noise ratio and rise time, from the electronic viewpoint. Spectral coverage was the primary constraint, because the main purpose of the present instrument was to cover the spectrum from 2,000 to 10,000 Å. Note in Fig. 2 that the relative orientation of the grating, the focusing mirror, and the exit slit is fixed. Therefore, the diffraction angle that directs light from the grating to the slit is fixed. This fact simplifies the use of the grating equation in explaining the factors affecting spectral coverage. Fig. 3 illustrates the optical factors involved. Equation (1) in this figure shows that the spectral coverage $\Delta\lambda$ is given, approximately, by the product of the angular sweep Δi and the distance between rulings on the grating. In ballistic ranges, window size usually limits the sweep angle to less than 10°. Therefore, to produce the desired 8,000 Å scan by a single channel would require b = 40,000 Å, corresponding to a grating with 250 lines/mm. The number of lines/mm has a strong effect on the spectral resolution as shown by Eq. (3) in the lower part of Fig. 3. This equation shows that spectral resolution is improved by using a grating with as many lines/mm as possible. Good replica gratings with 600 lines/mm are available and economical. However, with a 600 line/mm grating and Δi still restricted to 10°, the spectral coverage given by Eq. (1) is only about 3,000 Å. To cover the required 8,000 Å would then require more than one channel.

Spectral coverage must also be considered from the standpoint of instrument sensitivity, including grating efficiency and phototube response. Grating efficiency is enhanced by blazing for a particular wavelength, but the efficiency decreases rapidly at wavelengths away from the blaze wavelength. The response of the photocathode of the multiplier phototube further restricts spectral coverage, since each surface has good response over a limited spectral region. For these reasons a multiple-channel instrument appeared best to provide the wide spectral coverage with good response and to achieve reasonable resolution. There is, in addition to the optical requirements, the requirement that the electronic rise time be short enough to follow the signal increase as the model image crosses the exit slit. This is directly related to the time required for the model to move a distance given by the radiating gas-cap thickness. In the Ames facilities the minimum gas-cap thickness of interest is about 1 mm and the maximum velocity is about 10 mm/μsec. Therefore, the rise time must be less than 100 nsec.

FINAL DESIGN

The considerations discussed in the prior section led to the selection of a four-channel concept for the instrument design. Each channel has its own grating, focusing mirror, phototube, and associated electronics and covers a spectral range of 2000 Å for full spectral coverage. The gratings selected have 600 lines/mm and the spectral resolution for full spectral coverage varies from 10 to 100 Å, depending on gas-cap thickness (model size) and window width in the test facility. Resolution can be increased by using a longer focal length collimating mirror and moving the instrument away from the flight path. The enhanced resolution is obtained at the expense of the phototube signal which becomes weaker, and the resolution is ultimately limited by the signal-to-noise ratio of the system. In addition, the spectral coverage is limited when the instrument is moved back from the flight path as a result of vignetting at the test-section window. However, the entire spectrum can be swept out on successive tests.

A plan view of the completed instrument is shown in Fig. 4. Photographs of the instrument are shown in Figs. 5, 6, and 7. The voltage-divider amplifiers were designed by Mr. Donald Humphry of the Ames' Electronics Research Branch. The circuit design for these components is shown in Fig. 8. The amplifier is a current amplifier with a current gain of 100. The detectors used are 2.0-inch-diameter DuMont 10-stage photomultipliers with S-1, S-11, S-13, and S-20 surfaces. The rise time of the combined photomultiplier, voltage-divider, amplifier system has been measured, with the S-1 surface, to be about 50 nsec, which satisfies the requirement of less than 100 nsec.

WAVELENGTH CALIBRATION

Relative wavelength calibration of the instrument was performed by moving a slit illuminated alternately with Hg, Cd, and Ne light past the instrument in the position of the model flight path. This calibration is described in Fig. 9. It was found to be impractical to fix the wavelength scale precisely before a test is made. Therefore it is necessary to identify one feature in the spectrum to establish the absolute wavelength scale. The gratings and focusing mirrors are fixed in position and a common collimating mirror is used for all four channels, which fixes the wavelength increment between channels. Therefore, if one line or band can be identified in any channel, the wavelength scales in all four channels are determined.

INTENSITY CALIBRATION

The response of the instrument was determined by calibration with an NBS calibrated tungsten filament lamp. This intensity calibration was performed from 2,500 to 11,000 Å and is shown in Fig. 10. The dotted curve shown from 1,700 to 2,700 Å was estimated by combining estimates of the spectral variation of quartz transmission, grating efficiency, and photocathode sensitivity and scaling these results to match the measured response at 2,700 Å.

The intensities recorded during the calibration were measured by chopping the incident beam from the standard lamp at 80 cps and using a synchronous amplifier for readout. During the calibration it was necessary to use extreme care to

minimize transient effects in the photomultiplier circuitry. When each reading was taken, the high voltage was applied to the voltage-divider circuit and a shutter opened to let the chopped light strike the photocathode. The integration time in the synchronous amplifier required from 3-5 seconds to attain a steady reading. After the reading was recorded, the high voltage was turned off and the shutter was closed. By this technique calibration values could be repeated within 10 percent. Conditions for test-data collection are somewhat different from the calibration conditions in that the test data are recorded as a pulse of 10-20 μsec duration. Therefore, in addition to the above procedure, it was necessary to measure the initial transient effects in the photomultiplier, voltage-divider, amplifier circuit and correct the calibration data to zero time.

SAMPLE EXPERIMENTAL RESULTS

The instrument described in this paper has been in operation at Ames Research Center for about one year. An experimental spectrum reduced from the oscilloscope traces recorded by the four channels is shown in Fig. 11. Test conditions and a mass spectrographic analysis of a gas sample taken from the test section approximately three minutes before the test are given in the figure. The spectral resolution for this test is about 25 Å. The most prominent features of this spectrum are the band sequences of CN(Violet) from 3,500 to 4,500 Å and CN(Red) from 6,000 to 10,000 Å. Also identifiable are two C_2(Swan) band sequences at 4,700 and 5,100 Å, the NH band at 3,360 Å and the OH bands at 3,100 Å. A group of atomic oxygen lines at 7,775 Å and the atomic carbon line at 2,478 Å are also evident.

Theoretical predictions, assuming chemical and thermodynamic equilibrium in the gas cap, are shown in this figure for NO(Gamma), CO(4+), C_2(Swan), CN(Violet), and CN(Red). The theoretical values were computed by Mr. Henry Woodward of Ames, using the average Q-branch approximation described in Ref. 4. The theoretical spectral features can, for the most part, be recognized in the experimental spectrum. The measured and calculated intensities of the CN(Red) and C_2(Swan) systems are in reasonably good agreement. The difference between the measured and calculated intensity of the CN(Violet) system has been shown to be due to photocathode saturation and to black-body limiting. A curve for 1/10 black-body radiation at the mean gas-cap temperature of 7,600° K and a projected area of 8.6 mm^2 is shown in the figure. The problem of photocathode saturation was eliminated in later tests and agreement between theory and experiment has been greatly improved. The difference between theory and experiment from 1,900 to 2,500 Å is believed to be due to uncertainties in the calibration in this spectral region, to black-body limiting, and perhaps to the high f number used in calculating the intensity of the CO(4+) system. The f numbers used in the calculations are shown in table I. This figure demonstrates the utility of this instrument for identifying radiating species in the gas cap and measuring the radiant power emitted if proper care is used in calibration and testing.

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2. Reis, Victor H.: Oscillator Strengths for the N_2 Second Positive and N_2^+ First Negative Systems From Observations of Shock Layers About Hypersonic Projectiles. J. Quant. Spectr. Radiative Transfer, vol. 4, no. 6, 1964, p. 783.

3. Cooper, David M.: High-Resolution Experimental Spectra and Theoretical Studies of Equilibrium Radiation From a Blunt Body Traveling at 37,000 Ft/Sec. AIAA Paper 66-104.

4. Williams, M. J.; and Treanor, C. E.: A Method for Calculating Diatomic Spectra Using a Digital Computer. Rep. QM-1626-A-5, Cornell Aero. Lab., 1962.

TABLE I.- F NUMBERS USED IN THEORETICAL SPECTRA COMPUTATIONS SHOWN IN FIGURE 11

Species	F number
CN_V	0.02*
CN_R	.0072
C_2(Swan)	.034
CO(4+)	.15

*Corresponds to a heat of formation = 8.2 eV

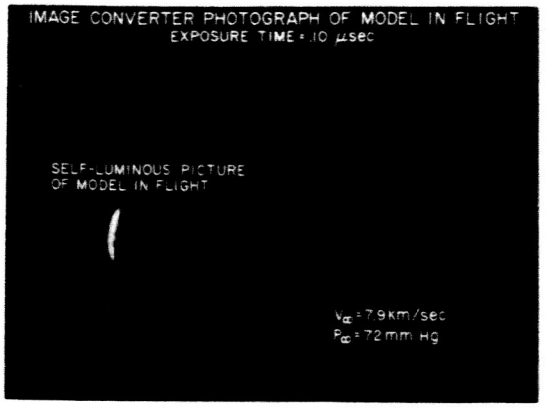

Fig. 1.- Image converter photograph of model in flight (exposure time = 0.10 μsec).

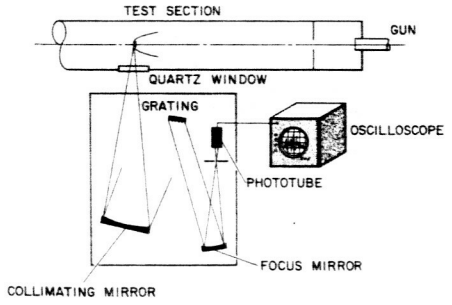

Fig. 2.- Diagram of moving source scanning spectrometer.

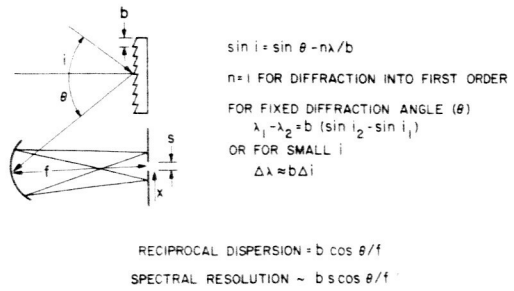

Fig. 3.- Factors affecting spectral coverage and resolution.

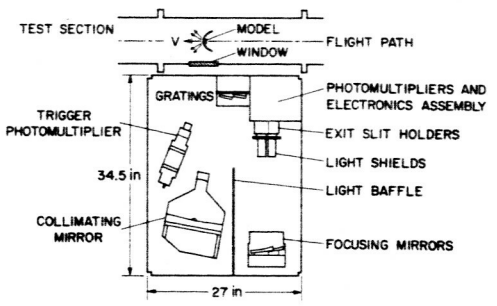

Fig. 4.- Four-channel spectrometer.

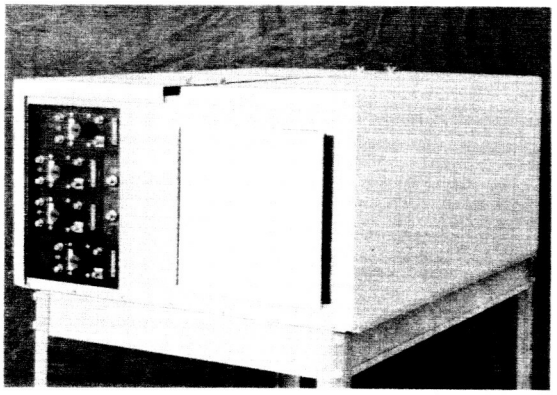

Fig. 5.- Scanning spectrometer.

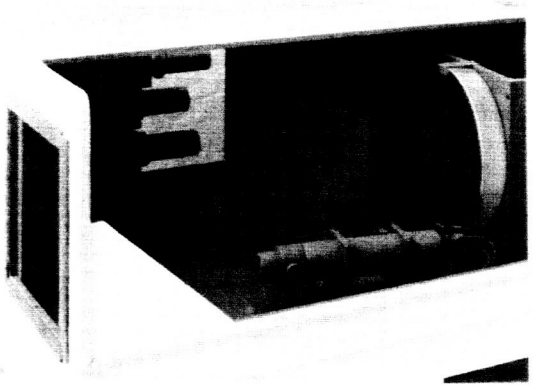

Fig. 6.- Scanning spectrometer, entrance port, trigger phototube, and collimating mirror.

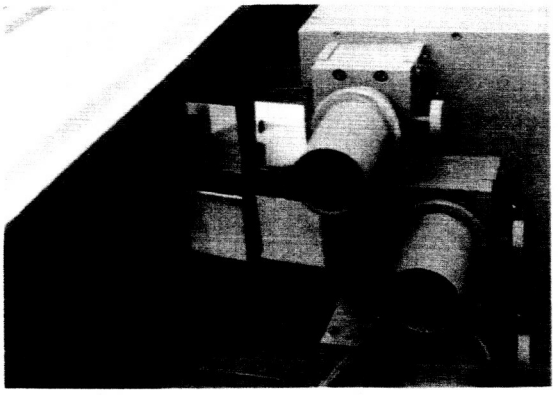

Fig. 7.- Scanning spectrometer, gratings.

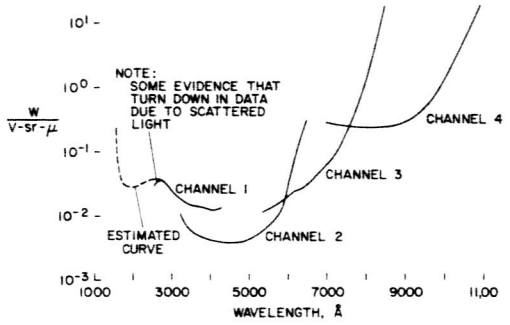

Fig. 10.- Intensity calibration of scanning spectrometer adjusted to high voltage = 1000 V.

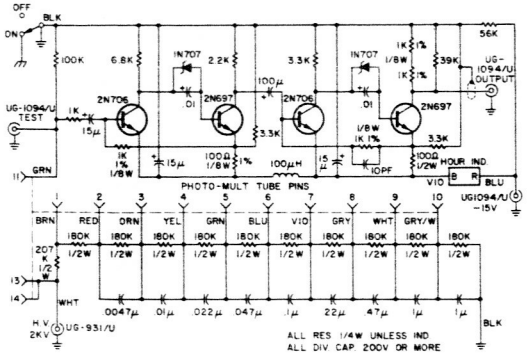

Fig. 8.- Voltage-divider, amplifier circuit.

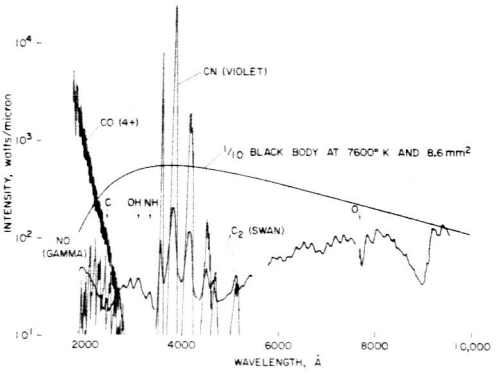

Fig. 11.- Experimental spectrum recorded by four-channel scanning spectrometer compared with theoretical spectrum calculated for equilibrium conditions.

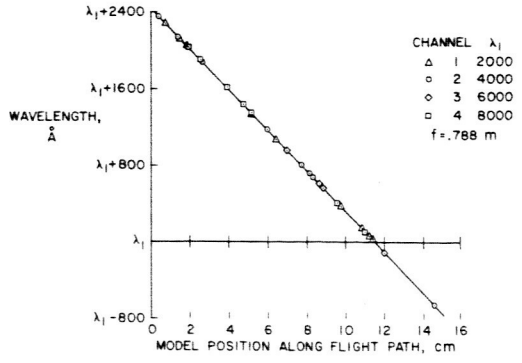

Fig. 9.- Wavelength calibration of scanning spectrometer.