High-Speed Observer: Automated Streak Detection in SSME Plumes

T.J. Rieckhoff
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

M. Covan and J.M. O'Farrell
United Space Alliance, Huntsville, Alabama

Acknowledgments

TRADEMARKS

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LIST OF ACRONYMS AND ABBREVIATIONS

ATCC   A-Side Test Control Center

CCD   charge-coupled device

fps   frames per second

f-stop   ratio of the focal length of a lens to the diameter of the entrance pupil

GB   gigabytes

HSO   High-Speed Observer

IRIG   interrange instrumentation group

LH_2 liquid hydrogen

lox   liquid oxygen

SSC   Stennis Space Center

SSME   Space Shuttle main engine

NOMENCLATURE

S	required columns
S_f	number of columns
S_τ	percentage of $S_{\tau,\max}$
$S_{\tau,\max}$	maximum number of streaks detected over time period τ
t_d	time delay
β	intensity threshold value
ρ	average frame rate per second
$\sigma_{\max}$	maximum number of streaks that can be detected in a frame
$\Sigma_{f,\tau}$	sum of S_f values over time period τ
τ	specified time period

TECHNICAL MEMORANDUM

HIGH-SPEED OBSERVER: AUTOMATED STREAK DETECTION IN SSME PLUMES

1. INTRODUCTION

A high frame rate digital video camera installed on test stands at Stennis Space Center (SSC) has been used to capture images of Space Shuttle main engine (SSME) plumes during test. These plume images are processed in real time to detect and differentiate anomalous plume events occurring during a time interval on the order of 5 msec. Such speed yields near instantaneous availability of information concerning the state of the hardware. This information can be monitored by the test conductor or by other computer systems, such as the integrated health monitoring system processors, for possible test shutdown before a catastrophic engine failure occurs.

During SSME firing in both test and flight, visual streaking in engine plumes has been observed. Under normal circumstances, combustion of liquid hydrogen (LH_2) and liquid oxygen (lox) yields nearly transparent plumes. Bright, distinguishable streaks in engine plumes are possible indicators of abnormal events.

Streaks in SSME plumes are typically generated during combustion of contaminant products in the fuel or oxidizer, as from significant erosion of metal. These streaks originate from within the combustion chamber and are visible as the gas is ejected from the nozzle exit plane. Typical engine streaks are shown in figure 1(a)–(e).

Debris falling into the plumes also produces visible streaks. Streaks associated with debris are generally short in duration and are initiated at the site of debris impact with the plume boundary. Such streaks are rarely positioned near the exit plane. A large debris-induced streak occurred on mission STS–58, as shown in figure 1(f).

On January 25, 1996, at SSC, SSME test 901–853 of the block II development engine 0523 (ref. 1) was terminated at 553 sec into a 754-sec test. Posttest analysis of images recorded by high-speed video camera revealed over 400 plume events during the test. Thirty-one of these plume events produced streaks that encompassed the entire circumference of the plume. The first such significant plume event was a bright white flash at T+130.284 sec. Termination of the test was called by a human observer due to continuous abnormal plume coloration that indicated equipment malfunction. Earlier termination of the test might have saved components that were consumed by the test and could have enabled evaluators to better analyze the failure mechanisms.

In the lessons learned section of the investigation report for SSME test 901–853, it was suggested that the possibility of real-time monitoring of the SSME plumes for events that might be indicative of engine malfunction be investigated. The High-Speed Observer (HSO) demonstrator program was initiated with the following goals: (1) Demonstrate that SSME streaks could be detected using video and (2) automate the detection process. The program has been extended to include development of an expert system that detects, quantifies, and reports anomalous streaks in the SSME plumes.
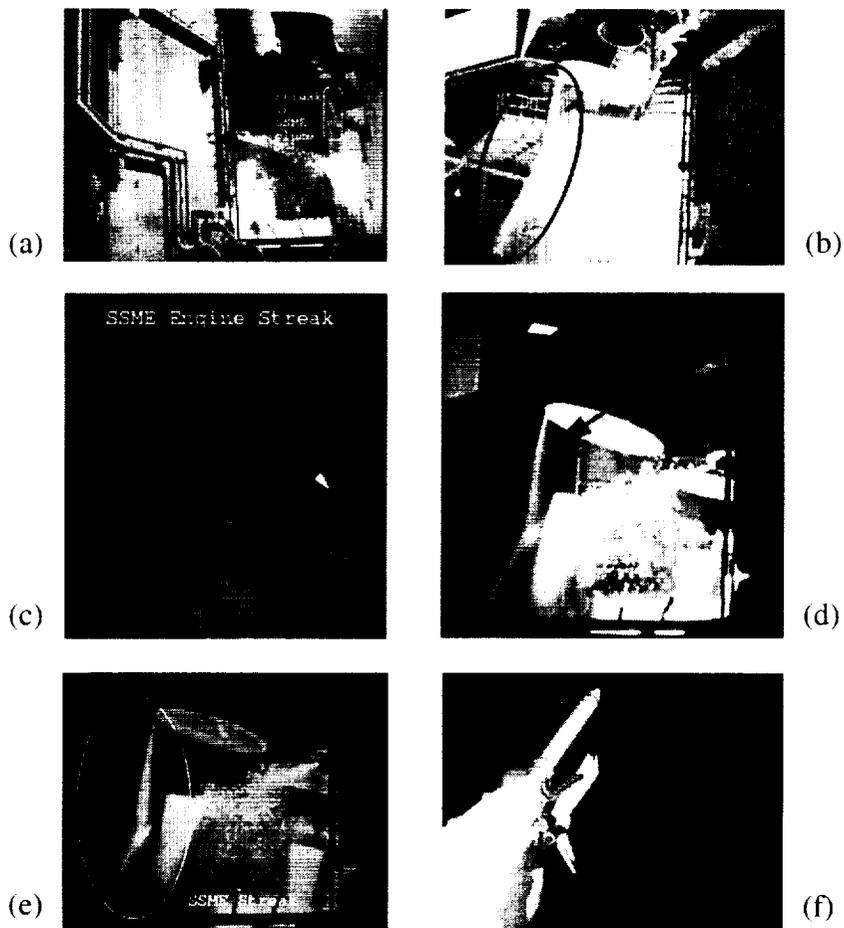
Figure 1(a)–(f). SSME plume streaks.

2. HIGH-SPEED OBSERVER SYSTEM

The HSO system was designed with commercially available off-the-shelf hardware components. The HSO system that is now being used at SSC monitors the SSME plume flowfield between the Mach disc and the engine nozzle exit plane. It has an image acquisition rate of ≈200 frames per second (fps) which allows the HSO system near instantaneous identification of anomalous events that may require immediate intervention.

2.1 Hardware

The HSO system, depicted in figure 2, uses a 200-fps, 256×256 pixel, DALSA® charge-coupled device (CCD) array camera to generate 8-bit, gray-scale digital images. This camera is mounted inside a PELCO® EHX6–16 explosion-proof housing for protection against the rugged environment experienced during testing. The HSO camera position at SSC is shown in figure 3. The ideal camera position on the test stand is on or slightly above a plane, horizontal with the midpoint between the nozzle exit plane and the Mach disc. This position provides a single line of reference at the nozzle exit plane for the region of interest.
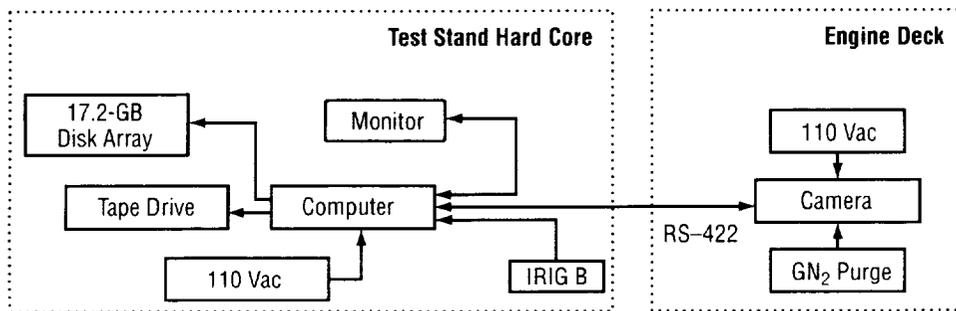
Figure 2. HSO system.
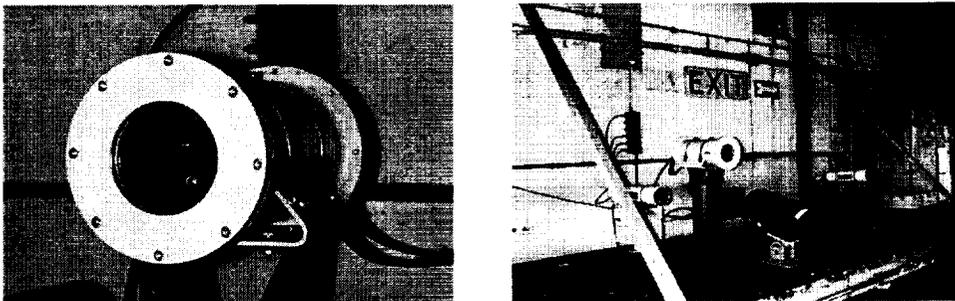
Figure 3. HSO installation at SSC.

The current HSO system uses a Dual Pentium® Pro 200-MHz computer running Microsoft Windows® NT with a BitFlow, Inc. Road Runner frame capture board to process images in real time. Each image frame is encoded with interrange instrumentation group (IRIG) timing and recorded on a 17.2-gigabyte (GB) redundant array of inexpensive disks disk system. After testing, images are stored on an 8-mm Exabyte® tape and shipped to Marshall Space Flight Center for posttest analyses.

The f-stop of the camera is set so that the high-intensity values of the image are in the midrange of the camera CCD response band. Although this high f-stop setting makes the images of the normal plumes in HSO imagery appear dark, the bright Mach disc and engine streaks are easily detected.

2.2 High-Speed Observer Operation

The image processing system software provides rapid data validation and plume streak detection between each frame acquisition. The "process image" box in figure 4 is expanded in figure 5.
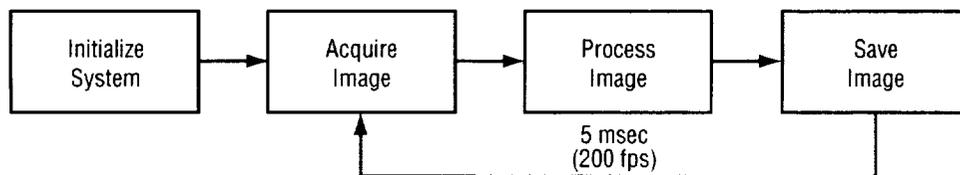
Figure 4. Overall HSO system operation.
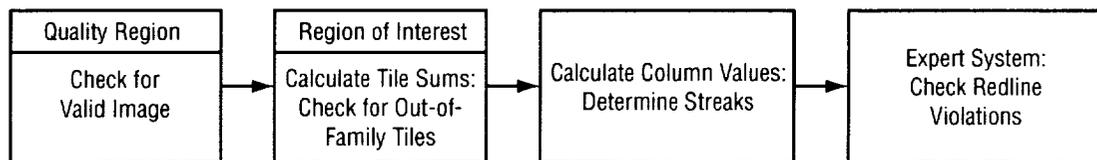
Figure 5. Image processing procedure.

2.2.1 Pretest

A setup program is executed to size and position the region of interest in the plume flowfield to be monitored during the test, set the expert system time-check intervals, and fix a quality region size and position for data validation. This setup information is stored in an initialization file.

There are four main segments of the image processing operation, all occurring in real time: (1) Image validation, (2) out-of-family tile detection, (3) streak detection, and (4) redline violation audit. During program operation, image data are acquired, validated, saved, and the streaks detected are counted. These processed streak data are then compared against redline violation criteria for several time-check intervals by the expert system, and notification is made concerning the state of the SSME hardware as determined by the plume status. Each segment of program operation is explained in more detail in the following sections.

2.2.2 Image Validation

Image data validation consists of checking a quality region for a valid data signal and an obscured field of view as shown in figure 6. The quality region currently employed by the HSO system is a small, presently 5×5 pixel, fixed array acting as a reference point for validation of the image. Since the intensity of the Mach disc is approximately the same as that of a streak, the quality region was selected in the Mach disc. The average intensity value of the quality region is called the quality region value. A valid data signal indicates that the hardware is functional, determined by checking for nonzero data in the quality region.

An obscured field of view is detected by comparing the quality region value against an intensity threshold value, β. The value selected for β is below the average intensity value for the quality region and above the average intensity of the region of interest. A quality region value lower than β indicates that the region of interest may be obscured. This may occur when vapors pass between the camera and the plume flowfield. When this condition is observed, a flag is set in the data stream from the expert system, indicating that data are unreliable.
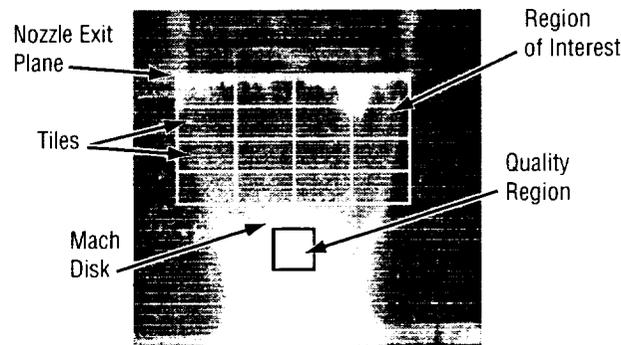

Figure 6. HSO image elements.

2.2.3 Out-of-Family Tiles

Plume streak detection utilizes a system based on a region of interest. The region of interest is a rectangular area extending from the nozzle exit plane to the Mach disc and bound by the width of the plume. This area, shown in figure 6, is divided into equal-sized, rectangular groups of pixels called tiles, figure 7(a). The number of pixels per tile varies with the size of the region of interest. In the current configuration, each tile is 32 × 32 pixels.

Pixel intensity in each tile is represented by an unsigned integer value from 0 to 255 (0 = black and 255 = white). A tile sum is computed by summing pixel intensity values over all pixels in a tile. If the summation is greater than a threshold value, the tile is said to be out of family and given a value of "1," otherwise, the tile value is "0." The tile threshold value is calculated using β multiplied by the number of pixels in the tile. Assigning a smaller value to β may include more reportable events and conversely assigning a larger value to β excludes reportable events.

2.2.4 Streak Detection

In the present configuration, a system of seven overlapping columns of tiles, extending between the engine nozzle exit plane and the Mach disc, are used to determine whether a streak has occurred. Figure 7(b) shows this seven-column configuration with a normal HSO recorded image in which the Mach disc is exposed for the midrange of the camera. Four main columns of tiles cover the region of interest, as represented by the solid lines in figure 7(b) and (c). While a plume streak may occur on the boundary between two of these four main columns of tiles, it was empirically determined that the intensity change due to a streak along a tile boundary is not always sufficient to indicate an out-of-family tile. However, streaks recorded in the center of a tile do yield a sufficient intensity change to indicate an out-of-family tile. To avoid missing these boundary streaks, three additional columns of tiles are used—dashed lines in figure 7(b). The centers of these three additional columns cover the intersecting boundaries of the four main tile columns.

Processing of each column begins at the nozzle exit plane, moving toward the Mach disc, as shown in figure 7(c). Figure 7(c) is an equalized image that permits observation of the plume boundary and nozzle exit plane. The main columns are processed first, followed by the overlapping columns. If each tile in a column has tile value "1," the column is said to contain a streak. If there is at least one tile in a column whose tile value is "0," the column is said to not have a streak. If a tile is encountered that has a value of "0," processing stops on that column and begins on the next column. The column location, size (number of columns), number of frames, and the duration of each streak are recorded.

(a) Single Tile

(b) Normal Image   (c) Equalized Image
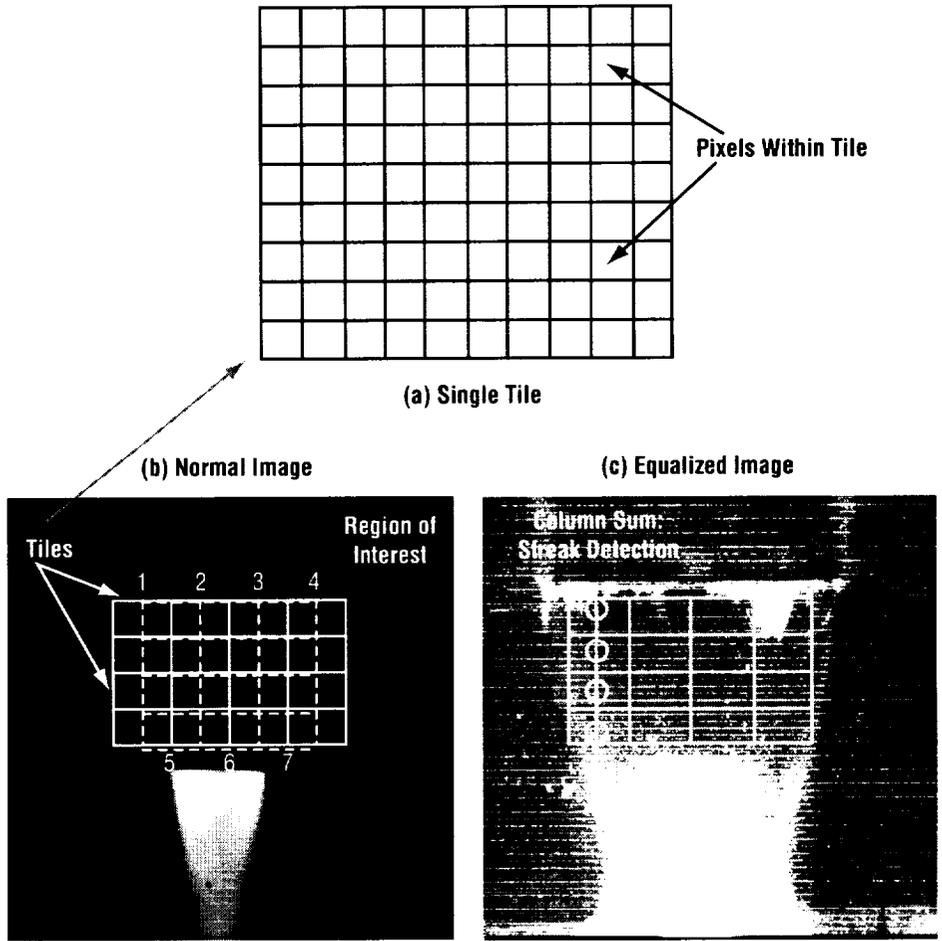
Figure 7. Streak detection elements.

2.2.5 Expert System: Redline Violations

The assessment system of the expert system takes input from the image analysis system and checks for redline violations indicative of a major malfunction. The program checks for redline violations at specific times during the preceding 2 sec of frame input data. The input data to the expert system for each video frame is the number of columns, S_f, that satisfy the plume streaking criteria.

Two constraints are imposed as part of the redline violation determination. The first constraint is a time delay, t_d, a period of time before the expert system makes any assessment about plume streaking, regardless of the streaking amount. This time delay corresponds to five successive images. For a 200-fps camera, the time delay is 25 msec. If most of the columns contain all out-of-family tiles for 25 msec, the plume condition is again thought to be anomalous.

The second constraint involves the number of columns of tiles that indicate continuous streaks over a particular time period. If only one streak appears, i.e., only one column contains all out-of-family tiles (not necessarily the same column), and continues for the duration of a 2-sec time interval, the condition is again thought to be anomalous.

To assess for redline violations, the expert system performs comparisons of the number of streaks in the image analysis data with threshold values. Over a specified time period, τ, with an average frame rate per second, ρ, and maximum number of streaks that can be detected in a frame, σ_{max}, the maximum number of streaks over τ is calculated:

$$S_{\tau,max} = \rho \times \sigma_{max} \times \tau . \tag{1}$$

At any instant in time, a percentage of $S_{\tau,max}$, denoted S_τ, is used as the threshold value to check for an anomalous condition and is a function of observation time, τ. For a full 2-sec time interval, 10 percent of $S_{\tau,max}$ is used; and for the time delay period, 25 msec at 200 fps, 90 percent is used. The number of columns required for redline violation for time checkpoints between 25 msec and 2 sec is obtained by evenly distributing percentage values from 90 percent at the time delay value to 10 percent at the 2-sec value.

For each observation period τ, S_τ is compared to the sum of S_f values for each frame during that time period, denoted $\Sigma_{f,\tau}$:

$$S_\tau \geq \Sigma_{f,\tau} \quad \Rightarrow \quad \text{No Redline Violation}$$

$$S_\tau < \Sigma_{f,\tau} \quad \Rightarrow \quad \text{Redline Violation} . \tag{2}$$

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The interpolated values for the number of columns required for redline violation versus time period are shown in figure 8.

This methodology can identify redline violations for full or near full plume streaks over a short period of time, small plume streaks over a long period of time, and conditions inbetween. This method integrates streaking activity over time to assess the health of the engine. Streaks which encompass the entire plume boundary for <25 msec will not cause redline violations on their own but may contribute to a redline violation determined over a longer time interval. Posttest data analysis documents individual streaking patterns, sizes, and locations.


Seconds	Total Streaks	Percent	Columns
0.000	0	–	–
0.025	35	90.0	32
0.050	70	76.7	54
0.100	140	63.3	89
0.250	350	50.0	175
0.500	700	36.7	257
1.000	1,400	23.3	327
2.000	2,800	10.0	280
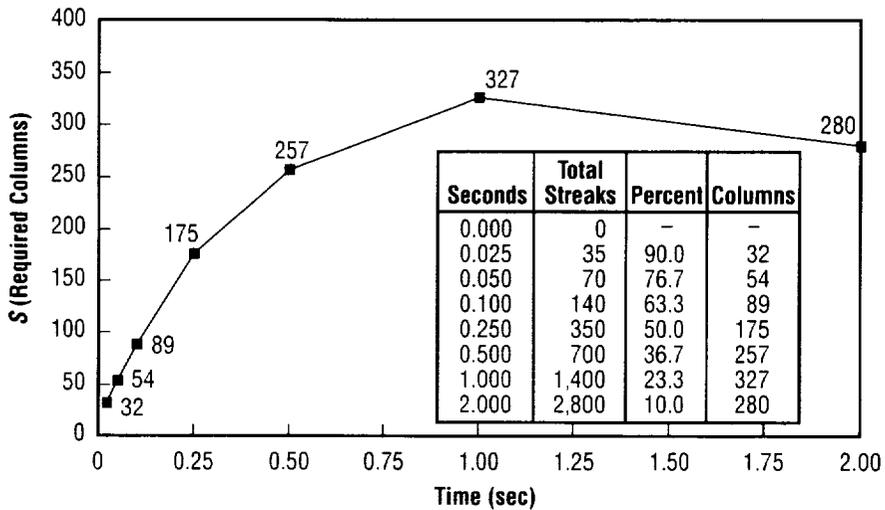
Figure 8. Number of required columns for redline violation with 200-fps camera.

2.3 Development and Testing of High-Speed Observer System

Development of the HSO system was accomplished in several stages:

(1) Testing HSO streak detection software with streaks simulated on 256 × 256 pixel HSO image format
(2) Testing the capability of the HSO system to detect streaks from standard video tapes of SSME tests where streaks were recorded
(3) Testing the capability of the HSO expert system to detect redline violations from generated data
(4) Testing the HSO streak detection and expert system in the test stand environment.

In order to test the HSO system capability to detect streaks, two scenarios were used. The first method of detection used the DALSA camera and simulated streak conditions.

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For the second method, videotapes of several different SSME tests were obtained and processed. In some of the videos analyzed, the frame rate was 30 fps, and thus the high-speed capabilities of the HSO system were not faithfully tested in those sequences. An example run using high-speed video (200 fps) of SSME test 901–853 is included in section 3.

The third step restricted itself to the expert system algorithms. Simulated streak column data were put into the expert system to determine whether or not the redline violation algorithm worked properly.

The fourth step was the installation of the HSO system at SSC. During the week of June 23, 1997, the HSO hardware was installed into the A1 test stand. The high-speed digital camera was mounted on level four to view the SSME plume. The image processing unit was installed inside the hard core on level four. A remote-controlled computer was installed in the A-Side Test Control Center and the fiber optic communication link was established between the remote-controlled computer and the image processing unit. After a systems check was performed to verify that the hardware was functioning, the HSO began recording data during a series of SSME tests on the A1 test stand the week of July 7, 1997. Over 25 SSME tests have been monitored. Example runs from the actual recovered test image data recorded by the HSO system are included in section 3.

3. RESULTS

Section 3.1 includes the analyses of the video of SSME test 901–853 and the actual HSO data from two SSME tests at SSC, tests 904–361 and 901–932.

3.1 SSME Test 901–853

This SSME test was performed on January 25, 1996, at SSC on test stand A1. A number of large streaks were visible during this test. The test was cut off early by a human observer and the engine suffered damage. Videotape of this SSME test was used to develop the HSO expert system. Figure 9 shows the mean plume intensity during SSME test 901–853. Streaking induces a plume brightening and this greater intensity is noted as plume streaks in figure 9.
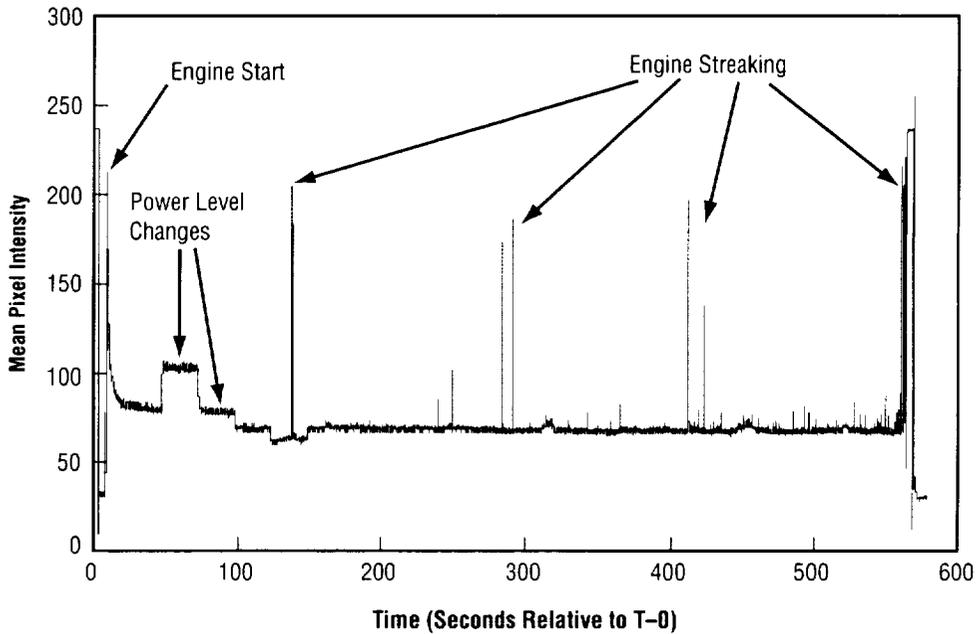

Figure 9. Test 901–853 mean plume intensity.

Figure 10 provides a magnified view of the HSO analysis for the first streak occurring at ≈140 sec. A redline violation occurs and was noted by the HSO expert system. The number of columns with streaks together with the continuing nature of the streaking during the five frames preceding the bold black line in the center of figure 10 produced a redline violation within 25 msec at frame 322.

HSO operational characteristics:
Frame acquisition rate: 200 fps
Image size: 256 × 256 pixels
Region of interest: 21 tiles in 7 columns, 3 rows, 3 overlapping columns
Size: 31 × 47 (1,457 pixels)
Threshold: 48

Quality region:
Size: 5 × 5 pixels
Threshold: 48
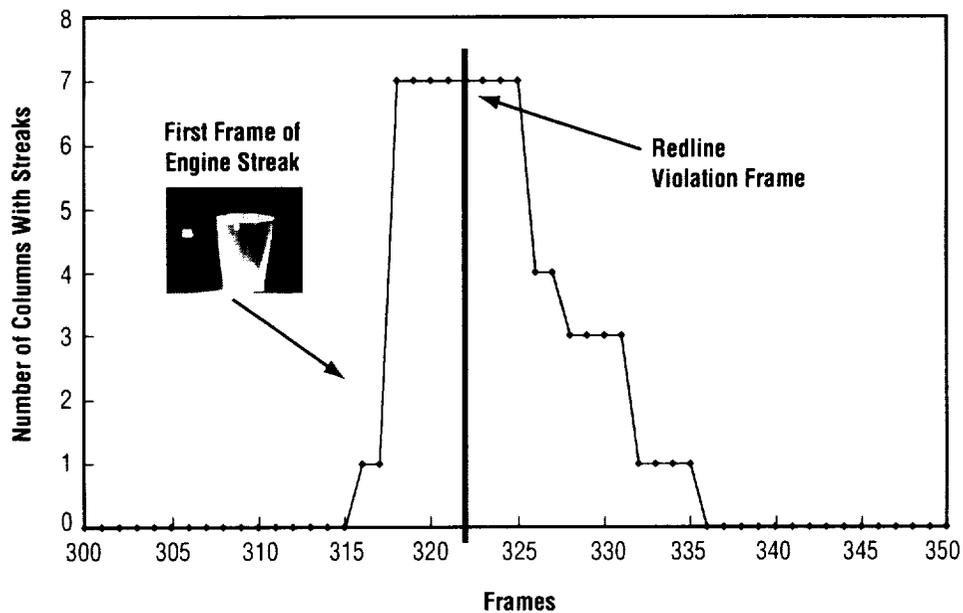
Figure 10. HSO analysis of first streak phenomenon for SSME test 901–853.

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3.2 SSME Test 904–361

This SSME test occurred at the B1 test stand at SSC on September 3, 1998. Two streaks were detected in the early startup phase, but no streaks were detected after that, as shown in figure 11. Test duration was 750 sec.

HSO operational characteristics:
Frame acquisition rate: 207 fps
Image size: 256 × 256 pixels
Region of interest: 21 tiles in 7 columns, 3 rows, 3 columns overlapping
Size: 31 × 46 (1,426 pixels)
Threshold: 16

Quality region:
Size: 5 × 5 pixels
Threshold: 16

Engine startup produces a situation where tile values indicate streaking. From the initial testing phase at SSC, it was determined that the expert system should be engaged only after mainstage is attained.
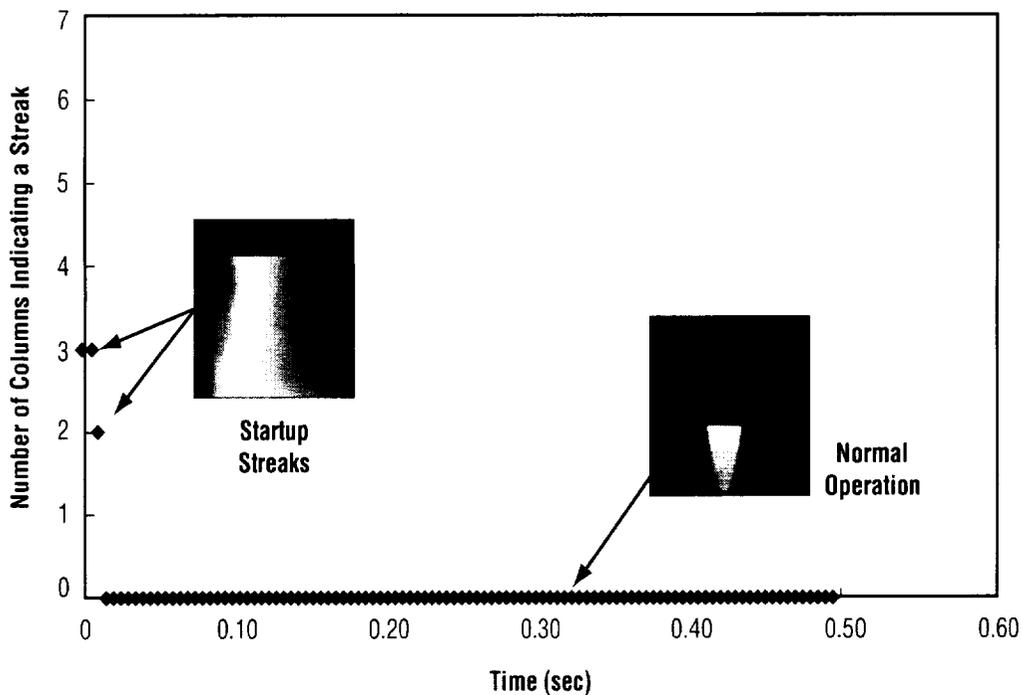

Figure 11. HSO analysis of SSME test 904–361 streak data from first 440 frames.

3.3 SSME Test 901–932

This SSME test occurred at the A1 test stand at SSC on August 23, 1997. As shown in figure 12, there were numerous streaks detected early in the startup phase but no anomalous streaks were detected. The camera was in the direct path of an exterior wall nozzle leak and the data were unusable after the camera malfunctioned due to overheating. Another problem experienced during the test was an incorrect exposure setting for the Mach disk. This overexposure caused the CCD array in the camera to bloom, a common phenomenon experienced in CCD array cameras when overexposed. To prevent this from creating false streaks, the camera is turned on the camera mount in such a way that the blooming effect is orthogonal to the direction of columns.

HSO operational characteristics:
> Frame acquisition rate: 175 fps
> Image size: 160 × 160 pixels
> Region of interest: 21 tiles in 7 columns, 3 rows, 3 columns overlapping
> Size: 48 × 90 (4,320 pixels)
> Threshold: 128

Quality region:
> Size: 5 × 5 pixels
> Threshold: 128
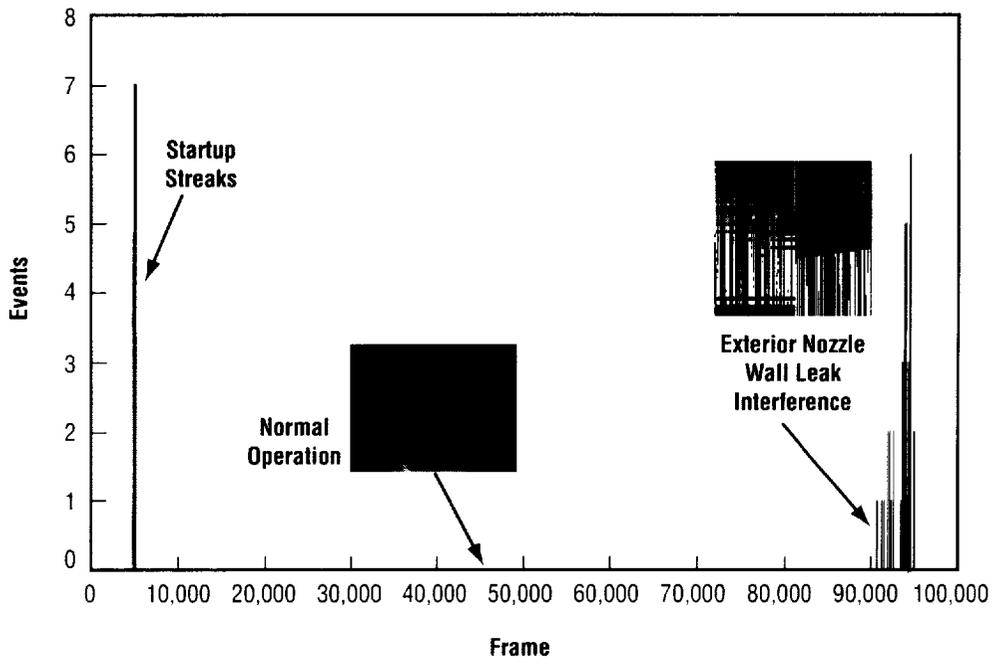
Figure 12. HSO analysis of engine test 901–932.

4. DISCUSSION

The HSO system has the ability to monitor SSME tests and quickly report the occurrence of anomalous engine streaking. The hardware and software systems are easily reconfigurable with off-the-shelf hardware and software and can provide streak data for health monitoring of LH_2-lox engines. Additionally, the HSO system can be used for posttest analysis of all plume events. Small, short-duration streaks can be evaluated against hardware inspection results and streaks correlated with hardware failure.

Several improvements to the current HSO system are envisioned. A remote camera interface utilizing a fiber optic cable between the DALSA digital camera and the image processing unit would eliminate the 40-ft restriction of cable length. This would permit the camera to be as much as 3 km from the image processing unit and would eliminate the need for a remote computer system to operate the image processing unit as HSO is now configured. Additionally, up to four cameras can be added to this system in a ring arrangement. These additional cameras would add to the image processing capacity and diminish the speed of image analysis.

The aerospike engine utilizes a ramp to guide engine exhaust as compared to a conventional nozzle for the SSME. Because the aerospike exhaust system is fundamentally different than that of an SSME, monitoring all aerospike engine plumes with the HSO system would require three cameras: Two to monitor the ramp, one on each side, and one to monitor the gas generator exhaust, which exits below the ramp. Images from earlier aerospike engine testing have revealed streaking from thrusters and have suggested that the "tile and column" image analysis approach to streak detection is reasonable. A variant of this approach encompassing each thruster would be employed to detect streaks. The same approach could be used to analyze the gas generator exhaust. Alternatively, a more coarse approach could be used where the average intensity of the plume is monitored to assess anomalies.

Upon completion of a developmental program, an operational system could be developed with an emphasis towards miniaturization. Image processing algorithms could be programmed into computer chips and with current state-of-the-art video camera miniaturization, a complete HSO system could be made small and lightweight, possibly as small as a single circuit board.

The HSO system may be employed to detect and analyze events other than intensity changes. Any event that can be recorded by an imaging device and recognized by software can be monitored. Events such as motions of objects, or gas or fluid leaks that generate vapors or have other visible characteristics, can be detected and monitored. With the use of an infrared camera, fires and heating of areas can be observed and monitored.

REFERENCE

1. "Engine 0523 Test Failure: January 25, 1996: At Stennis Space Center," Board of Investigation Report, Marshall Space Flight Center, AL, March 1, 1996.

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T.J. Rieckhoff, M. Covan,* and J.M. O'Farrell*

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13. ABSTRACT (Maximum 200 words)

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