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ROCKET PLUME SPECTROMETRY--A SYSTEM PERMITTING ENGINE CONDITION MONITORING, AS APPLIED TO THE TECHNOLOGY TEST BED ENGINE

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ABSTRACT

Visible artifacts have been seen by observers of Space Shuttle Main Engine (SSME) test firings, either directly or on film, prior to several failures, some of which were catastrophic. A program was undertaken to attempt to identify, in the plume of an SSME, anomalous atomic--or molecular--species resulting from wear, normal or excessive, of internal parts, allowing real time monitoring of engine condition or detection of failure precursors. To this end, measurements were taken during test firings on stand A1 at Stennis Space Center and on SSME, and other engines, at the Santa Suzanna Facility in California. The results indicated that a system having high spectral resolution, a fast time response, and a wide spectral range was required to meet all requirements, thus two special systems have been designed and built. One is the Optical Plume Anomaly Detector (OPAD) polychromator--a 16 channel spectroradiometer having adjustable optical bandwidth and center wavelength and a time response of 1mS. This instrument has been described elsewhere. The other instrument is the superspectrometer, an optical multichannel analyzer having 8,192 channels covering the spectral band 250 to 1,000 nm. This instrument is described in this paper.

INTRODUCTION

During the process of testing Space Shuttle Main Engines (SSME), movie film surveillance is routinely employed. These films typically form the major source of information available after unusual occurrences. Film is used because rates such as 400 frames-per-second are not uncommon and high frame rates are needed to capture many of the anomalies observed. It is not unusual for "streaking" to occur for one frame only. "Streaking" is a visible (on film) phenomenon thought to result from extraneous material being injected, by some method, into the propellant streams within the engine.

The most commonly observed "streaking" appears to be at the periphery of the plume. It is assumed that anomalies occurring upstream of the Main Combustion Chamber (MCC) will be diffused throughout the plume and, therefore, also in the "mach disc." Anomalies occurring downstream of the injector face plate may appear only at the plume edge.[1,2]

BACKGROUND

It has been theorized that if such events can be seen on film, and indeed occasionally with the naked eye, then it should be possible to use electronic-optical detection to devise a system allowing automatic engine health monitoring. Such a system might permit the prevention of a catastrophic event. Much effort has been expended in background work in the attempt to build a data base on which such a detection system could be based. Multispectral photometric measurements (Fig 1) were acquired over about a 2-year period at test stands at Stennis Space Center (SSC) in Southern Mississippi[3,4] and at the SSME development stand (A3) at the Santa Suzanna Test Facility (SSTF) in California.[5] Some data was also obtained from tests of other than SSME.[5] Using relatively low spectral resolution equipment, several elemental signatures were found in the spectra acquired from tests. The base data acquired showed a very strong continuum from OH emission. That background is sufficient to cover most of the elemental spectra since those lines are very narrow and normally of low amplitude. The nature of the background places demands upon the equipment such that commercially available instruments can be used only to detect the most significant incidences. It would be preferable to be able to follow over a period of time several of the individual elemental or molecular spectral lines so that detectable variations from the norm may be properly interpreted.

RESULTS AND OBSERVATIONS

Calcium (Ca) was identified some time before a bearing cage failure occurred on an SSME; Ca was also seen during the sudden failure of a small H_2/O_2 engine having a compound combustion cycle. The increased level of Ca was detected as an erratic and significant increase in the normally observed level (believed to come from the H_2). During another SSME test at SSTF an injector face plate carrying intentionally plugged LOX tubes suffered some damage and that damage resulted in a "seeded" plume. Spectra indicated the presence of iron (Fe), nickel (Ni), chromium (Cr), and some copper (Cu). Other species were also noted in trace quantities. In truth, this event was a massive failure--the sort which would be extremely serious were the engine a flight unit.

Another unplanned incident occurred at SSTF. Certain shipping procedures for SSMEs at SSC require that minor cracks in the MCC be sealed with a copper foil tape to allow maintenance of an inert dry purge. The tape was not removed at SSTF and when the engine was fired, the copper tape rather handily "seeded" the plume. This event was also detected easily.

INSTRUMENT DESIGN

The basic instrument for the Optical Plume Anomaly Detector (OPAD) program is called a Polychromator (PCM)[10]; for further base data a Superspectrometer (SSM) was designed. The PCM provides 16 individually adjustable spectrophotometer channels; the wavelengths are adjustable, the slit-widths are selectable, the amplifiers provide high-speed autoranging, the computers permit setting alarm limits or multichannel complex algorithyms for decision-making, and a second computer allows archival storage on removable magnetic disc. This system employs a quartz fiber-optic input system, allowing mounting of the optics and electronics inside the hard-core of the test stand, where the environment is friendly to non-ruggedized equipment. It is this instrument which is the prototype of the safety monitoring system. All the spectral lines accruing from previous failures are monitored as well as OH at 308 nM and two broad banded background channels to observe such things as spurious light and variable occlusions (such as vapor (H_2O). The spectral band covered ranges from 250 nM to 1,000 nM. This is a continuous device with a digital data system; the sample time is about 1.5 ms.

The system speed is chosen with the fact in mind that the films indicate some events occur within 2.5 ms (400 frame-per-sec film). It is not assumed that these events are individually significant, but rather may be indicative of normal wear. Confounding the ability to see these "streaks" is the fact that they cover a relatively small percentage of the total emitting area of the plume. Edge phenomena are therefore difficult to capture; mach disc inclusions might well be much easier to find, since the higher temperatures of the disc cause elemental emission strength to increase. Experience with the system will tell more about the area of the plume which should be observed.

The other instrument (the SSM) is intended to provide overall surveillance of the plume perchance some species for which the PCM has not been set appears. It had to have a wide spectral range, high data capability, and high spectral resolution. Since no commercial instrument provides all these features, a special one was designed. It is based upon a 1/2 meter grating spectrometer, uses an input system similar to that of the PCM--telescope and fiber optic cable--, and has at the exit slit folding mirrors directing the dispersed spectrum onto four 2,048 element self-scanning linear silicon diode arrays, for a total of 8,192 elements. The outputs are digitized and processed by computer for display and storage (Fig 3); storage for archiving is by optical disc.

The input system is composed of two telescopes (Fig 2), two quartz multifilament optical fiber cables. The numerical aperture of the fibers, projected onto the plume, does not quite cover the whole plume. The mounting point on the Test Bed Stand is about 63 feet from the "mach disc," and at that distance the viewed field is about 6-1/2 feet across. Two input sets are used because one cable will illuminate only half the entry slit of the spectrograph. Using a direct viewing optic system would eliminate these difficulties of the fiber optics but would also require that the spectrograph and detector set be mounted on the engine deck in some way. All in all, the cable route was considered the most practical. The cables used are round at the telescope end and rectangular at the spectrograph entry slit in order to maximize light transfer at both ends; that scheme also isolates the field of view from the slit shape.

The range of coverage is similar to that of the PCM--250 nM to 1,000 nM, yielding an ultimate resolution of less than 1A (0.1 nM). The sampling technique used, combined with the factory provided service boards (for the arrays), allows at least 10 samples per second. The system normally will display each sample as a line spectrum; several modes would allow detailed examination of selected narrow ranges.

The computer for this system is an "AT" style machine whose prime purpose is to store the data and display it. The archival data is placed on WORM (write once, read many) optical disc; because of the data rates the WORM drive cannot accept the continuous stream of data, but the internal high capacity hard disc can. Therefore, the processed data is loaded into the hard disc, then on completion of the acquisition run, the hard disc is dumped to the WORM drive. Intensive data processing is done after-the-fact; too much is required of the computer to achieve real-time processing of this data.

SUMMARY

These two instruments should be sufficiently flexible and capable of acquiring spectral data to allow an in-depth study of the plume for most any reason. These systems will be used in an ongoing program wherein the proper algorithyms will be determined through experience. At first "simple" redline cuts are envisioned as the operational mode for the PCM, but more complex computations may be necessary. Each channel is presently corrected for background conditions, but multichannel dependence could drive a change to the basic philosophy.

Also, the PCM could be considered a conceptual (from a systems, or scientific, standpoint) prototype for a flight unit. This system, as such, cannot fly--it is much too heavy, bulky, and fragile to put on a shuttle--but the concept is valid, whatever the configuration of a final system. Also, the problem of viewing the proper place in the plume affects the design; the varying nature of the plume with respect to altitude forces considerable compromises on the system. For example, it may be desirable to view the MCC (Main Combustion Chamber) directly by some method. The Technology Test Bed operation should indicate what will be required and how to affect it.

ACKNOWLEDGEMENTS

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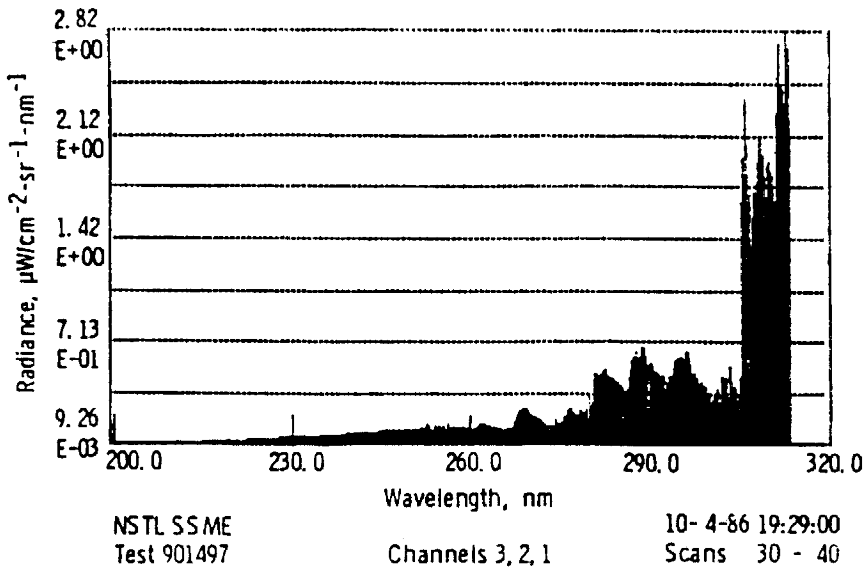
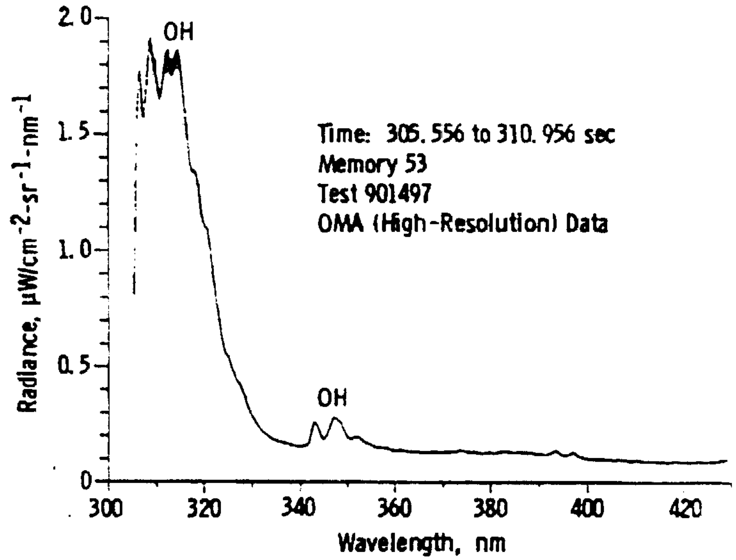
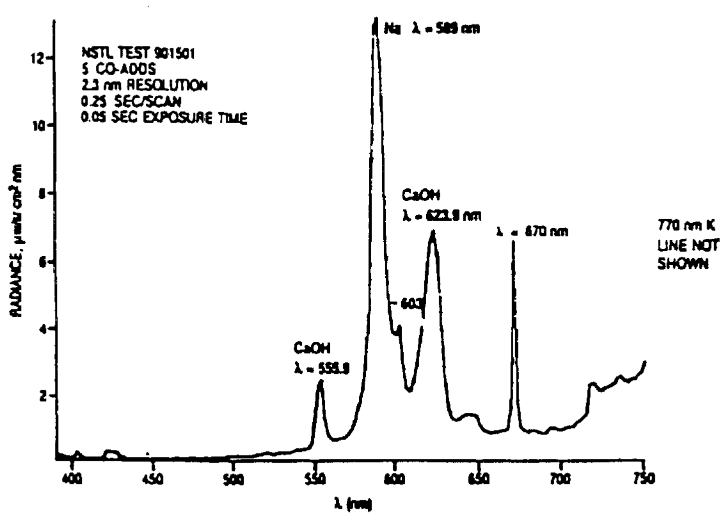
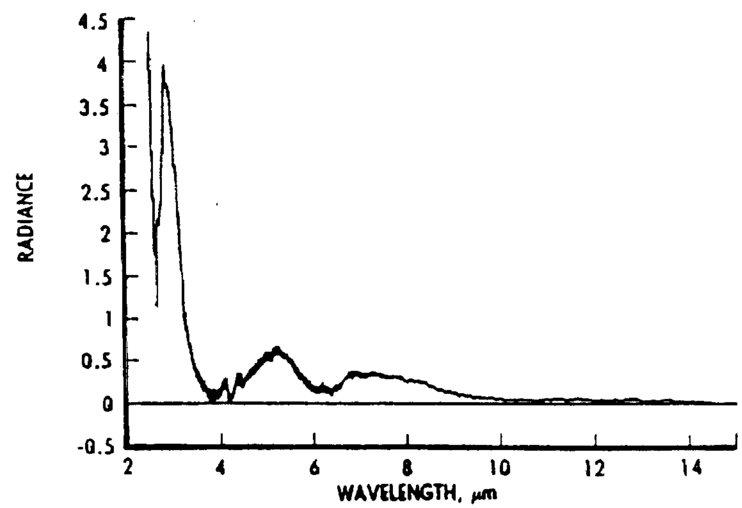


a. Far UV



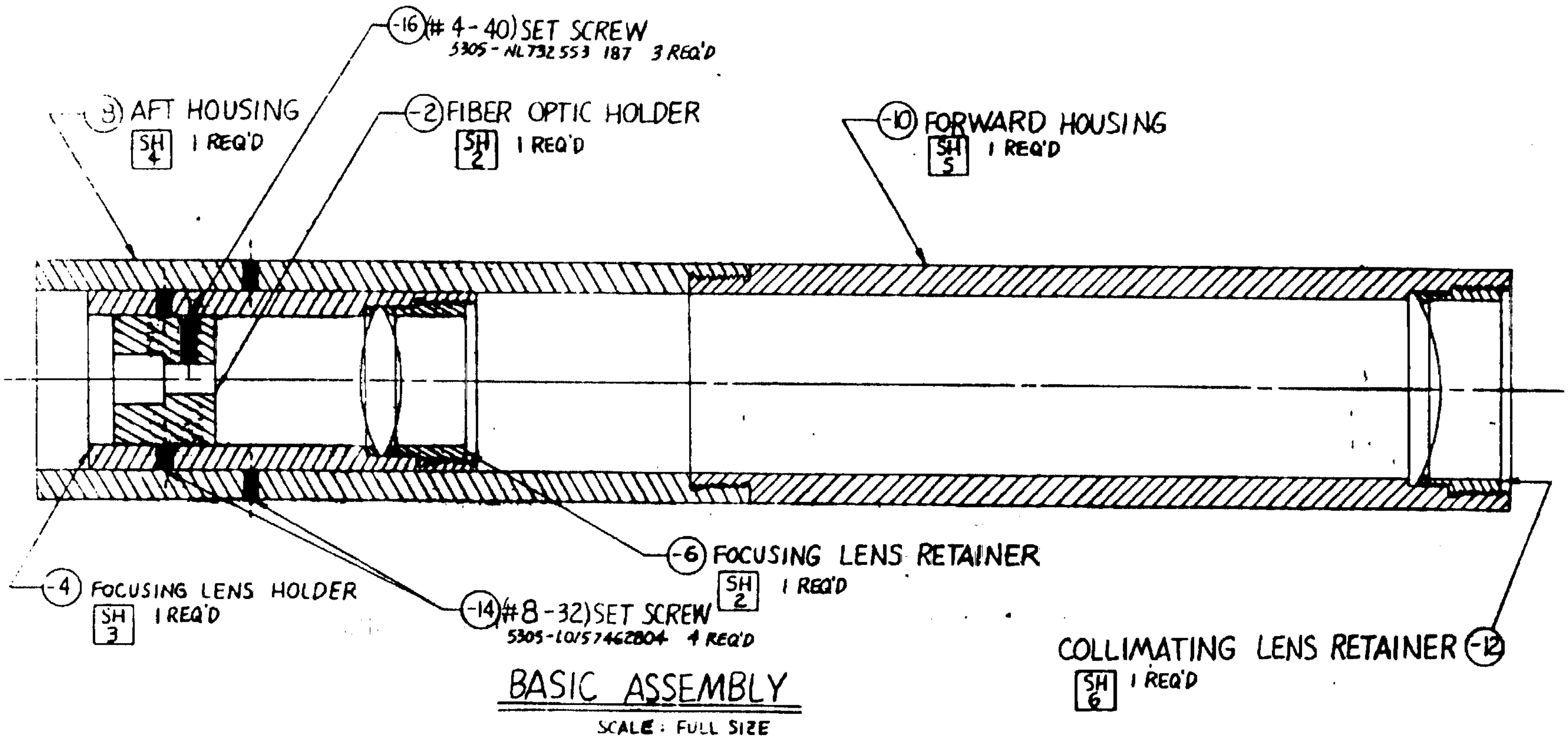


Detail in the 500-700 nm band.



CVF IR spectrometer response.

Figure 1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SH 4 1 REQ'D
-2 FIBER OPTIC HOLDER
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-10 FORWARD HOUSING
SH 5 1 REQ'D
-6 FOCUSING LENS RETAINER
SH 2 1 REQ'D
-4 FOCUSING LENS HOLDER
SH 3 1 REQ'D
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SCALE: FULL SIZE

Figure 2

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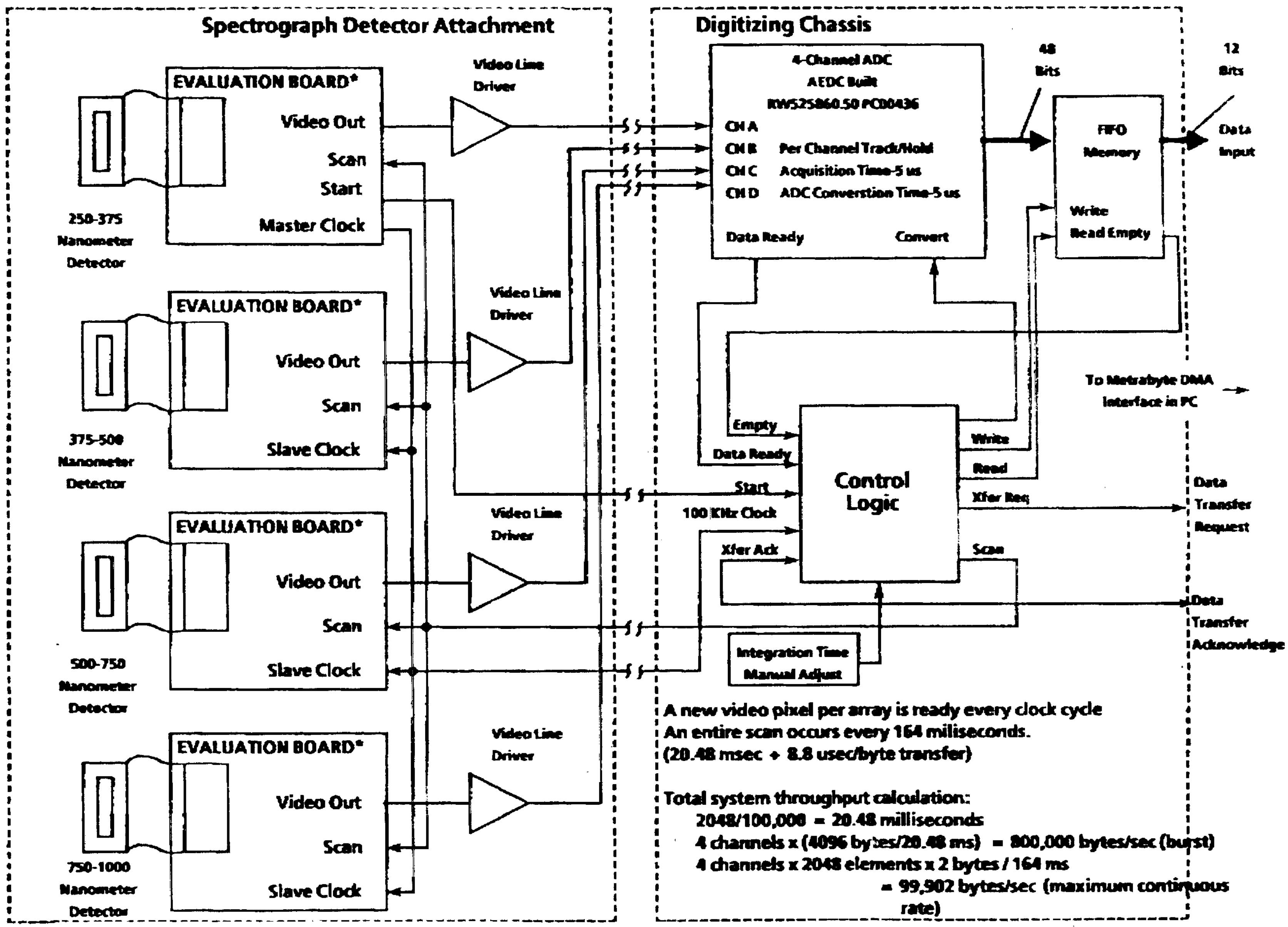

*Evaluation Boards are scanning circuits for Reticon arrays. Maximum clock rate = 100 KHZ.

NASA/OPAD Spectrometer Electronics.

Figure 3