REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-98- 0477

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
30 April 1998

3. REPORT TYPE AND DATES
Final Technical Report

4. TITLE AND SUBTITLE
High speed/resolution/dynamic-range imaging system for subsonic and supersonic turbulent flows

5. FUNDING NUMBERS
F49620-95-1-0199

6. AUTHOR(S)
Paul E. Dimotakis, Daniel B. Lang, and Mark V. Wadsworth

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Graduate Aeronautics Laboratories
California Institute of Technology
Pasadena, Ca 91125

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
110 Duncan Avenue, Ste B115
Bolling AFB, DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-95-1-0199

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release, Distribution Unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Work performed under the sponsorship of this grant focused on instrumentation development leading to a high-speed, high-resolution and dynamic range digital imaging system, for use in subsonic and supersonic turbulent-flow applications, as well as applications in aerooptics and long-distance ground-based and air-borne platform observations. Accomplishments include the completion of an intermediate-capability system, based on a 1 k2 CCD, designed by JPL for the Cassini space mission and integrated for laboratory use at 10 frames/s, at full resolution, and 20 frames/s at half resolution (5122), the development and near-completion of a 1000 frame/s, 1 k2-pixel digital imaging (KFS) system, as described in the original proposal, and the specification and development of a high pulse repetition frequency (up to 1kHz), diode-pumped, high-average-power (> 100W at 532 nm), pulsed YAG laser system. A few remaining system components, as yet incomplete as of this writing, are expected to be completed, or delivered, during the current calendar year.

19980615 039

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

DTIC QUALITY INSPECTED 3

GRADUATE AERONAUTICAL LABORATORIES
CALIFORNIA INSTITUTE of TECHNOLOGY
Pasadena, California 91125

High speed/resolution/dynamic-range imaging system for subsonic and supersonic turbulent flows

Paul E. Dimotakis, Daniel B. Lang, and Mark V. Wadsworth

Air Force Office of Scientific Research
Grant No. F49620-95-1-0199

Final Technical Report: Period ending 28 February 1998

GALCIT Report FM98-8

30 April 1998

Summary/overview

Work performed under the sponsorship of this grant focused on instrumentation development leading to a high-speed, high-resolution and dynamic range digital imaging system, for use in subsonic and supersonic turbulent-flow applications, as well as applications in aerooptics and long-distance ground-based and air-borne platform observations. Accomplishments include the completion of an intermediate-capability system, based on a $1\,\mathrm{k}^2$ CCD, designed by JPL for the Cassini space mission and integrated for laboratory use at 10 frames/s, at full resolution, and 20 frames/s at half resolution (512^2), the development and near-completion of a 1000 frame/s, $1\,\mathrm{k}^2$-pixel digital imaging (KFS) system, as described in the original proposal, and the specification and development of a high pulse repetition frequency (up to 1 kHz), diode-pumped, high-average-power ($> 100\,\mathrm{W}$ at 532 nm), pulsed YAG laser system. A few remaining system components, as yet incomplete as of this writing, are expected to be completed, or delivered, during the current calendar year.

1. Introduction

The purpose of this instrumentation-development effort was to extend digital-imaging technology to allow high-speed and multidimensional imaging in fully-developed, subsonic and supersonic turbulent flows. This was a high-risk, collaborative effort, between,

- the Graduate Aeronautical Laboratories at Caltech (GALCIT),
- the Caltech Physics and Astronomy departments, and
- Computer Science department;
- the imaging group at the Jet Propulsion Laboratory;
- the Laser Division of the Lawrence Livermore National Laboratory;

and, for the high-power, pulsed-laser development,

- Cutting Edge Optronics, Inc.

The system is predicated on the development of an imaging system that can deliver a digital-image frame sequence:

a. at a resolution of 1024×1024 pixels/frame;

b. with a dynamic range in excess of 60 dB, *i.e.*, a signal amplitude-to-noise ratio of 1000:1, or, 10 bits/pixel, or greater (the system developed utilizes 12-bit A/D converters);

c. at a rate up to $\simeq 10^3$ frames/s;

and

d. capable of recording at least 1000 frames/run, or more.

Such a system places a severe strain on the various component technologies with the success of the overall effort relying on substantial advances in the state-of-the-art of the various subsystems that were necessary. In particular, the system specifications dictated advances that were realized in:

1. the illuminating (pulsed) laser, for high-frame-rate imaging of turbulent-flow fields;
2. the front-end (CCD) focal-plane image detector in the digital camera head;

3. the camera head, control electronics, and timing circuitry of the CCD imager;
4. the analog-to-digital (A/D) data-acquisition system;
5. real-time high-speed data compression;
6. the high-speed-data storage and transfer technology;

and

7. the subsequent multidimensional image data processing and visualization.

In addition to the primary support from this grant, the broadly-collaborative effort this development necessitated reliance on additional support from a variety of sources, also benefiting and leveraging work in other related efforts. These include funding and efforts supported by:

- AFOSR Grant No. F49620–94–1–0353, titled, "Chemical Reactions in Turbulent Mixing Flows" (PI's: P. Dimotakis and A. Leonard);
- AFOSR Grant No. F49620–93–1–0338, titled, "Interaction of Chemistry, Turbulence, and Shock Waves in Hypervelocity Flow" (PI: H. Hornung, *et al.*);
- the Caltech/JPL President's Fund (PI's: C. Martin and S. A. Collins);
- NSF Grant No. AST9618880, titled, "Ex-Post Facto Diffraction-Limited Imaging Through Atmospheric Turbulence" (PI: C. Martin, Co-PI's: P. Dimotakis and T. Prince);
- Caltech Northrop Chair (P. Dimotakis) and other funds,

as well as,

- JPL support and internal funding.

Preliminary and intermediate-technology parts of the system were completed earlier and have been in laboratory use for some time, permitting high-quality measurements to be realized for the first time. The remaining components of the system are expected to be completed during the current calendar year.

2. Technical report

2.1 Intermediate (Cassini) digital-imaging system

A preliminary version of the originally-proposed system was completed first, to permit us to gain experience on generic issues related to high-frame-rate and multidimensional imaging, before committing to the final design. This intermediate-technology system utilized a CCD detector designed by the JPL imaging group, with James Janesick as the principal designer,* that was used in the Cassini space mission. This in-house-developed digital-imaging system, dubbed the "Cassini system," uses a 2-readout-channel data-acquisition system, programmable-gain and -bandwidth preamplifiers, and 12-bit A/D converters with sufficient on-board storage for 42 full-resolution image frames (with byte packing). It delivers high signal-to-noise ratio images, at a resolution of 1024 × 1024 pixels, and can be framed at 10 frames/s, at full resolution (1024^2 pixels), or 20 frames/s, at a 512^2-pixel resolution (using on-board pixel binning before readout). In particular, the signal-to-noise-ratio performance of this system, at 1 k^2-pixels/frame and a 10 frame/s readout rate, with the CCD detector at room temperature, was comparable to that of cryogenically-cooled, commercially available digital-imaging systems available at the time. The latter, however, require several $(10-20)$ seconds/frame readout time.

The Cassini system has already been used in several AFOSR-supported efforts, including:

- scalar-field measurements in liquid-phase turbulent jets (Catrakis 1996, Dimotakis & Catrakis 1996);
- Image Correlation Velocimetry (ICV) exploratory studies of a cylinder wake and other test flows (Tokumaru & Dimotakis 1995), and of the flow over an accelerating NACA–0012 airfoil (Gornowicz 1997);
- in collaboration with Prof. Chris Martin (Caltech, Physics) and his group, in studies of atmospheric optical-propagation aerooptical phenomena using the Caltech 200″ telescope at Palomar (*cf.* Dimotakis 1998a);

as well as,

- studies of 3-D, spatial and space-time scalar fields in turbulent flows (continuing work in progress).

---

* Presently with PixelVision Corporation.

2.2 Thousand-frame/sec (KFS) digital-imaging system

During the first year of this effort, we became aware of two commercial, kiloframe/s CCD designs that were in progress (Lockheed/Martin and Reticon). Both these CCD's utilize a 32 readout-channel architecture. Our own development system was originally predicated on a 64 readout-channel design, *i.e.*, one that traded a more complex data-recording system, for lower bandwidth and noise.

As a safeguard against an unsuccessful development effort for the originally-envisaged, 64-channel, in-house high-frame-rate CCD imager, in collaboration with JPL, we decided to improve the preliminary design to allow for an increase in the individual channel A/D conversion rate, from the originally-specified rate of 20 MHz/channel, to 40 MHz/channel. The system, as it evolved, can accommodate both 32-channel and 64-channel CCD's and will be able to record data from a (purchased) kframe/s CCD, should that prove necessary. No such CCD's were available at the time of our proposal. We are happy to report that it proved possible to both increase the A/D conversion rate to 40 MHz, as will be documented below, and retain the Correlated Double Sampling (CDS) feature that is a necessary capability, if the low-noise, high-dynamic-range performance we must have is to be realized.

While two commercial prospects for CCD's have emerged during this year, our discussions with the two developers suggested that they do not have the signal-to-noise-ratio and sensitivity performance that is required. Both commercial designs include line-transfer technology and will be electronically gateable. While these are desirable features, they come at the expense of fill-factor (light-sensitive area fraction on the CCD), compared to full-frame CCD. This indicated early on that we should continue pursuing the collaborative CCD-development effort with the imaging group of the Jet Propulsion Laboratory. This effort is now nearly completed, with two CCD designs fabricated, as will be documented below.

The second design decision for the data-acquisition and control electronics entailed moving most of the analog electronics out of the camera head, where real estate is at a premium because of the large number of channels, and onto the A/D boards.

Thirdly, it was decided to proceed with a second-generation A/D board, building on the Model 1 version developed for the Cassini system described above, with 4 A/D-channels/board, so that a single VXI crate can accommodate 8 boards for a total of 32 channels. A second VXI crate can be added to increase the total to

64 channels, to accommodate other CCD designs in the future, should that prove necessary. This keeps the total system compact enough, even at 64 channels, to fit into a single rack enclosure. This represents a considerable improvement over the original design, as envisaged at the time of the proposal, in terms of portability and potential ease of use of the system under laboratory and field conditions.

The principal designer of the Cassini CCD was Jim Janesick, while at the Jet Propulsion Laboratory.** He was also responsible for the early exploratory designs of the KFS CCD, in conjunction with S. Andy Collins and S. Tom Elliott (JPL), and Dan Lang and Paul Dimotakis (Caltech). The principal designer of the two KFS CCD's is Mark Wadsworth, in collaboration with S. Tom Elliott, S. Andy Collins (JPL), in collaboration with Dan Lang, Paul Dimotakis, and Chris Martin (Caltech). The principal designer of the data-acquisition system and camera-head electronics is Dan Lang, in collaboration with Paul Dimotakis (GALCIT) and Stephen Kaye (Space Astrophysics Lab, Caltech). The KFS camera-head mechanical and cryogenic-cooling design was a collaborative effort between Paul Dimotakis, Dan Lang, and Pavel Svitek (GALCIT); and Brian Kern (Astronomy, Caltech) and Chris Martin (Physics, Caltech)

As regards the laser source, we were informed during the first year of this effort that the proposed laser vendor (Lumonics) that had given us a quote for a 1 kHz pulse repetition rate (PRF) Excimer laser (XeCl, 308 nm), had withdrawn the unit from the market. The highest rep-rate lasers of this kind presently offered produce a 300 Hz PRF, with lower energy/pulse relative to that required for gas-phase imaging. This was a serious setback to this effort. One possibility that emerged was a collaborative effort with the Laser Division of the Lawrence Livermore National Laboratory, who are interested in our image-technology development. They expressed a willingness to develop a pulsed laser for us, with the necessary PRF and energy/pulse. Unfortunately, the estimated (1.5M) budget for such a laser-development effort was not in hand. An alternate solution was arrived at, in the Fall of 1997, with a commercial vendor (Cutting Edge Optronics, Inc.) offering to develop a new doubled-YAG laser for us, utilizing diode-pump technology, with design assistance and technical monitoring by Lawrence Livermore National Labs and Caltech. This laser is presently under development and fabrication, with funding support from this grant as well as other sources (*cf.* Introduction), with an expected delivery date of end-of-September 1998.

** Presently, with PixelVision, Inc.

2.2.1 KFS CCD detector specifications

The design and optimization of the CCD detector for the KFS imaging system must contend with an important trade-off between signal-to-noise ratio and output frame rate. Considering the high pixel rates from each of the output channels, a high output frame rate dictates high-bandwidth output amplifiers with an attendant high readout-noise figure, as the noise spectrum subtended by the amplifier bandwidth increases.

The 10^3 frame/s specification, dictated by the turbulent flow and other flow imaging application requirements, requires 3-stage output amplifiers for each readout channel. For many applications, however, including some for aerooptics and atmospheric-turbulence research, for which low light levels are expected, it was decided that a 100 frame/s, or so, specification would suffice. For lower frame rates, two-stage, lower-bandwidth/-noise-figure amplifiers would suffice and also exploit the higher beam-quality output of the diode-pumped laser for gas-phase imaging applications, as will be discussed below.

Accordingly, two different CCD designs were implemented by Mark Wadsworth on the silicon wafer that was fabricated to produce these CCD's. These were dubbed the KFS32 and KFS32LN (low-noise), denoting the 32-channel readout-channels common to both designs. The design specifications for the two CCD's are listed below.

1. Specifications common to the KFS32 and KFS32LN CCD's.
    a. Number of output channels: 32.
    b. Full-well capacity: 100,000 e's.
    c. Number of A/D converter boards required: 8.
    d. Amount of frame store memory: 512 MBytes/board, or 4 GBytes total for 8 boards.
    e. Number of contiguous frames acquired using 4 GBytes of frame store memory:
        - Without compression: 2712.
        - With compression: 4000 to 8000 (depending on image features).[†]

[†] On-board, real-time, loss-less data-stream compression.

2. KFS32 CCD specifications.
    a. Maximum framing rate:
        - With current CCD timing microsequencer: 500 frames/s.
        - With second-generation microsequencer: 1000 frames/s.
    b. Estimated noise figure:
        - 125 frames/s: 50 e's RMS (2000:1 dynamic range).
        - 500 frames/s: 80 e's RMS (1250:1 dynamic range).
        - 1000 frames/s: 100 e's (1000:1 dynamic range).
3. KFS32LN CCD specifications.
    a. Maximum framing rate:
        - With either CCD timing microsequencer: 125 frames/s.
    b. Estimated noise figure:
        - 30 frames/s: 12 e's RMS (8300:1 dynamic range).
        - 125 frames/s: 30 e's RMS (3300:1 dynamic range).

More detailed documentation for these CCD's is included as an Appendix to this report.

The design dynamic-range figures above can be covered by the 4096:1 single-conversion dynamic range corresponding to the 12-bit A/D converters employed in the data-acquisition boards. The higher dynamic range expected at the lower framing rates of the KFS32LN, *e.g.*, $\lesssim$ 30 frames/s, can be accommodated by the multiple-conversion dither (staircase-reference) mode of the 12-bit A/D converters, as will be mentioned below. This data-acquisition feature can also be used for other, higher-dynamic-range data-input applications.

Once two of the next-generation CCD microsequencers (CCDTIM2) are completed, it will be possible to use 16 A/D boards, doubling the total buffer memory from 4 GBytes to 8 GBytes.

At this writing, the fabricated CCD wafers have been returned to JPL by the silicon foundry (Lockheed/Martin, Milpitas). Preliminary testing on uncut-wafer CCD's indicates that both the KFS32 and KFS32LN designs are functioning. Further testing will take place following packaging in custom-designed and fabricated packages. Heat-transfer requirements dictated special ceramic surface mounts, in turn mounted in special packages that provide the multiple-pin connections to the camera head CCD board. The very large number of pins required by the multiple-channel output and control signals necessitated the custom packaging.

2.2.2 KFS camera head

The KFS CCD is mounted in a specially-designed camera head, providing the 32-output-channel analog data into the digital acquisition system, described below, various timing and control signals, as well as voltages and control lines to operate the CCD. The 32 signal outputs are supplied through 32 hermetically-sealed coaxial connectors to minimize EMI and stray-noise pickup. The front flange is designed with a standard Nikon lens mount for 35 mm SLR cameras. Through the rear flange, the camera head provides for optional cryogenic cooling from an attached liquid-nitrogen dewar. It is hermetically sealed and designed so it can be operated under vacuum, as necessary when cryogenically cooled.

The KFS camera head contains two printed-circuit boards. The first printed circuit board is the camera power supply regulator board, CAMH3PWR, which generates low-noise regulated voltages for the CCD clock drivers and CCD output amplifiers. This board derives from the board developed for the Cassini CCD (CAMH2PWR). CAMH3PWR has increased output-current capability, as required by the KFS CCD. It also adds the VLODG output, which controls the quiescent output current in the KFS CCD output amplifier stage. This board has the following features:

1. Programmable D/A converters allow computer programming of:
    a. Upper and lower serial clock voltages,
    b. Upper and lower parallel clock voltages,
    c. Upper and lower reset clock voltages,
    d. VDD, VREF, VOTG, and VLODG voltage levels to CCD.

2. Platinum RTD sensor bridge and amplifier for measuring CCD temperature.
3. Heat-dissipating components are mounted on aluminum blocks that bolt onto the rear of the CCD camera case for efficient heat removal even if the case is evacuated.
4. All voltages used by the CCD and amplifiers are locally regulated and filtered to eliminate external noise and interference.

The CAMH3PWR power regulator board has been completed and successfully tested after correcting 2 minor wiring errors.

The second printed circuit board is the KFS CCD driver and preamplifier board, CAMH3KFS, which contains the KFS CCD, CCD clock drivers, and 32 amplifiers. This board has the following features:

1. High-speed serial clock drivers allow serial operation to 40 MHz.
2. High-current parallel clock drivers allow parallel operation to 1 MHz.
3. 32 low-noise amplifiers placed very close to the CCD to minimize capacitive loading of the CCD outputs and minimize noise pickup.
4. Jumper settings allow controlling computer to identify which CCD the board is used for (KFS32 or KFS32LN).
5. Low-Voltage Differential Signaling (LVDS) drivers are used for the high-speed communications link between the CCD timing controller board in the VXI crate and the CAMH3KFS board in the camera head. This minimizes noise pickup and generation. A copper-foil-shielded ribbon cable is used to further minimize noise.
6. 32 subminiature coaxial connectors (one per video output) are used to minimize crosstalk between video signals.

At this writing, while awaiting packaging of selected KFS CCD detectors, the CAMH3KFS PC board is in the PC board layout stage and should be completed in a few weeks.

The camera head is connected to the A/D boards, as well as the timing and control boards, described below. At this writing, the KFS camera head is in its final mechanical-design stages, including integration with the liquid-nitrogen dewar assembly.