Inexpensive photodiode arrays for use in rocket plume and hot source monitoring and diagnostics

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Abstract
The spectroscopic analysis of plume emissions is a non-intrusive method
which has been used to check for fatigue and possible damage throughout
the pumps and other mechanisms in a rocket motor or engine. These
components are made of various alloys. Knowing the composition of the
alloys and for which parts they are used, one can potentially determine from
the emissions in the plume which component is failing. Currently, optical
multichannel analyser systems are being used which utilize charge coupled
devices, cost tens of thousands of dollars, are somewhat delicate, and
usually require cooling. We have developed two rugged instruments using
less expensive linear photodiode arrays as detectors. A high-resolution
system was used to detect atomic emission lines while a low-resolution
system was used to detect molecular emission bands. We have also written
data acquisition software and built electronic circuits to control the arrays
and collect data. While the National Aeronautics and Space Administration
has used similar systems for characterization of the space shuttle main
engine, the emissions from other rocket systems have not been surveyed so
well. The two instruments described will be utilized to study hybrid rocket
emissions at the University of Arkansas-Little Rock hybrid rocket facility.

Keywords: atomic metallic species, molecular combustion intermediates,
atomic emission, molecular emission, UV–Vis spectroscopy, photodiode
array, non-invasive plume monitoring, combustion diagnostics, rocket
engine testing, engine health monitoring

1. Introduction

In the late 1980s and early 1990s, the National Aeronautics
and Space Administration (NASA) was plagued with several
manned and unmanned mission mishaps costing taxpayers
millions of dollars. The most infamous of these mishaps was
the Challenger disaster in 1986. Because these events cause
negative public opinion toward NASA, coupled with the need
to cut federal spending and the effect of increasing foreign
competition, pressure was put on NASA for methods to assure
that its boosters would perform satisfactorily at each launch.

One way to assure the proper performance of launch
vehicles is to employ extensive engine ground testing on test
stands designed for this purpose at research facilities. Using
spectroscopic analysis of plume emissions, the 'health' of the
engine (that it is performing well, not failing), particularly
combustion efficiency and the existence of component fatigue,
can be determined. The high temperatures and pressures
found in a rocket plume make excellent sources for atomic
line and molecular band emissions from the near ultraviolet
to middle infrared. Currently, monitoring systems are being
used which employ charge coupled devices and/or Fabry–
Pérot interferometers, cost tens of thousands of dollars, are
somewhat delicate, and usually require cooling.

A spectrometer using a rugged photodiode array mounted
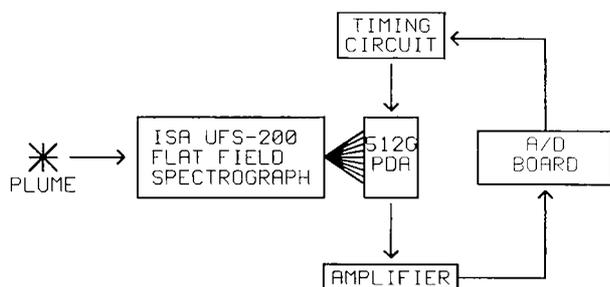in the focal plane of an imaging spectrograph can be used for

Figure 1. Block diagram of the low-resolution spectrograph.

Figure 2. Timing signals for scanning the array.

the analysis of UV–Vis emissions from rocket plumes. Gases such as CN, CO, N_2, and NH_3, and molecular species such as OH, C_2, and CH_2 emit in the visible region and can potentially be monitored. Also, most metals emit in the visible region, which is beneficial for detecting component fatigue or failure. Prior research conducted on the liquid-fuelled space shuttle main engine (SSME) has shown the ability to detect wear from several alloys along the hot gas path [1, 2]. Just such spectrometers are discussed in this paper, including designs for a low-resolution and a high-resolution unit. The low-resolution unit utilizes a very inexpensive diode array such as commonly available on the surplus market, while the higher resolution unit uses a special purpose diode array purpose-built for spectral use. The results found with each unit follow.

2. Materials and methods

2.1. Low-resolution spectrometer

A low-resolution spectrometer for molecular band emission studies was constructed as shown in figure 1. The components for the spectrometer were positioned in a similar manner to that in a standard flame emission spectrometer [3]. The components include the photodiode array with associated timing and output electronics, the collection optics, an imaging spectrograph, an oscilloscope, and a computer.

The photodiode array used in the low-resolution spectrometer was an EG&G Reticon 512G monolithic, self-scanning, linear array. This array has 512 photodiodes on 25 μm centres, thus giving a sensitive length of 12.8 mm. Each photodiode is 26 μm in height, which is relatively small when compared to the height of the slit on the spectrograph. Because of the array's monolithic, dual-inline-package (DIP) design, it was mounted into an 18-pin DIP socket that in turn was mounted to a circuit board. According to the manufacturer, this array was designed for use in low-cost facsimile and optical character recognition applications. While not optimized for spectroscopy, it offered a low-cost alternative and was readily available.

Timing signals needed to drive the array were generated externally. The three required signals, clock, start, and reset, are shown in figure 2 and were produced by the circuit in figure 3. The circuit that produced the timing signals was mounted on a circuit board separate from the board to which the photodiode array was mounted. Pins 8 and 9 on the 512G array produce a video and dummy output, respectively. These outputs were sent to a differential amplifier to extract the video signal and then through a low-pass filter before being sent
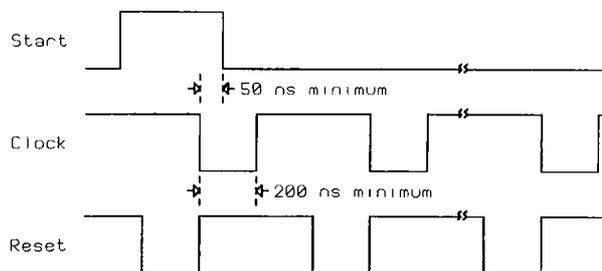
simultaneously to the oscilloscope and to the Channel 0 high input on the analogue-to-digital converter board installed in the computer. Figure 4 shows the circuit board with the array and video output circuit [4].

The detector circuit board was positioned so the photodiodes in the array are in the focal plane of an Instruments SA UFS-200 Flat Field Spectrograph [5]. The UFS-200 employs an aberration corrected concave holographic grating. This grating is 70 mm in diameter and is blazed with 200 grooves mm^{-1}. Its spectral range is from 200 to 800 nm with a dispersion of 24 nm mm^{-1}. The entrance slit is 3.8 mm high and 100 μm wide.

The collection optics were simply a convex lens and aperture stop. The lens was made of glass and housed in an aluminum bracket. It was 10.1 cm in diameter and had a focal length of 23 cm. This lens was able to focus a small part of the flame on the entrance slit. Using a glass collection lens was justified since the window on the photodiode array was also made of glass. The aperture was mounted to the lens housing and used to control the amount of light reaching the entrance slit. It had a maximum diameter of 9.78 cm and a minimum diameter of 0.56 cm.

A Zenith 80286AT personal computer equipped with an 80287 math coprocessor, and Computer Boards C10-AD16JR-AT analogue-to-digital conversion board (A/D board) was used to collect and store data. Data acquisition was controlled by a Borland Turbo C program which first prompted the user for the name of the file to which the data were to be written, the number of scans to be taken, and the amount of time delay between scans. Next, a TTL pulse was sent out from the Digital Output 0 (Dig. Out 0) to the circuit on the array board shown in figure 4. The signal produced by this circuit was sent to the Digital Input 0/Trigger (Dig. In 0/TRIGGER) on the A/D board. The signal to the Dig. In 0/TRIGGER was in sync with the clock pulses, however, they only occurred after the start pulse and only for 512 pulses and resets the LS7474 flip–flop to await the next scan. A timing diagram for these pulses is shown in figure 5 [6, 7]. The collected data for each scan was stored via direct memory access (DMA) to a specified memory segment. After all scans had been taken, the data were saved, along with all corresponding pixel numbers, to a file on the computer's internal hard disk drive. The data were written to an ASCII file in a format that allows them to be read and plotted by the graphing program, SPLOT.

2.2. High-resolution spectrometer

The high-resolution spectrometer for atomic line emission and detailed molecular band studies was constructed as shown
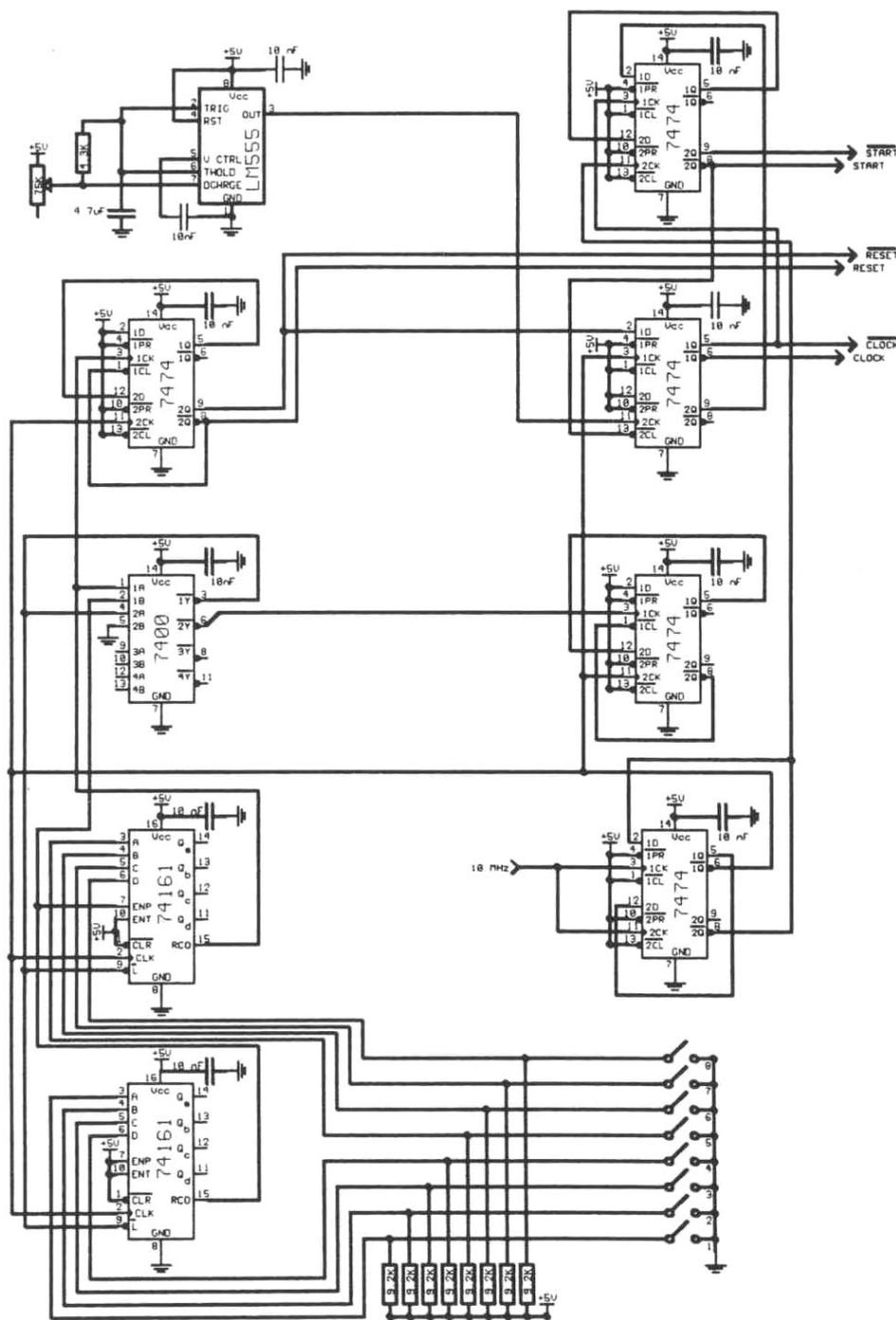
Figure 3. Circuit to produce the timing signals in figure 2.

in figure 6. Again, the components for the spectrometer were positioned in a similar manner to that in a standard flame emission spectrometer [3]. The components include a photodiode array with associated timing and output electronics, the collection optics, an imaging spectrograph, an oscilloscope, and a computer.

The photodiode array used in the high-resolution spectrometer was an EG&G Reticon 1024S monolithic, self-scanning, linear array. This array had 1024 photodiodes on 25 μm centres, thus giving a sensitive length of 25.6 mm. Each photodiode array was 13 μm wide and 2.5 mm high.

According to the manufacturer, the 1024S was designed for spectroscopic studies. The slit-like geometry of each photodiode allows for the maximum amount of light possible to strike the photodiodes [8]. The photodiode array was set in an EG&G Reticon RC1001 Satellite Board.

The satellite board was connected to an EG&G Reticon RC1000 Mother Board via a 16-pin ribbon cable for digital signals and a six lead cable for analogue signals. The RC1000 produced the required timing signals for the array, and it also had the necessary video processing circuitry. A single BNC connector allowed the video signal to be output to an
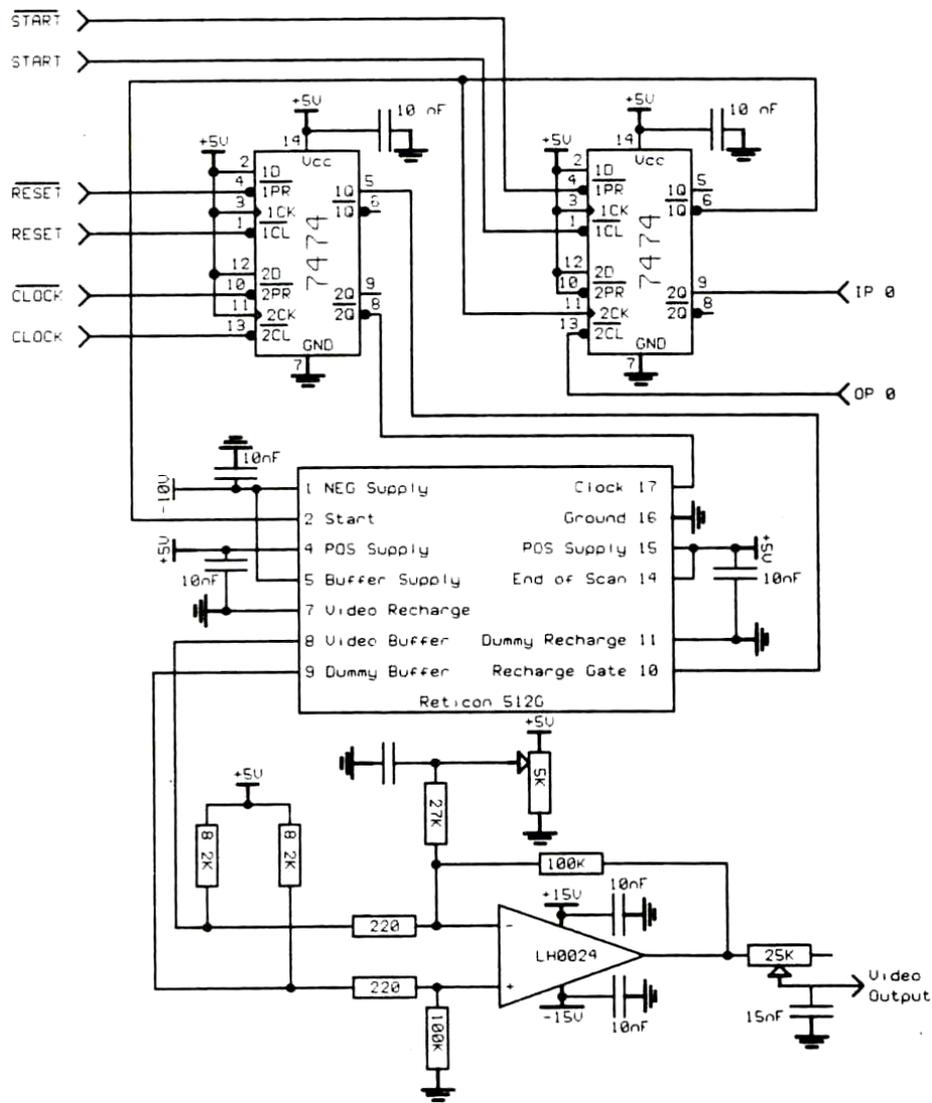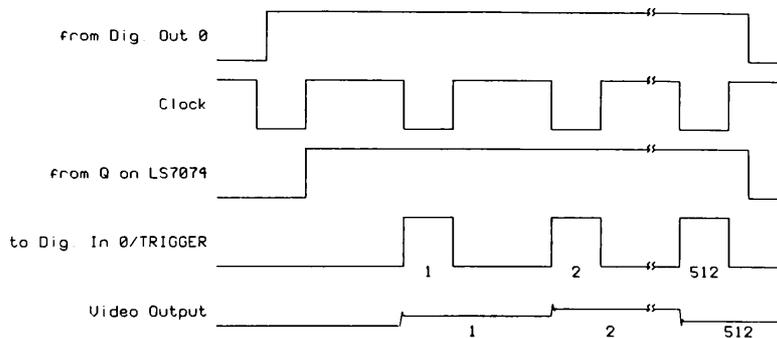
Figure 4. Sensor board schematic.

Figure 5. Timing diagram for interfacing the 512G and A/D board.

oscilloscope. In this setup, the video signal was sent to an oscilloscope and the computer as used previously [9].

The combination of the EG&G Reticon RC1000 and RC1001 was designed for evaluation of photodiode arrays. It comes from the manufacturer ready to be hooked up to an oscilloscope, but not to a data acquisition system. A circuit

was designed to interface between the RC1000 and a Computer Boards CIO-AD16Jr-AT analogue-to-digital converter board. This interface circuit is shown in figure 7. It produces a start pulse which was sent to the external start input on the RC1000. The circuit also produces active high TTL signals to the Dig. In O/TRIGGER input on the A/D board. These signals were
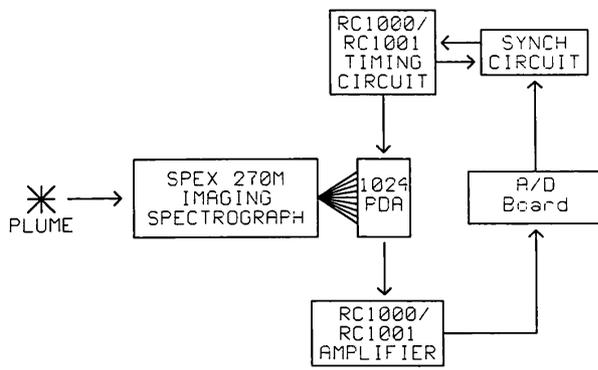
Figure 6. Block diagram for the high-resolution spectrometer.

synchronized so that one sample was taken for each pixel of the 1024S photodiode array. Figure 8 shows the timing diagram for the interface circuit. In order for the interface circuit to perform properly, the start pulse input jumper on the RC1000 had to be set from internal to external. The timing and signal processing circuitry that was designed and built for the low-resolution unit were not used for the high-resolution unit because of the outstanding performance of the RC1000/RC1001.

The 1024S photodiode array was positioned in the focal plane of a SPEX 270M imaging spectrograph. The 270M employs two holographic gratings mounted on a motorized turret, so the optimum grating could be chosen depending on the wavelength to be analysed. Both gratings had

1200 grooves mm^{-1}, one blazed for 250 nm and the other for 630 nm. Its spectral range was from 0 to 1100 nm with a dispersion of 3.1 nm mm^{-1}. The flat field area in the focal plane was 25 mm wide by 12 mm high, which gives 77 nm of coverage over the 25 mm width. The motorized turret allowed a specific range of wavelengths to be observed. The entrance slit was 1.52 cm high and its width variable in 12.5 μm steps. The settings on the 270M were selected using the SPEX Hand Scan hand-held controller. This controller allowed the user to select the desired grating, wavelength range, and entrance slit width [10, 11].

A BK Precision 20 MHz model 2120A oscilloscope was used for alignment and calibration of the instrument. It was also used to set the proper integration time to attain a maximum signal without saturation. Channel 1 was used to monitor the video output. The sync output from Pin M on the RC1000 was sent to channel 2 to provide a trigger pulse.

A Gateway 2000 486 personal computer with a Computer Boards CIO-AD16JR-AT A/D board was used to collect and store data, although more recently a 'lunch-box' portable PC (386 or 486) has been used to increase portability. Data acquisition was controlled by a Borland Turbo C program which first prompted the user for the name of the file to which data were to be written, the number of scans to be taken, and the amount of time delay between scans. The program then prompts the user for the integration time or exposure. The value entered for the integration time was not the actual exposure time, but was the value written to counter 2. To determine the integration time the following equation was used:
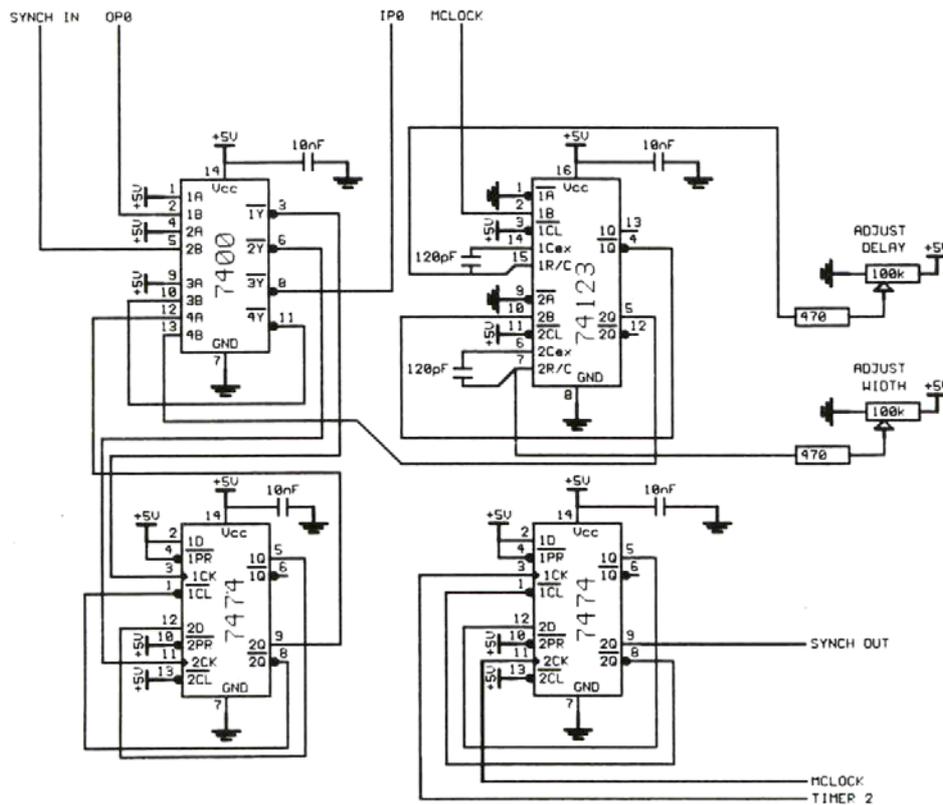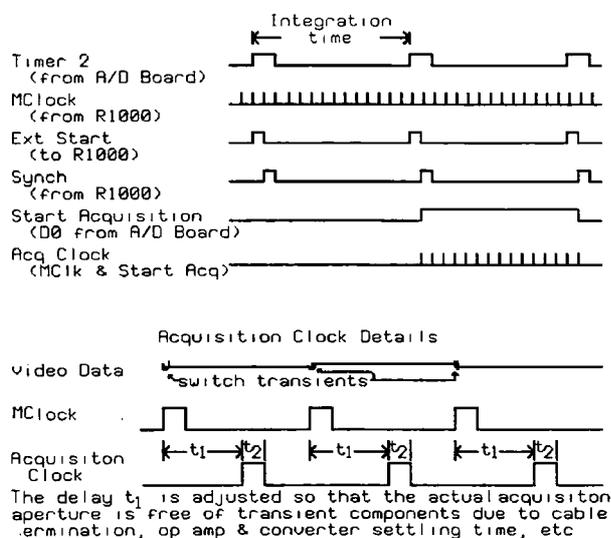

Figure 7. Schematic for the interface circuit.

Figure 8. Timing diagram for interfacing the 1024S and A/D board.

Integration time $= (256 \times \text{counter 2 value})/1\,000\,000$.

The integration time pulse was sent out from the A/D board on counter 2 out to the interface board. The pulse sent from the interface board to the Dig. In 0/TRIGGER on the A/D board triggered the sampling of the video signal which came in on Channel 0 High. The collected data for each scan were stored via DMA to a specified memory segment. After all scans had been taken, the data were saved, along with the corresponding pixel numbers, to an ASCII file on the computer's internal hard disk drive. The data were written to the file in a format to be read and plotted by the graphing program SPLOT [12].

3. Results and discussion

3.1. Low-resolution software

The Reticon 512G has a sensitive width of 12.8 mm. When mated with the UFS-200, which has a dispersion of 24 nm mm^{-1}, the 512F/UFS-200 combination gives a spectral window of 307.2 mm. Because this window does not cover the entire 200–800 nm range of the spectrograph, the array board was positioned in varying locations along the focal plane to see different portions within the UV–Vis region. Each time the array was repositioned, a scan of the emissions from a Pen-Ray mercury lamp was taken for wavelength calibration.

To obtain a useful spectra from the raw data, several steps had to be taken, all of which were carried out in the SPLOT program. The first step was to subtract the dark signal from the data. This step takes out most of the fixed pattern noise, which is common in photodiode arrays operating at room temperature. Being able to do this allowed us to decrease costs because the array does not have to be cooled. The next step was to convert the x values of the data from pixel number to wavelength. This was accomplished by scaling the x value by an amount determined by the following equation:

$$\text{Scaling factor} = \frac{\text{Dispersion} \times \text{Sensitive length}}{\text{Number of pixels}}$$

which has a value of -0.6 for the 512G/UFS-200 combination. The scaling factor was negative because the data was collected in decreasing values of wavelength with increasing values of pixel number. After multiplying by this negative value, the data has increasing wavelength values along the increasing x-axis of the plot. The next step was to offset the x-axis by 307.2 so the first point of the spectra was at zero nanometres. Finally, the appropriate amount of offset on the x-axis was determined by the Hg lamp spectra.

Initial studies were conducted by analysing the flame produced by a Perkin–Elmer atomic absorption (AA) burner. The acetylene/air mix was adjusted to produce a lean flame with a bright blue interconal region. The spectra of this interconal region is shown in figure 9. The molecular bands centred at 463, 509, and 559 were created by the C_2 species. The bands centred at 382 and 427 were created by the CH series [13]. The hump centred at 587 is not due to an emission band but was caused by fixed pattern noise.

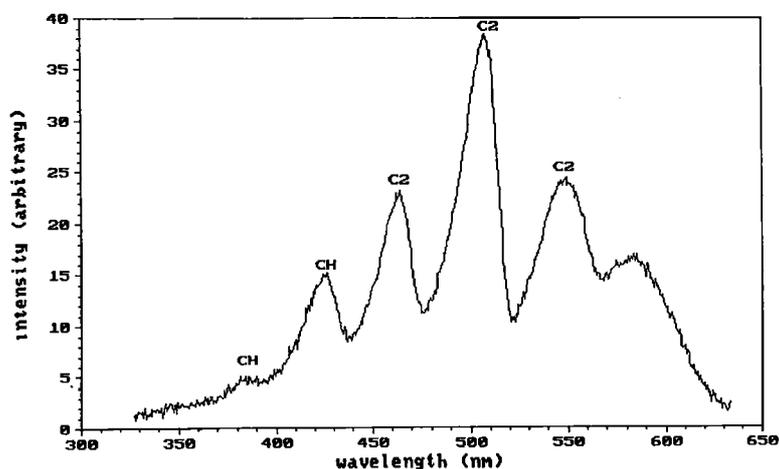Studies have also been done by aspiring NaCl solutions of varying concentration into the AA burner to determine

Figure 9. Spectra of the interconal region of a C_2H_2/air flame recorded with the low-resolution spectrometer system.
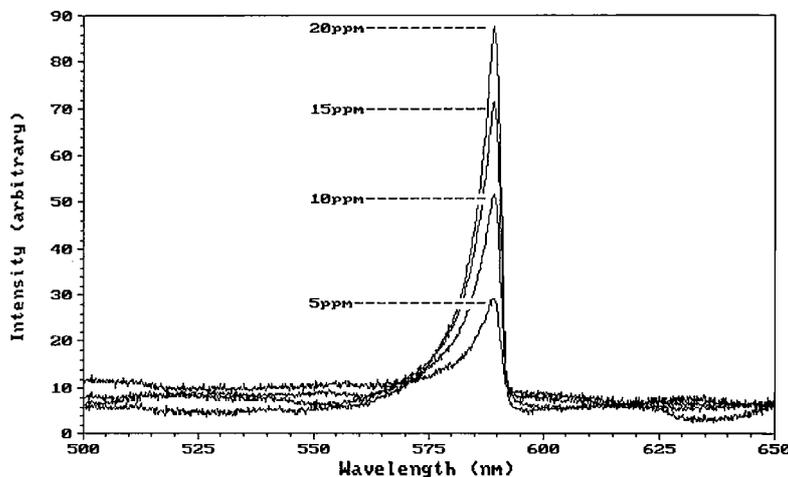
Figure 10. Spectra of Na emission in a C_2H_2/air flame with varying concentrations of Na recorded with the low-resolution system.
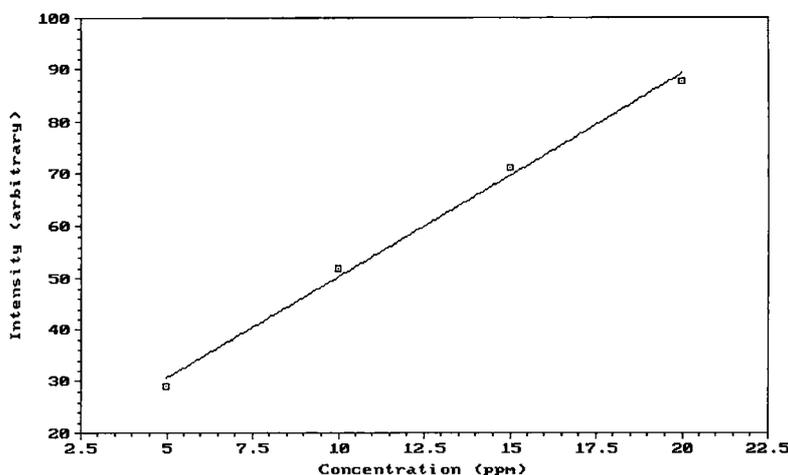

Figure 11. Plot of peak intensity versus concentration at 589 nm showing a linear increase in intensity with increasing Na concentration.

how well the low-resolution unit could detect atomic emission lines. Figure 10 shows the Na emission line at 598 nm for concentrations of 5, 10, 15, and 20 ppm. As expected, the peak intensity at 598 nm increased linearly with increasing Na concentration (figure 11).

3.2. High-resolution spectrometer

The Reticon 1024S has a sensitive width of 25.6 mm. When mated with the SPEX 270M, which has a dispersion of 3.1 nm mm^{-1}, the 1024S/SPEX 270M combination gives a spectral window of 79.36 nm. Because of this narrow window, the wavelength selector on the 270M was always set to centre the atomic line emission wavelength of the species to be observed.

For the high-resolution spectrometer, only two steps have to be taken to obtain a useful spectra from the raw data. Again these steps were carried out in the SPLOT program. Unlike the low-resolution unit, the dark signal does not have to be subtracted because of the reduced fixed pattern noise and high-quality video signal output of the RC1000/1001. The first step was to convert the x values of the data from pixel number to wavelength. This was accomplished by scaling the x values

by an amount determined by the following equation:

$$\text{Scaling factor} = \frac{\text{Dispersion} \times \text{Sensitive length}}{\text{Number of pixels}}$$

which has a value of 0.0775 for the 1024S/SPEX 270M combination. The scaling factor was positive for the high-resolution unit because the data were collected in increasing values of wavelength with increasing values of pixel number. The next step was to offset the x-axis by the value for the wavelength selector minus 39.68. This was done because the wavelength selector determined the wavelength falling on the centre pixel, so half of the spectral window, 39.68 nm, must be subtracted, to allow the proper wavelength values to be assigned to the spectra.

Several studies were being conducted on the emissions radiating from the plume of the hybrid rocket motor at the University of Arkansas-Little Rock's combustion diagnostics facility [14]. During initial tests of the high-resolution unit, data was collected on the Na emission line at 589 nm and K emission lines at 763 and 766 nm. Definitely Na, and possibly K, were present in the glass phenolic spacers originally used in the pre- and post-combustion chambers of the thruster and K seems present in the igniter charge. Data for Na and K were taken for three-second burns.
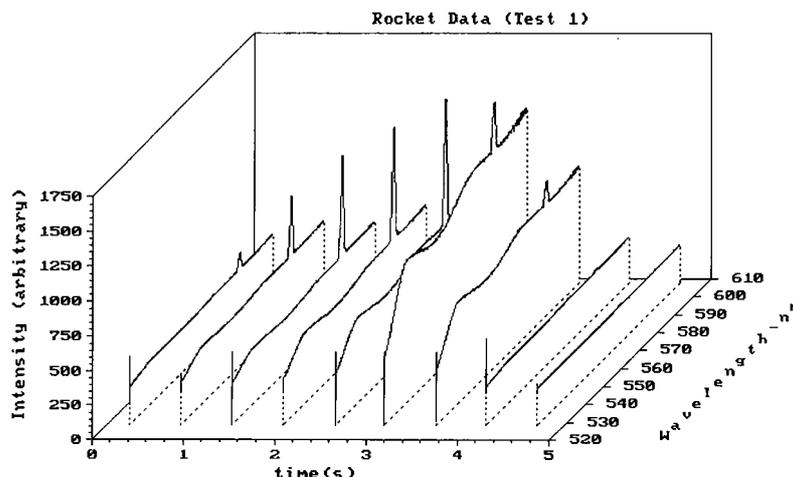
Rocket Data (Test 1)

Figure 12. Plot of Na emission from a HTPB hybrid rocket grain during a three-second firing.
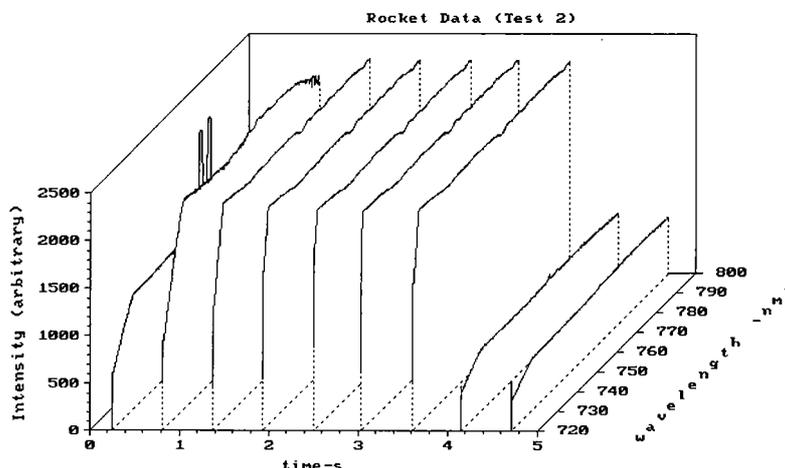
Rocket Data (Test 2)

Figure 13. Plot of K emission from a HTPB hybrid rocket grain during a three-second firing.

Figure 12 shows that the Na emission gradually rises throughout the burn. After the oxidizer was shut off at three seconds, the blackbody curve rises which is indicative of fuel rich combustion. After four seconds, the N_2 purge gas extinguishes all combustion. This strong Na emission resulted in a minor redesign of the thruster insulators, which were changed to graphite to minimize such emissions in later work [14].

Figure 13 shows that the K emission starts off strong, but was overwhelmed by the blackbody radiation. Part of this was due to the fact that the region in which the K lines are present is approaching the near IR where blackbody radiation curves are thought to be more predominant. However, further analysis indicates that K may be present to a greater extent in the igniter charge, so this spectral drop-out is to be expected [15].

4. Conclusions

Both the 512G and 1024S detectors were able to observe spectral features. Both units as designed were able to monitor signals in the source noise limited mode for all of the experiments we attempted. This means that their signal-to-noise characteristics were sufficient for the design purposes of this work. Therefore, questions of band-spread, spectral windowing, detector noise interference, and practical usage predominate in utilizing these detectors for spectroscopy.

The 512G diode array unit enabled us to see spectral features, but had some significant problems. The fixed pattern noise of the 512G was more difficult to deal with, and may have no direct solution. The small active area of the detector also meant that signals monitored with the 512G were not as strong, and the shape of the elements did not match with the exiting light conditions of the spectrograph. Finally, the 512G had half of the number of elements as the 1024S unit, and this limited its usefulness. The fact that it is inexpensive and can operate to provide useful low-resolution data might lend it to certain applications. Possibly, similar arrays exist that can be operated like the 512G, but provide more useful data for operations on a budget, but that would be a topic for another study.

The 1024S detector and SPEX 270M unit provided excellent results. By speeding up the timing and decreasing the integration time, we should have an instrument that can perform, in many applications, as well as or better than commercial optical multichannel analysers, without the higher cost or need for cooling [1, 2, 14, 15]. Spectra taken with the 1024S/SPEX 270M unit can be directly compared to those taken with more expensive commercially

available spectrometer/detector combinations. The planned improvement of the high-resolution unit by controlling the 270M through its RS-232 port should also enhance the spectrometers performance and capabilities. Additionally, the high-resolution unit can be operated at lower resolution by appropriate settings, such as opening up the entrance slit, and this has been employed in later projects. Of the two units described, the 1024S/SPEX 270M unit is the most versatile and capable instrument.

Future studies will involve casting hybrid rocket fuel grains with known concentrations of metal salts to simulate wear within the liquid oxygen pumps of a full-scale booster hybrid rocket motor. Also, we plan to study molecular band formation in plumes, and the unit operating in a low-resolution mode has worked very well in initial work done for those studies [16, 17]. We plan to use the 1024S/SPEX 270M unit in all subsequent plume work, whether low-resolution or high-resolution mode.

Acknowledgments

References

[1] Garner D G, Bircher F E, Tejwani G D and Van Dyke D B 1990 A plume diagnostic based engine diagnostic system for the SSME *AIAA* 90-2235

[2] Tejwani G D, Van Dyke D B, Bircher F E and Gardner D B 1992 Spectroscopic evaluation of rocket engine materials in the exhaust plume environment: spectral line identifications of SSME elements and materials *NASA Contractor Report* 4453, NAS12-290

[3] Ingle J D and Crouch S R 1988 *Spectrochemical Analysis* (Englewood Cliffs, NJ: Prentice-Hall) p 590

[4] G Series: 128, 256, 512 and 1024 elements *EG&G Reticon Data Sheet* 1992 (Sunnyvale, CA: EG&G Reticon) p 8

[5] *UFS-200 Flat Field Spectrograph. Instruments S.A. Data Sheet* (Metuchen, NJ: Instruments S.A.) p 5

[6] Schildt H 1990 *Turbo C/C++: The Complete Reference* (Berkeley, CA: Osborne McGraw-Hill) p 1016

[7] *CIO-AD16JR-AT User's Manual* 1991 (Mansfield, MA: Computer Boards, Inc.) p 103

[8] S Series Solid State Line Scanners: 128, 256, 512, and 1024 elements *EG&G Reticon Data Sheet* 1991 (Sunnyvale, CA: EG&G Reticon) p 6

[9] RC1000/RC1001 operation and alignment instructions *EG&G Reticon Data Sheet* 1991 (Sunnyvale, CA: EG&G Reticon) p 10

[10] *270M Rapid Scanning Imaging Spectrograph/Monochromator User Manual* 1993 (Edison, NJ: SPEX Industries, Inc.) p 79

[11] *Hand Scan Hand-Held Controller Manual* 1993 (Edison, NJ: SPEX Industries, Inc.) p 32

[12] Hood W G *SPLOT Software Package* http://hybrid.ualr.edu/~hudson/splot/splot.htm

[13] Gaydon A G 1974 *The Spectroscopy of Flames* (London: Chapman and Hall) p 412

[14] Shanks R and Hudson M K 2000 A labscale hybrid rocket motor for instrumentation studies *J. Pyrotech.* **11** 1–10

[15] Hudson M K, Shank R B, Snider D H, Lindquist D M and Luchini C B 1998 UV, visible, and infrared spectral emissions in hybrid rocket plumes *Int. J. Turbo Jet Engines* **15** 71–87

[16] Maxwell K L, Chouinard A P and Hudson M K 1999 Investigation of metallic molecular bands in hybrid rocket plumes *AIAA* 99-2137

[17] Maxwell K L and Hudson M K 2000 Spectral study of metallic molecular bands in hybrid rocket plumes *AIAA* 2000-3887