



High-Speed Observer: Automated Streak Detection for the Aerospike Engine

T.J. Rieckhoff

Marshall Space Flight Center, Marshall Space Flight Center, Alabama

M.A. Covan and J.M. O'Farrell

United Space Alliance, Huntsville, Alabama



The NASA STI Program Office...in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results...even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at (301) 621-0134
- Telephone the NASA Access Help Desk at (301) 621-0390
- Write to:
NASA Access Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320



High-Speed Observer: Automated Streak Detection for the Aerospike Engine

T.J. Rieckhoff

Marshall Space Flight Center, Marshall Space Flight Center, Alabama

M.A. Covan and J.M. O'Farrell

United Space Alliance, Huntsville, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

Acknowledgments

The authors would like to acknowledge the assistance of Phil Best and John Suter at Marshall Space Flight Center for their support and funding of development of the High-Speed Observer (HSO) program with the aerospike engine and Michael Ladner and Brian Sproles at Stennis Space Center for their continued support of the HSO program. We wish to thank William Doss and Kay Glover, editors, and Janine Roskowski, illustrator, Marshall Space Flight Center, Scientific and Technical Publication, for their insightful comments and expert help in preparation of this document.

TRADEMARKS

Trade names and trademarks are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

TABLE OF CONTENTS

1. INTRODUCTION	1
2. HIGH-SPEED OBSERVER SYSTEM	2
2.1 High-Speed Observer Hardware Upgrades	3
2.2 High-Speed Observer Software and Evaluation Model Modifications	4
3. AEROSPIKE STREAK DETECTION ALGORITHM	5
4. AEROSPIKE ENGINE RAMP CHARACTERISTICS	9
5. CATEGORIES OF HIGH-SPEED OBSERVER OBSERVED AEROSPIKE ENGINE EVENTS	10
6. CHARGE-COUPLED DEVICE BLOOM MITIGATION	12
7. RESULTS	14
7.1 Engine Test A1X019	14
7.2 Engine Test A1X020	14
7.3 Engine Test A1X021	14
7.4 Engine Test A1X022	14
7.5 Engine Test A1X023	15
7.6 Engine Test A1X024	17
7.7 Engine Test A1X025	17
7.8 Engine Test A1X026	17
7.9 Engine Test A1X027	17
7.10 Engine Test A1X028	17
7.11 Engine Test A1X029	18
7.12 Engine Test A1X030	18
7.13 Engine Test A1X031	18
8. DISCUSSION	20
BIBLIOGRAPHY	21

LIST OF FIGURES

1.	HSO camera and aerospike engine at SSC	2
2.	HSO hardware configurations	3
3.	Control value intensity determination for an image frame	6
4.	Candidate streak selection	6
5.	Streak growing algorithm	7
6.	Streak confirmation	8
7.	Aerospike ramp temperature-dependent lines and streak growth.....	9
8.	Categories of HSO observed events	11
9.	Growth of bloom during test A1X026	12
10.	Growth of bloom during test A1X027	13
11.	Growth of bloom during test A1X030	13
12.	Streak detection: test A1X023/frame 3021	15
13.	Intensity values used to determine a streak	16
14.	Power level and mixture ratio changes	19
15.	Plume streaks	19
16.	Glowing area on ramp and flex seal material	19

LIST OF TABLES

1.	Streaks detected in test A1X023	15
----	---------------------------------------	----

LIST OF ACRONYMS

CCD	charge-coupled device
fps	frames per second
FS	fuel side thruster
GB	gigabyte
HSO	High-Speed Observer
I/O	input/output
IRIG	interrange instrumentation group
LH ₂	liquid hydrogen
lox	liquid oxygen
MB	megabyte
MSFC	Marshall Space Flight Center
RAID	redundant array of inexpensive disks
SSC	Stennis Space Center
SSME	Space Shuttle main engine

TECHNICAL MEMORANDUM

HIGH-SPEED OBSERVER: AUTOMATED STREAK DETECTION FOR THE AEROSPIKE ENGINE

1. INTRODUCTION

During Space Shuttle main engine (SSME) firing, in both test and flight, visual streaking in engine plumes has been observed. Under normal circumstances, combustion of liquid hydrogen (LH₂) and liquid oxygen (lox) yields nearly transparent plumes. Bright, distinguishable streaks in engine plumes are possible indicators of abnormal events. The High-Speed Observer (HSO) concept demonstrator program began with the goal of demonstrating that SSME engine streaks, which might indicate engine malfunction, could be detected using video and automating the detection process. The program was extended to include development of an expert system that detects, quantifies, and reports anomalous streaks in the SSME plumes.

The HSO technology, developed for detecting and differentiating SSME plumes, has been extended to incorporate detection and differentiation of anomalous plume streaking for the aerospike engine structure and plume characteristics. In changing from SSME to aerospike plume analysis operation, both hardware and software upgrades were necessary. This memorandum documents upgrades to the HSO system and results of HSO monitoring of aerospike engine tests on the test stand A1 at Stennis Space Center (SSC).

2. HIGH-SPEED OBSERVER SYSTEM

The basic HSO system uses a 200-frames per second (fps), 256×256 pixel DALSA[®] CCD array camera to generate 8-bit gray scale digital images. This camera is mounted inside a PELCO[®] EHX6-12 explosion-proof housing for protection against the rugged environment experienced during testing. The HSO camera position at SSC used for single-engine testing is shown in figure 1. The current HSO system uses a dual Intel 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 interrangle instrumentation group (IRIG) timing and recorded on a 17.2-gigabyte (GB) redundant array of inexpensive disks (RAID) system. After testing, images are stored on an 8-mm Exabyte[®] tape and shipped to Marshall Space Flight Center (MSFC) for posttest analysis.



Figure 1. HSO camera and aerospike engine at SSC.

The aerospike engine configuration differs significantly from that of an SSME. Modifications to the method of operation of the HSO were made to accommodate engine differences. At present, only one side of a single module of the engine (cover photo) is being monitored for anomalous plume streaking with only one operational camera (HSO II) as shown in figure 2. Another camera (HSO III) will be added when the full-up configuration of the aerospike engine (two of the modules shown in the cover photo) is tested.

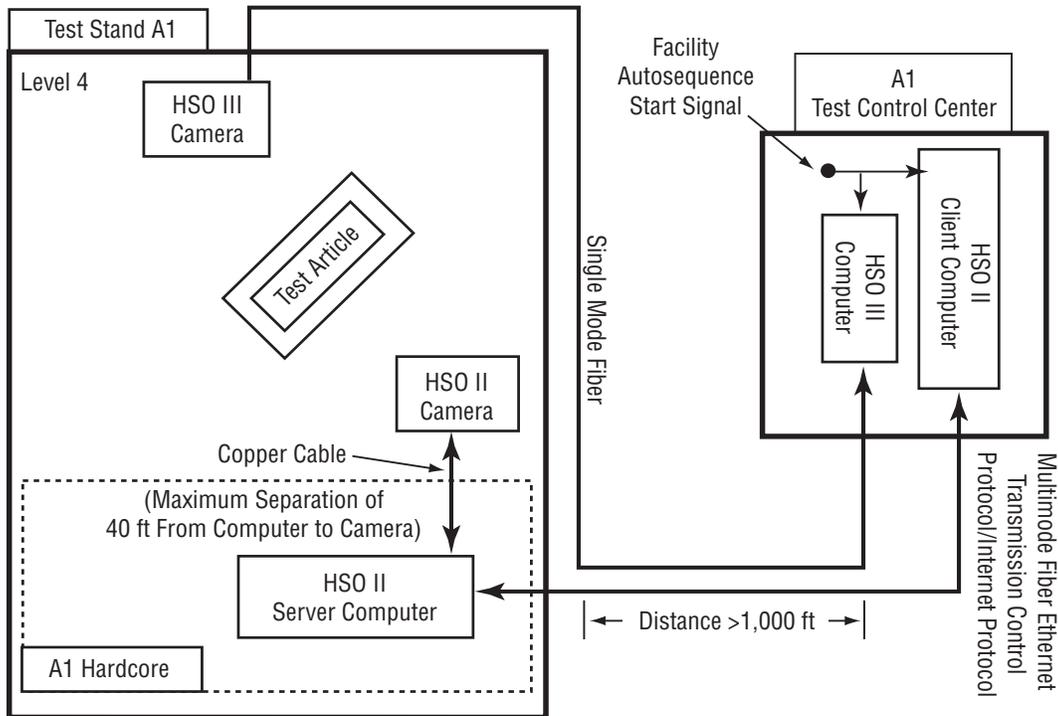


Figure 2. HSO hardware configurations.

2.1 High-Speed Observer Hardware Upgrades

Hardware upgrades to the HSO system included (1) installation of an input/output (I/O) board and communications link to detect test initiation and shutdown, (2) repositioning of the HSO client system and camera, and (3) a new replacement RAID disk system for the HSO server.

- (1) Installation of an I/O board and communications link to detect test initiation and shutdown—A communication link was established to allow the HSO system access to the test start and test cutoff signals.
- (2) Repositioning of the HSO server system and camera—The HSO camera position at SSC for aerospike engine tests has been changed from the position of the last series of SSME tests. The ideal camera position on the test stand would be perpendicular to the line of combustors and on or slightly above a plane horizontal with the midpoint between combustor exit planes and the edge of the ramp. Although, the view angle from the camera to the combustors is not a right angle, making a head-on view unavailable, it is sufficient to provide separation of combustor plume areas. The height positioning of the camera provides the necessary single line of reference at the combustor exit plane for the region of interest.

- (3) A new replacement RAID disk system for the HSO server—The previous 9-GB RAID system used to store images failed and a new disk system was necessary. The new system can store ≈ 17 GB and transfer data at 40 megabytes (MB)/sec compared to the old 9-GB system that had a 15-MB/sec data transfer rate. This provides additional capability for camera operation at maximum frame acquisition speed.

2.2 High-Speed Observer Software and Evaluation Model Modifications

Initial software upgrades to the HSO system included (1) an HSO server routine to monitor test status and initiate camera functions, (2) modification to region of interest, (3) elimination of quality region; subsequent changes in software included (4) a new streak detection algorithm.

- (1) Routine to monitor test status and initiate camera functions—A software routine was written for the HSO server to monitor the test status communications link and initiate camera operation upon receipt of the test initiation signal. The software also stops camera operation and initiates backup procedures when the test cutoff signal is received.
- (2) Modifications to the region of interest—Each side of the aerospike engine is composed of a set of combustors, each producing a plume to be monitored. As with the SSME plume monitoring setup, the region of interest was broken into separate columns, each column evaluating the plume of one combustor. There were ten such columns, with each column composed of three tiles. There were no overlapping tiles in the setup for monitoring this engine.
- (3) Elimination of the quality region—The quality region, centered on the Mach disc of an SSME plume, had been used as an intensity control area. An image was assumed to be valid if the quality region intensity remained above a threshold value. The aerospike engine has no such stable gray-scale value region readily available. At present, all images are assumed valid from engine start to cutoff, unless they are totally black.

As the testing program progressed, more software changes were necessary. The algorithm to detect streaks was determined to be inadequate to resolve the type of streaking observed in test A1X023. Whereas SSME plume streaks are broad and generally increase brightness over a large area, aerospike plume streaks observed tend to be thin and do not necessarily increase the brightness level significantly. A new algorithm was implemented to detect streaks.

- (4) Development of new streak detection algorithm—A new algorithm to detect streaks was developed. This algorithm searches a path parallel to the ramp edge, looking for intensity changes indicative of streaks. Upon finding such intensity changes, an attempt is made to grow a path of pixels with similar intensity values from that point to a point near the thrusters on the opposite side of the ramp. If such a path can be found, the path is judged to be a streak.

3. AEROSPIKE STREAK DETECTION ALGORITHM

The SSME streak detection algorithm was found to be inadequate for detecting streaks in plumes produced by an aerospike engine. The SSME algorithm employed a threshold tile algorithm to detect streaks. The arrangement of aerospike thrusters required reassessment of column structure for detecting brightness increases:

1. Over time, aerospike plumes generate an intensity profile with both high and low average levels. By setting a general, static streak, intensity threshold, as with the SSME streak detection algorithm, either many possible streaks were removed from consideration or during certain time periods everything was considered a streak.
2. The aerospike cooling ramp induced bright areas having many characteristics of plume streaks. There was no such structure needing compensation with SSME plume analysis.
3. Whereas SSME streaks are often broad and provide substantial brightness increases in plumes, aerospike streaks are thin and do not significantly raise overall brightness levels.
4. An additional problem, which became apparent when streaks were present, was water on the camera faceplate. Because of the thin nature of the aerospike plume streaks, a droplet of water on the camera faceplate can cause a dark area in the image and streaks that cross into this area appear to be discontinuous across the plane of the ramp.

To account for these differences, a new streak detection algorithm was created. First, a control intensity value for streak detection is determined for each frame (fig. 3):

1. A column of pixels midway down the ramp from the thrusters to the end of the ramp is chosen to be a control column.
2. An average of the pixel intensity values along the column, which are less than the “wash-out” intensity of a bloom region, is obtained.
3. A maximum of the pixel intensities, which are less than the wash-out intensity of a bloom region, is also obtained.
4. The control intensity value for detecting streaks is determined as 80 percent of the difference from the average to the maximum intensity.

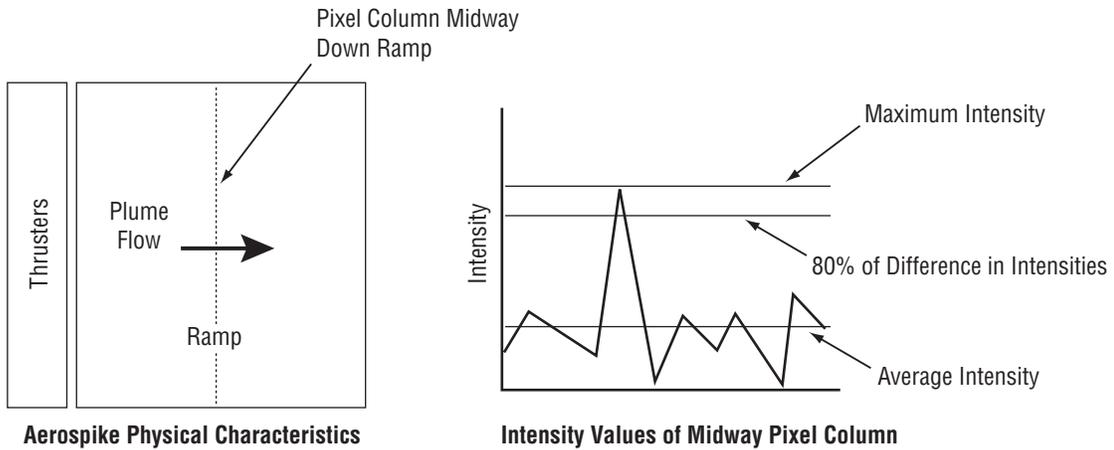


Figure 3. Control value intensity determination for an image frame.

Next, candidate streak seed points are chosen from local maxima along a row of pixels at the edge of the ramp (fig. 4):

1. Along the column of pixels at the end of the ramp area, local maxima are consecutively selected and tested.
2. If a local maximum value is not greater than the control intensity, it is not considered as a candidate for a streak.
3. If a local maximum value is greater than the control intensity, a streak growth algorithm, using local greatest intensity values is initiated.

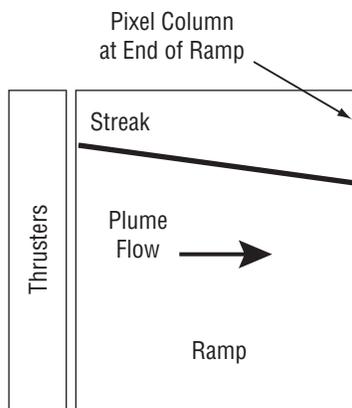


Figure 4. Candidate streak selection.

Candidate streaks are grown from local intensity value maxima in the pixel column at the end of the ramp (fig. 5):

1. Local maximum intensity values above the control intensity value provide initial seeds for the growth algorithm.

2. Three adjacent pixels in the streak growth direction; i.e., toward the thrusters, are tested.
3. The pixel with the highest value within 15 percent or above the control intensity value is chosen as the next seed pixel.
4. If all three pixels have intensity values <15 percent of the control value, the next three adjacent pixels are tested. This process is repeated up to five times. If no seed pixel is detected, the streak growth is ended and the next local maximum in the pixel column at the end of the ramp is inspected.
5. If the column of pixels near the thrusters is encountered, the algorithm labels the starting local maximum as a streak generating pixel.

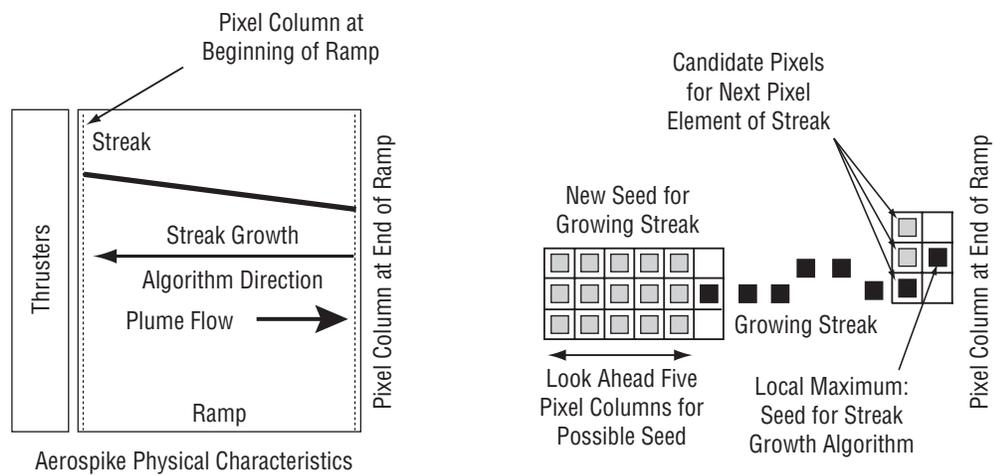


Figure 5. Streak growing algorithm.

The streak length and streak growth direction confirm candidate streaks (fig. 6):

1. Each thruster provides a lane for growth of a streak; i.e., a streak should not enter the plume of two thruster plumes. There are 10 thrusters on the aerospike panel and the number of pixels in a column covering a single plume area averages ≈ 110 . Therefore, no streak should grow in the column direction more than 11 pixels from the starting pixel column location.
2. The pixel distance from the end of the ramp to the beginning of the ramp near the thrusters averages 120 pixels, a growing-slope ratio of ≈ 10 percent.
3. A growing-slope ratio bound of ≈ 15 percent, evaluated as the streak is growing, serves to keep the streak growth reasonably within a plume. This check is initiated only after the streak has grown by 10 pixels.
4. If a growing path reaches the pixel column at the beginning of the ramp, this indicates a reportable streak was found.

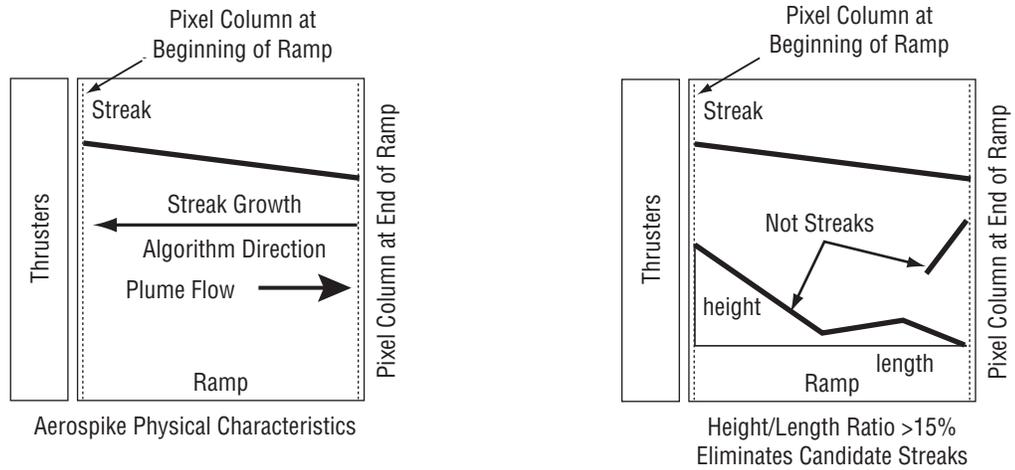


Figure 6. Streak confirmation.

This streak detection algorithm was tested and found to recognize streaks in aerospike engine plumes. It can discriminate many of the near streak-type events from true streaks and deal with certain types of anomalous events which prevent contiguous pixels in a streak from being illuminated; i.e., water droplets on the camera faceplate. This algorithm was first implemented on aerospike engine test A1X023 data.

4. AEROSPIKE ENGINE RAMP CHARACTERISTICS

The ramp of the aerospike engine is cooled much like the nozzle bell of the SSME. Several temperature-dependent areas on the ramp produce light colored areas that often appear in the same intensity range and run in the same directions as streaks (fig. 7). The streak growth algorithm attempts to take this into account as it traverses the path of the suspected streak.

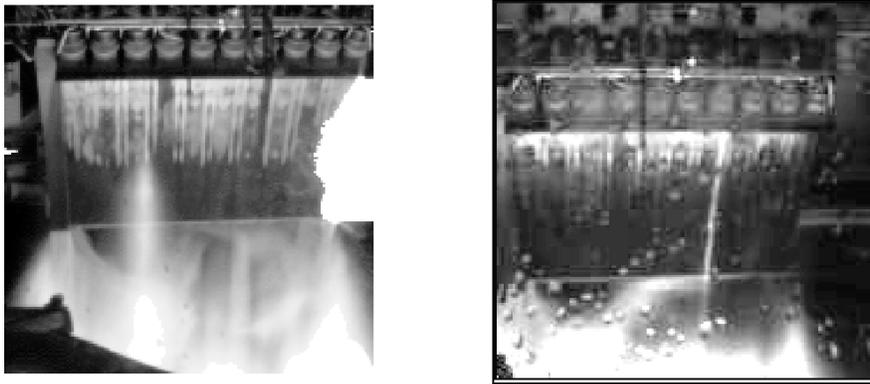


Figure 7. Aerospike ramp temperature-dependent lines and streak growth.

Note that true engine streaks are usually visible from the end of the ramp up to the thruster nozzle exit area. Because of the higher average intensity value of pixels in the nozzle exit area, the differences in intensity of streak pixels to pixels surrounding the streak in the thruster nozzle exit area are consequently a little less.

If an engine streak exists and a growth path reaches one of the temperature-dependent streak patterns of the ramp near the nozzle exit area, it is probable that the growth algorithm will complete the path and a streak will be reported, since the intensity of the streak and the temperature dependent area become very similar. Conversely, if a streak does not exist, it is entirely possible that a partial streak growth path matches with one of the temperature dependent high intensity areas and the streak growth algorithm will push forward to the beginning part of the ramp and report a streak.

The 80-percent value between the maximum and the average value for a pixel row midway between the dark end section of ramp area and lighter nozzle exit area portions of the ramp will exclude many false streaks that would grow along a ramp temperature induced intensity line since intersections with these lines are included in the average calculation. However, close-in to the thruster nozzle exit planes, nearly all streak candidates will finish their growth paths. Most incomplete growth paths are weeded out early and certainly before 90 percent of a complete streak path is final.

5. CATEGORIES OF HIGH-SPEED OBSERVER OBSERVED AEROSPIKE ENGINE EVENTS

Several types of events have been observed during aerospike engine testing. None have led to catastrophic failure; therefore, none are judged to be critical. Some have, however, been associated with damage to thrusters. Most of these events (shown in fig. 8) are plume fluctuations that have not been correlated to any specific event. These events do produce spikes in the average intensity data calculated across one row of pixels parallel to the lower edge and in the midsection of the ramp.

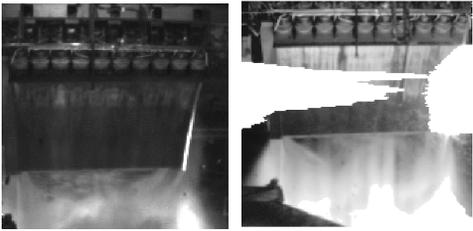
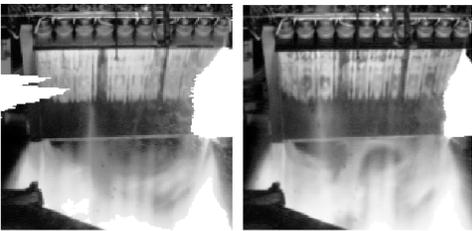
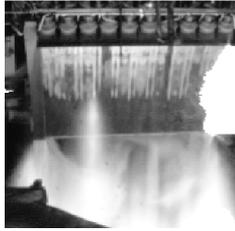
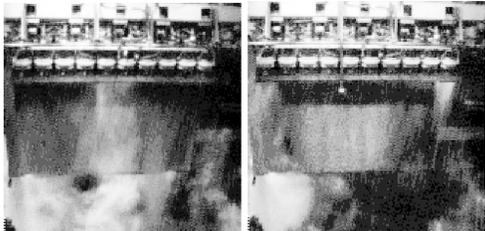
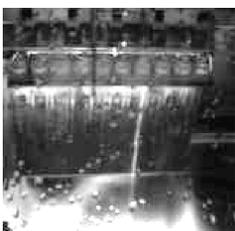
Category	Description	Examples
CCD Bloom	Maximum intensity region, derived from CCD pixel voltage overflow. All pixel values in this region have numeric value 255.	
Light Intensity Linear Plume Anomaly	Very diffuse streak-type phenomenon. Boundary not well defined. Insufficient intensity to be considered a streak.	
Strong Intensity Linear Plume Anomaly	Boundary not well defined. Sufficient intensity to be considered a streak.	
Startup Pop	Strong intensity linear phenomenon, extending from thruster nozzle exit plane to midramp area. Occurs during startup.	
Debris Induced Streak	Linear plume phenomenon caused by debris hitting the plume. Starts from a position below the thruster nozzle exit planes.	
Engine Produced Streak	Well defined border. Intensity much greater than surrounding pixels. Starts from thruster nozzle exit planes.	

Figure 8. Categories of HSO observed events.

6. CHARGE-COUPLED DEVICE BLOOM MITIGATION

Blooming (a voltage well of a pixel fills, spilling charge into adjacent pixels) has become a problem for capturing data near the outboard side of the present aerospike engine configuration. An ablative layer was applied to the outboard side of the engine ramp. This layer glowed brightly during engine firing and produced substantial blooming in the DALSA Camera CCD. The intensity of the outboard ramp edge overfills pixel charge wells and large areas of the ramp can be obscured due to the bloom. No significant information can be gained from this area.

Blooming on the HSO DALSA camera spills charge directionally along a column of pixels. On tests A1X024–A1X026, the charge spilling direction of the camera was directed onto the ramp area from the edge (fig. 9). To mitigate the effects of blooming on the HSO camera, the camera was turned 180 degrees. Since the bloom originated near the edge of the ramp, this reversal of charge spilling direction within the camera allowed the charge to drain away from the ramp area.

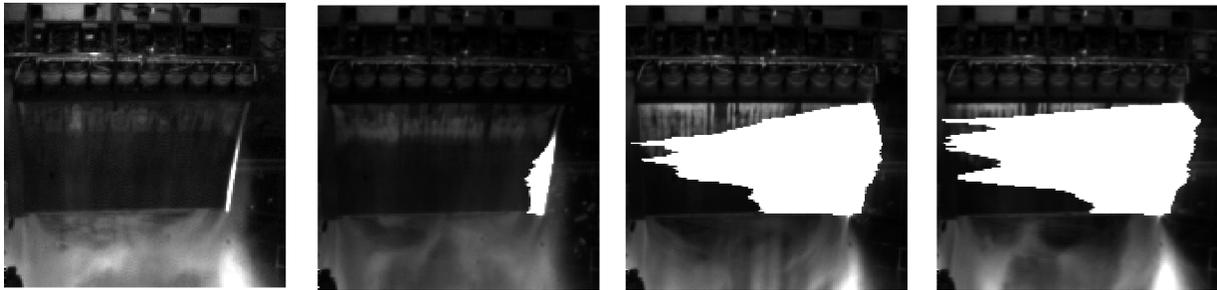


Figure 9. Growth of bloom during test A1X026.

Turning the DALSA camera 180 degrees in its mount partially mitigated the blooming problem. As shown in figure 10, the direction of blooming moved away from the origination area on the ramp toward the frame edge. Note the bloom direction travels in the opposite direction from that in figure 9. A wraparound effect, however, continued the bloom and made it reappear on the opposite side of the frame. At 100-percent power level, the bloomed area entered the ramp area from the side of the frame opposite the area where the bloom initiated and eventually touched the area where the bloom had initiated. Even at power levels <100 percent, it appeared the distance from the bloom initiation point to the frame edge was not sufficient to absorb enough energy to prevent the wraparound blooming effect.

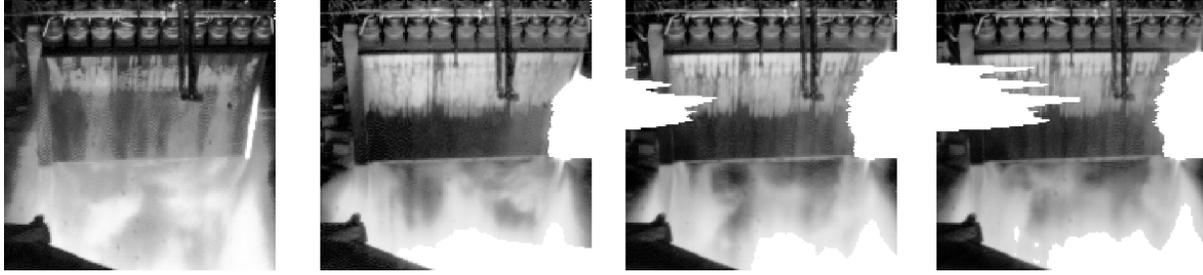


Figure 10. Growth of bloom during test A1X027.

Since the bloom originated in an area at the side of the ramp, turning the camera, so that the bloom proceeded parallel to the plume flow across the ramp, allowed the camera CCD to bloom, yet preserved much of the image for streak analysis. Figure 11 illustrates the growth of the bloom. Only the region directly below or above the glowing ablative layer is affected by the bloom, permitting streak analysis of most of the thruster exhaust plume area.

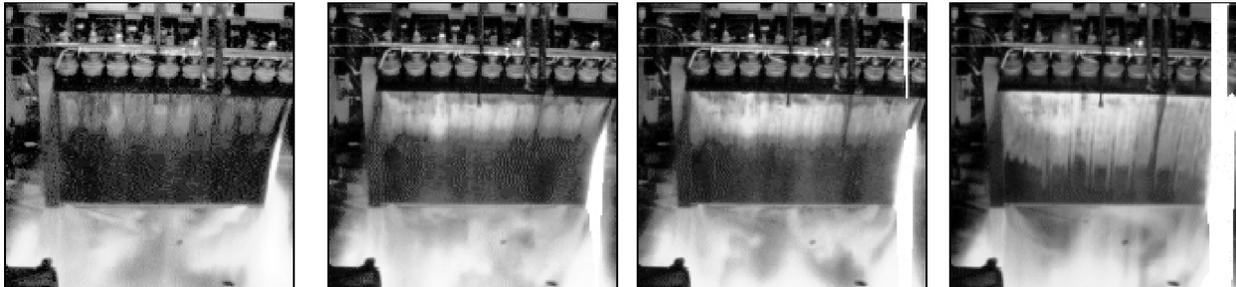


Figure 11. Growth of bloom during test A1X030.

7. RESULTS

Data from thirteen aerospike engine tests at SSC, A1X019–A1X031, have been obtained and processed. The following section includes the analysis and results of that HSO data. Engine test A1X023 motivated the change in streak detection algorithm. Tests preceding A1X023 were reevaluated using the newer streak detection algorithm.

In addition to the streak algorithm being tested on data from each test, each data set was observed visually and observations recorded. This was done to check the accuracy of the streak detection algorithm. It is sometimes difficult to determine exactly on which thruster an event occurred and the event from the designated thruster may have occurred on the adjacent thruster plume boundary. The best estimate of the origin of the event is listed.

7.1 Engine Test A1X019

This aerospike engine test was performed at SSC on test stand A1 on Wednesday, November 17, 09:41:43, 1999. No substantial streaks were observed by the HSO system and visual inspection of data revealed no significant streaks.

7.2 Engine Test A1X020

This aerospike engine ignition test was performed at SSC on test stand A1 on October 27, 1999, at 6:20 p.m. No substantial streaks were observed by the HSO system and visual inspection of data revealed no significant streaks.

A series of small diffuse anomalies occurred between 300:18:20:26.619 and 300:18:20:26.642 c.s.t. Another very diffuse streak-like anomaly occurred at 300:18:20:25.372 c.s.t.

7.3 Engine Test A1X021

This aerospike engine test was performed at SSC on test stand A1 on November 11, 1999. The test ran the planned 10 sec. No substantial streaks were observed by the HSO system and visual inspection of data revealed no significant streaks.

There were numerous small diffuse streaks observed on this test. Sixteen of the anomalous events were on fuel side thruster No. 1 (FS–1), four were on FS–3, three were on FS–6, one was on FS–5, and one on FS–8.

7.4 Engine Test A1X022

This aerospike engine test was performed at SSC on test stand A1 on November 22, 1999. No substantial streaks were observed by the HSO system and visual inspection of data revealed no significant streaks.

7.5 Engine Test A1X023

This aerospike engine test was performed at SSC on test stand A1 on December 18, 1999. Planned duration of the test, 10 sec, was achieved.

The streak detection algorithm detected streaks in frames 2998, 3003–3005, 3021–3027, and 3169. Visual inspection of image data revealed streaks observed in frames 2997–2999, 3003–3005, 3019–3027, 3111, and 3169–3172 at thruster FS–4. Posttest inspection of the hardware revealed erosion in this thruster.

Table 1 lists the frames where a streak was reported by the new streak detection algorithm. The older streak detection algorithm had failed to detect any streaks during this test. Also listed in table 1 are the 80-percent level intensity control value, the intensity value observed for the local maximum which was selected as the seed point for growing possible streak, and the location of the seed point for growing the streak path. Figure 12 illustrates the type of streak observed during test A1X023.

Table 1. Streaks detected in test A1X023.

Frame	80%	Seed Value	Location
2998	32	32	(114, 70)
3003	37	40	(114, 69)
3004	38	41	(114, 70)
3005	36	41	(114, 69)
3021	57	71	(114, 70)
3022	56	64	(114, 70)
3023	67	88	(114, 70)
3024	65	79	(114, 70)
3025	41	50	(114, 69)
3026	32	43	(114, 69)
3027	42	60	(114, 69)
3169	32	38	(114, 70)

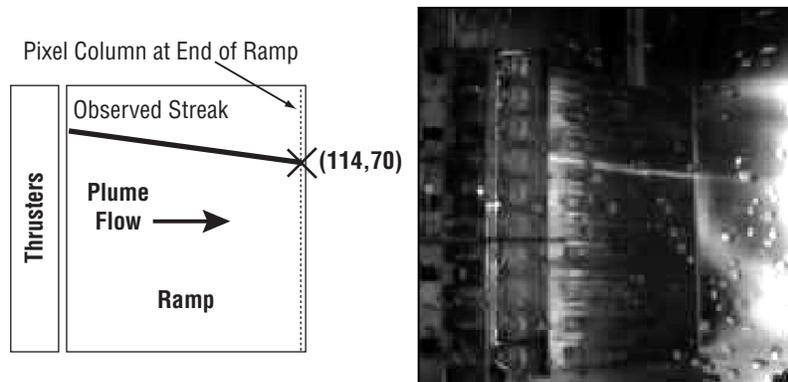


Figure 12. Streak detection: test A1X023/frame 3021.

The streaks noted in test A1X023 are long and thin; they begin at the thruster exit plane and extend past the ramp. The boundaries of the streaks are well defined with intensity levels within the streaks much greater than the average intensity of the surrounding pixels.

Figure 13 illustrates the operation of the streak detection algorithm. The three intensity values, the mean intensity of a column, the maximum intensity of the pixels in a column, and the control intensity used to determine a threshold value for local maxima selected as seed pixels, are shown in the figure from 0 to 4200 frames. A closeup of the region from frames 2990 to 3040 shows the pixels chosen as seed points and their relation to the control intensity.

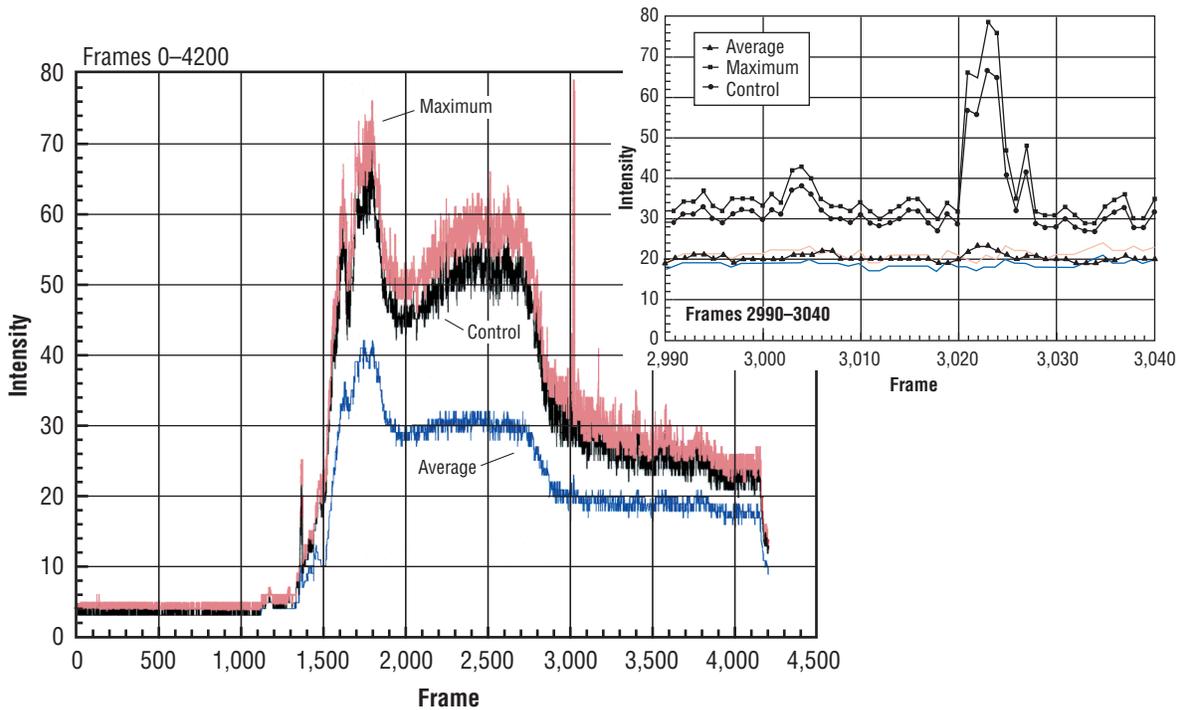


Figure 13. Intensity values used to determine a streak.

Streaks are usually the brightest elements in a frame and are therefore related to the maximum intensity. The streak intensity value changes along the length of the streak path and a range of values must be allowed to admit enough values along the streak path for the streak path to reach the nozzle exit plane. The average intensity provides a floor for the intensity values along a column. The intensity of this floor changes with each frame. In figure 13, near frame 1750 the average intensity is ≈ 40 , whereas near frame 3250 the average intensity is ≈ 20 , indicating an overall average brightness change of ≈ 20 units between control columns in the two frames. The nonnormalized intensity value of ≈ 75 near frame 1750 does not indicate a streak when normalized with the high average column intensity, whereas the nonnormalized intensity value of 79 at frame 3024 normalized against the control intensity of ≈ 20 , indicates a possible streak.

7.6 Engine Test A1X024

Aerospike engine test A1X024 was performed on test stand A1 at SSC on Friday, January 21, 2000, at 10:09 p.m. c.s.t. The test ran the planned 60 sec. No substantial streaks were observed by the HSO system and visual inspection of data revealed no significant streaks.

7.7 Engine Test A1X025

The aerospike engine test A1X025 occurred at SSC on Thursday, February 3, 2000, at 16:50 p.m. c.s.t. Planned duration of the test, 125 sec, was achieved.

Video real-time observation by test stand operators indicated three significant streaks from the thrusters. Preliminary inspections showed several of the base flex seal straps to be broken and several burnthrough areas in the base flex seal covering. Tactile inspection of the thrusters indicated a coolant channel burnthrough in two thrusters.

Due to blooming, no substantial streaks were observed by the HSO system and visual inspection of data was unable to reveal significant streaks.

7.8 Engine Test A1X026

The aerospike engine test A1X026 occurred at SSC on Wednesday, February 16, 2000, at 4:27 p.m. c.s.t. Planned duration of the test, 175 sec, was achieved.

HSO operated from T-5 seconds until the end of test as programmed, recording 30,800 images for an average run speed of ≈ 170 fps. No substantial streaks were observed by the HSO system and visual inspection of data revealed no significant streaks. However, blooming effects as shown in figure 9, such as experienced during the last tests, precluded detection of engine streaks over a large section of the ramp.

7.9 Engine Test A1X027

The aerospike engine test A1X027 occurred at SSC on Thursday, March 9, 2000, at 3:26 p.m. c.s.t. Planned duration of the test was 220 sec. The test was terminated at 75.44 sec by the Fuel Pump Discharge Pressure Control Qualification limit. This was the first engine redline system cutoff.

The HSO system operated from T-7 sec until engine shutdown, recording 14,174 images for an average run speed of ≈ 173 fps. No substantial streaks were observed by the HSO system. Several flashes were observed during the test. These flashes were not considered anomalous.

7.10 Engine Test A1X028

The aerospike engine test A1X028 occurred at SSC on March 22, 2000, at $\approx 7:00$ p.m. c.s.t. The test duration was ≈ 225 sec.

The HSO system began operation at T-7 sec (82:19:00:00.470 c.s.t.), recording 38,498 images for an average camera speed of ≈ 170 fps. No substantial streaks were observed by the HSO system. However, several flashes were observed near the FS-3 and FS-4 thruster locations during the test.

7.11 Engine Test A1X029

The aerospike engine test A1X029 occurred at SSC on April 6, 2000 at ≈10:27 p.m. c.s.t. The test duration was ≈235.0 sec.

The HSO system began operation at T-7 sec (97:22:26:57.299 c.s.t.), recording 44,098 images for an average camera speed of ≈180 fps. No substantial streaks were observed by the HSO system. One faint flash was observed. This flash was not considered anomalous and was probably a debris-induced streak. However, bloom was still a problem, with at least 50 percent of the ramp area obscured by bloom during portions of the test.

7.12 Engine Test A1X030

The aerospike engine test A1X030 occurred at SSC on May 2, 2000, at ≈4:00 p.m. c.s.t. The test duration was ≈250 sec.

The HSO system began operation at T-7 sec (123:16:55:59:986 c.s.t.), recording 46,538 images for an average camera speed of ≈173 fps. No substantial streaks were observed by the HSO system. However, several small flashes were observed during the test. One faint flash at 123:16:57:37.838 c.s.t., another flash at 123:16:58:15.002 c.s.t., and a third very faint flash at 123:16:59:40.708 c.s.t. Rotation of the camera allowed the bloom to proceed vertically, providing a minimal area obscured by the bloom.

7.13 Engine Test A1X031

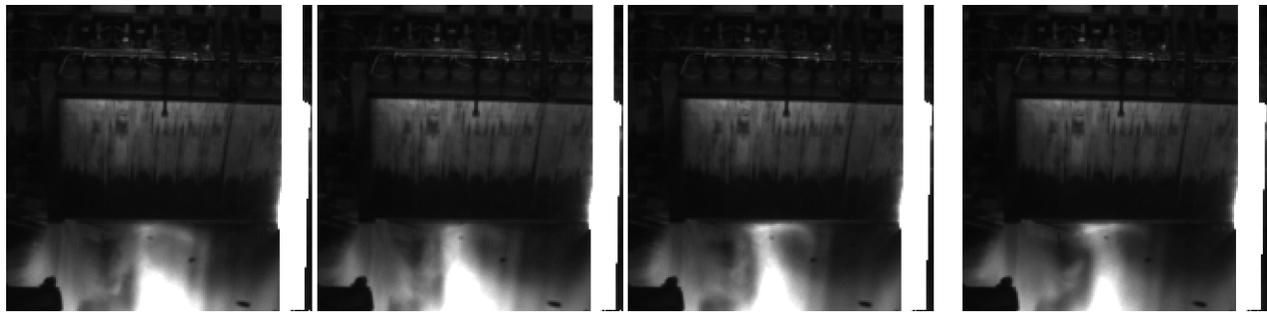
The aerospike engine test A1X031 was conducted at the SSC on May 12, 2000, at ≈4:30 p.m. c.s.t.. The test was terminated at ≈290 sec by the test conductor due to a flex seal burnthrough.

The HSO system began operation at 133:16:49:13.247 c.s.t. and ended operation at 133:16:54:09.290 c.s.t., recording 50,738 images over 296.043 sec for an average camera speed of ≈171 fps. No substantial streaks were observed by the HSO system.

Changes to the fuel mixture ratio and power level were evident in the aerospike engine plumes in the area just beyond the ramp. Figure 14 illustrates a narrowing of the bright area of the plume below the ramp, which corresponds to the change to a 63-percent power level and mixture ratio of 5.

Prior to the flex seal burnthrough, a number of streaks were observed in the plumes below the ramp. Figure 15 illustrates several such streaks. The streaks occurred in the region where the burnthrough was noted.

A glowing area appeared at the edge of the ramp, shown in figure 16, in the region of the burnthrough, well before the thermal protective flex seal material became evident as it dropped into the plume.



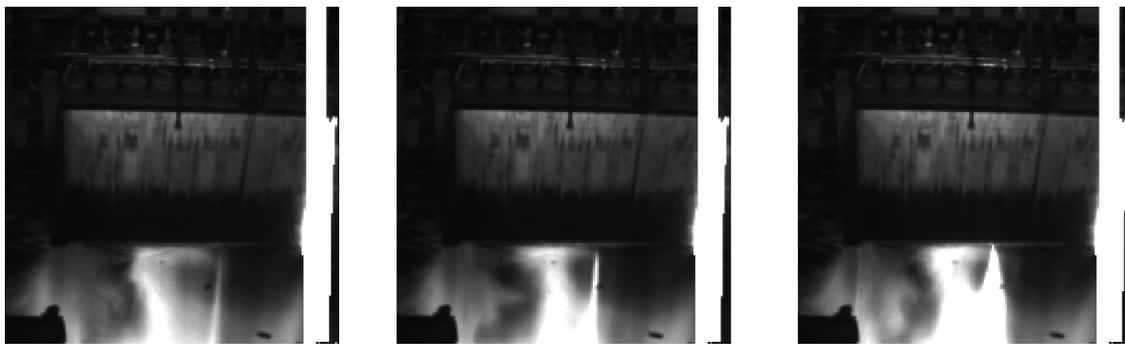
133:16:53:42.991

133:16:53:42.997

133:16:53:43.002

133:16:53:43.008

Figure 14. Power level and mixture ratio changes.

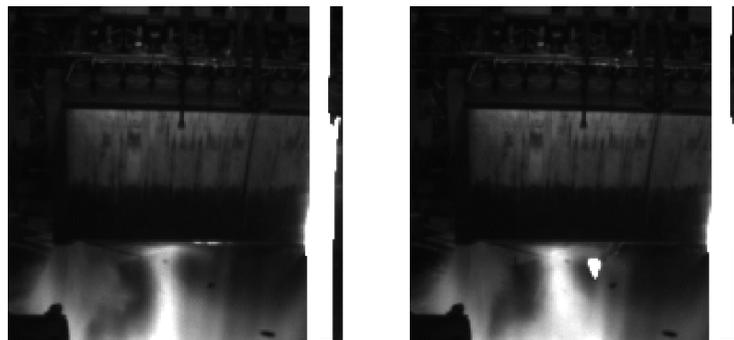


133:16:53:43.941

133:16:53:44.004

133:16:53:44.089

Figure 15. Plume streaks.



133:16:53:53.031

133:16:54:05.474

Figure 16. Glowing area on ramp and flex seal material.

8. DISCUSSION

The HSO system has shown the ability to monitor SSME and aerospike engine tests and quickly report the occurrence of anomalous engine streaking. The hardware and software systems are easily re-configurable with off-the-shelf hardware and software and can provide streak data for health monitoring of LH₂-lox engines. Additionally, the HSO system can be used for indepth posttest analysis of all plume events. Reported events can be evaluated against hardware inspection results and correlated with hardware failure.

From the testing accomplished using the new streak detection algorithm, major streaks were correctly distinguished from the myriad of minor fluctuations that occur during engine test. This technique is not limited to the aerospike engine characteristics and can be applied to the SSME plumes to detect streaks as well. Adaptation of the algorithm to streak detection in SSME plumes at the launch site is the next step in evolution of the HSO project.

Due to the wide range of intensities encountered in the aerospike engine plume images, it was natural to encounter bloom. The only possibilities for bloom mitigation for the DALSA camera presently used are reduction of the light entering the camera aperture or orientation of the camera so that bloom proceeds away from the area being investigated. The gray-scale intensity of light (0–255) in the areas not being affected by bloom averaged between 10 (dark areas) and 50 (near thruster exit planes) as compared to areas affected by bloom which had values >255, creating spillover to adjacent pixels. Solutions to bloom mitigation that reduced the intensity of light were not the most favored solutions. Such solutions would also reduce the ability of the system to accurately distinguish streaks, since the margin of error on streak intensity detection would be increased corresponding to the amount of light reduction. Fortunately, bloom mitigation was accomplished by orientation of the camera in a direction so that the bloom did not encroach upon the ramp area. In the future, the DALSA cameras employed will be upgraded to include antibloom technology.

BIBLIOGRAPHY

1. "Engine 0523 Test Failure: January 25, 1996: At Stennis Space Center," Board of Investigation Report, Marshall Space Flight Center, Alabama, March 1996.
2. Rieckhoff, T. J.; Covan, M.; and O'Farrell, J.M.: "High-Speed Observer: Automated Streak Detection in SSME Plumes," NASA/TM, Marshall Space Flight Center, January 2001.

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503				
1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE June 2001	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE High-Speed Observer: Automated Streak Detection for the Aerospike Engine			5. FUNDING NUMBERS	
6. AUTHORS T.J. Rieckhoff, M.A. Covan,* and J.M. O'Farrell*				
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Marshall Space Flight Center, AL 35812			8. PERFORMING ORGANIZATION REPORT NUMBER M-1005	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA/TM-2001-210879	
11. SUPPLEMENTARY NOTES Prepared for Vehicle and Systems Development Department, Space Transportation Directorate *United Space Alliance				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 35 Nonstandard Distribution			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A high-frame-rate digital video camera, installed on test stands at Stennis Space Center (SSC), has been used to capture images of the aerospike engine plume during test. These plume images are processed in real time to detect and differentiate anomalous plume events. Results indicate that the High-Speed Observer (HSO) system can detect anomalous plume streaking events that are indicative of aerospike engine malfunction.				
14. SUBJECT TERMS high-speed photography, photographic analysis, aerospike, engine streaks, image processing			15. NUMBER OF PAGES 28	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	