PROCEEDINGS
SPIE—The International Society for Optical Engineering

Sensor Fusion II

Charles B. Weaver
Chair/Editor

28–29 March 1989
Orlando, Florida

Sponsored by
SPIE—The International Society for Optical Engineering

Cooperating Organizations
Applied Optics Laboratory/New Mexico State University
Center for Applied Optics Studies/Rose-Hulman Institute of Technology
Center for Applied Optics/University of Alabama in Huntsville
Center for Electro-Optics/University of Dayton
Center for Excellence in Optical Data Processing/Carnegie Mellon University
Center for Microwave-Lightwave Engineering/Drexel University
Center for Research in Electro-Optics and Lasers/University of Central Florida
Jet Propulsion Laboratory/California Institute of Technology
Optical Sciences Center/University of Arizona
Optoelectronic Computing Systems Center/University of Colorado,
Colorado State University

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone 206/676-3290 (Pacific Time) • Telex 46-7053

Volume 1100

SPIE (The Society of Photo-Optical Instrumentation Engineers) is a nonprofit society dedicated to advancing engineering and scientific applications of optical, electro-optical, and optoelectronic instrumentation, systems, and technology.

Designing an infrared system to map and detect wildland fires

J. David Nichols, Gary S. Parks, Jeffery M. Voss, Robert A. Mortensen, Thomas L. Logan

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena California 91109

ABSTRACT

The "Firefly " project is developing an infrared remote sensing system to provide near real-time wildland fire information for fire management and suppression. Recent technological advances in several areas now allow the design of an end-to-end, infrared system to map and detect wildland fires. The system components will include an airborne infrared sensor, automatic onboard signal and data processing, telecommunications link, and integration into a ground data terminal. The system will provide improved performance over current systems in terms of increased timeliness of data delivery, quantifiable accuracy, data consistency, reliability, and maintainability. The system will be the next generation of wildland fire mapping and detection system for the United States Forest Service.

1. INTRODUCTION

In the spring of 1983, a feasibility study was initiated to examine the application of advanced technology to forest fire detection and mapping. The study was conducted by NASA's Jet Propulsion Laboratory (JPL) and sponsored jointly by NASA and the Forest Service, United States Department of Agriculture. This task designated as the "Forest Fire Advanced System Technology (FFAST)"[1], led to the beginning of the Firefly project.

The FFAST study was an outgrowth of past efforts by JPL and the Forest Service on the Fire Logistics Airborne Mapping Equipment (FLAME) Task[2]. The objective of the FLAME Task was to update the electronics within the existing Forest Service infrared (IR) line-scanner systems. This was necessary because the line-scanners were early 1960s vintage. Increased system down time, due to maintenance difficulties and scarcity of adequate replacement parts, hampered full utilization.

The FLAME System provided improvements to the IR line-scanning capability. However, FLAME required manual image interpretation in order to process the IR output. The ability to deliver timely, consistent, and quantifiably accurate IR fire information to fire management personnel continued to be a serious problem even after the delivery of FLAME. The FFAST study concluded that an advanced system could be developed to produce an end-to-end thermal IR fire detection and mapping information system.

The FFAST definition phase defined system functional requirements, subsystem performance specifications and overall design approach to build a system which meets the Forest Service fire detection and mapping mission needs[3].

The Forest Service intends to take advantage of the advanced technology system design approach, defined by the FFAST task, in the development of a new system designated Firefly. Firefly will build upon research, development, and operational use conducted over the last 25 years, and engineering studies and analyses conducted over the last 5 years[4,5]. State-of-the-art data collection, transmission, processing, and display systems will be utilized by the Firefly system.

2. OBJECTIVE

The Firefly task will develop and implement a state-of-the-art wildland fire mapping and hot spot or small fire detection information system to gather, transmit and display near real-time forest fire data. The system will enable fire suppression and management personnel to acquire detailed fire information necessary for fire management and logistics.

3. DESIGN APPROACH

The Firefly implementation design approach is to develop a modular system to eliminate obsolescence by incorporating newly developed equipment, and maturing technology available in the early 1990s. The system design will be based on the development of a "user-friendly" system with emphasis upon reliability and maintainability. The output products will be produced in a near real-time environment defined as delivery to the fire manager within thirty minutes of data collection. Application of new technology must translate into cost savings and improved performance, if the system is to meet Forest Service operational information needs.

The Firefly System will be smaller and lighter than existing systems to permit operation from small aircraft. The modular design of Firefly will allow additional spectral coverage through integration of sensor capabilities to facilitate non-fire use of the system. This includes vegetation applications such as the mapping of vegetation vigor and stress. Private industry will participate as subcontractors contributing specialized expertise, and supplying major components of the system.

4. SYSTEM DESIGN CONCEPT

The Firefly System will be a remote sensing system designed to identify and locate forest fire perimeters and related hot spots using a special purpose IR sensor. The Firefly System uses information on aircraft parameters, terrain parameters, and sensor field-of-view to plot the location of fire data onto a geographic data base.

The Firefly operational system consists of an aircraft unit and a ground terminal. The Firefly System concept is depicted in Figure 1. The aircraft takes off and flies over the fire area as directed by the Fire Incident Commander. The flight path is designed to enable the on-board sensor to cover the entire fire perimeter area. The aircraft unit images the ground scene, detects fire spots, computes fire perimeter and hot spot locations, correlates fire data to geographic coordinates, and transmits these data to a ground terminal. The aircraft unit operation is controlled by the Firefly airborne unit operator. The operator activates the system when over the fire area, monitors system performance, and relays flight information to the pilot to optimize the flight path. The operator also has the capability to append messages to the data based upon observations of the raw infrared imagery data.

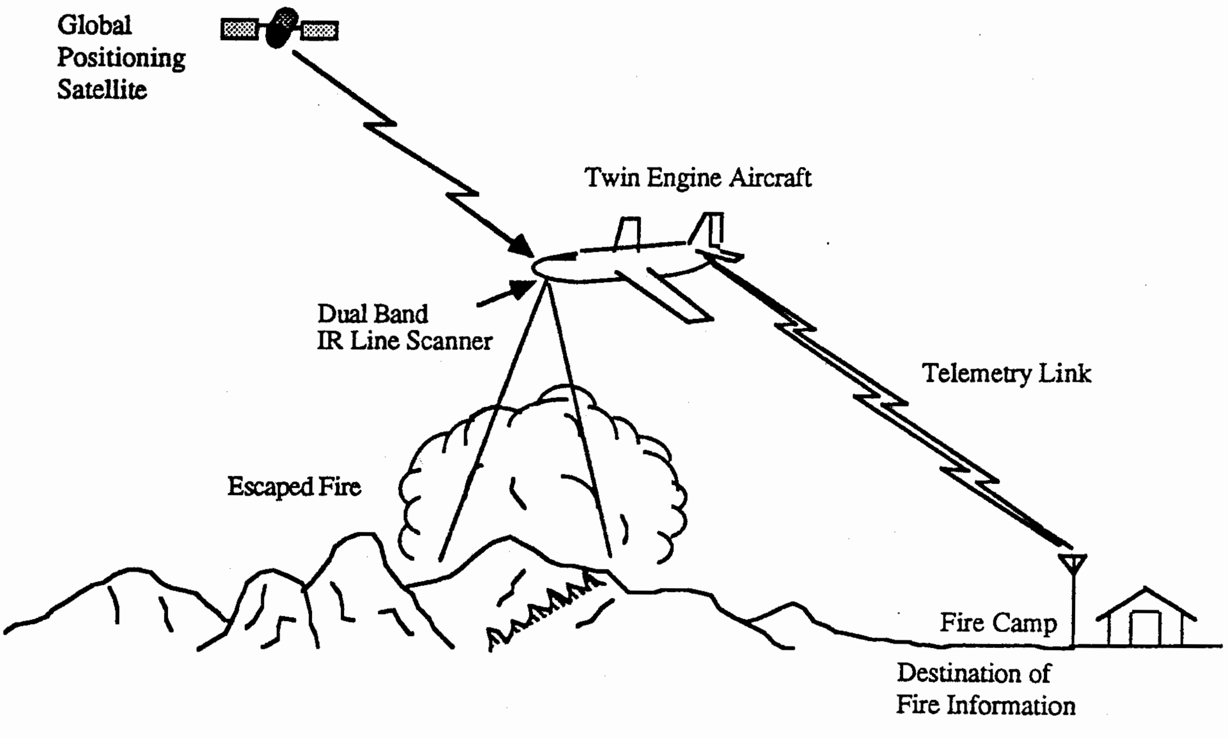

Figure 1. Firefly System Concept

At the completion of the data gathering portion of the flight, the aircraft flies to within line-of-sight of the ground terminal (located at the fire camp) to allow the aircraft and ground terminal computers to transfer the results of the mission via a telemetry data link.

The ground terminal is the primary interface to the system user. The ground terminal receives the fire perimeter and hot spot data from the aircraft, and plots these results in a specified geographic scale onto a map or other media.

5. GEOREFERENCING CONCEPT

Georeferencing is the procedure for determining the fire or hot spot locations relative to a geographic base for plotting the system output onto a map base. Georeferencing is accomplished by detecting and then graphically locating the fire spots. Separate outputs from a dual color infrared line-scanner generate imagery which is processed to detect picture elements (pixels) which pass the fire detection criteria. This processing combines both IR images and quantizes each resultant pixel for comparison to known thresholds. A Global Positioning System (GPS) receiver is used to determine aircraft position, and gyroscopes are used to determine aircraft attitude and heading. The aircraft position, attitude, and heading information allows the absolute determination of the fire location along a three dimensional line-of-sight from the airborne sensor. The information is combined with the range (or distance) the pixel is from the aircraft, which allows the determination of the absolute position of each pixel.

The Firefly georeferencing method for determining the line-of-sight range of a hot spot from the aircraft uses existing United States Geological Survey digital elevation database. The database divides the continental United States into 100 meter squares, each with an indicated average terrain elevation. This method, called Digital Elevation Models (DEM) georeferencing, uses the elevation database, aircraft altitude, aircraft attitude and heading, and sensor look angle to solve for range. The DEM method allows the raw imaging coverage rate to equal the effective georeferencing coverage rate because no stereo swath overlap is required. The elevation database resides on the on-board processor.

The fundamental accuracy of the Firefly georeferencing technique depends on the capability to accurately measure aircraft position, heading and attitude. Uncertainties in measuring these parameters will directly correspond to position uncertainties which depend on aircraft altitude and sensor field-of-view. An uncertainty in the aircraft position (typically 25 to 100 meters for GPS) corresponds directly to an uncertainty in the plot location. Similarly, an uncertainty in the platform attitude and heading (typically 0.1º to 2.0º depending on gyro accuracy) corresponds directly to an uncertainty in the vector angle from the aircraft to the fire. As the line-of-sight range between aircraft and fire increases, this angular error translates into greater positional error. Therefore, increasing swath width (and coverage rate for a given airspeed) decreases georeferencing accuracy. This can be accomplished by increasing altitude or increasing the sensor field of view. The position accuracy for Firefly will be ±500 feet.

6. SUBSYSTEM DESIGN DESCRIPTION

A high level block diagram indicating the relationship between major system components in each of the two segments (aircraft unit and ground terminal) is shown in Figure 2. The aircraft unit consists of five subsystems: 1) Sensor Subsystem for remotely sensing and imaging the fire areas on the ground; 2) Navigation Subsystem for aircraft location, attitude and heading information; 3) Signal Processing Subsystem for combining the two sensor bands, quantizing fire spots, and integrating navigation data; 4) Data Processing Subsystem for computing the fire location; and 5) Tele-communications Subsystem for transmitting the data to the ground terminal. The Ground Terminal Subsystem consists of the tele-communications component for receiving the aircraft sensor fire data, and the data output component for processing and displaying the fire location data.

6.1. Sensor Subsystem

The Sensor Subsystem receives infrared radiation from the fire and converts this radiation into electrical signals for imaging and subsequent processing in the Signal Processing Subsystem. The Sensor Subsystem consists of a special purpose IR instrument to detect and locate fire and flame hot spots on the ground. Infrared scene emittance is gathered in two IR spectral regions to provide false alarm rejection with optimumsensitivity detection. The requirements for bi-spectral imaging, large field of view (FOV), and high spatial resolution make an IR line-scanner the sensor of choice. The IR sensor requirements are

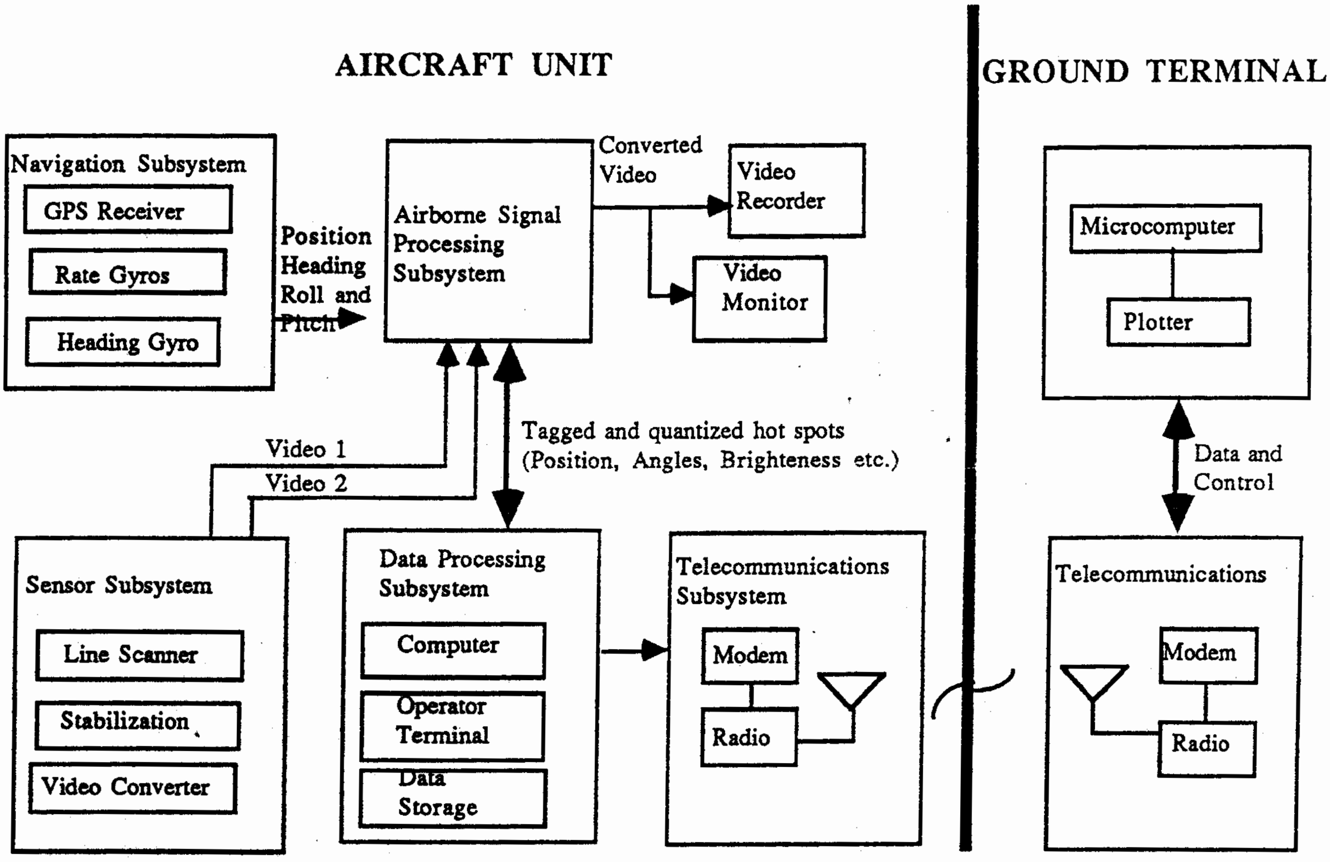

Figure 2. Firefly System Block Diagram

listed in Table 1.

Table 1: IR Sensor Requirements

Field of View	>80 degrees cross track
Detector IFOV	≤ 2.5 mrad
Spectral Bands	3-4.8 µm (Channel A)
	8.5-12.5 µm (Channel B)
Sensitivity	≤0.2 K (Both Bands)
Maximum V/H	≥.21 radians/second

Functionally, the IR sensor must address the two primary tasks of mapping fire perimeters, and detection of point fires ("hot spots"). Mapping large fires requires large field-of-view (at least 80 degrees cross track) and high sensitivity in the long wave IR (LWIR) channel for terrain imaging. Hot spot detection requires bi-spectral imaging for false alarm rejection, wide FOV to maximize the area searched, and high sensitivity in both spectral channels.

Infrared line-scanner performance was assessed using the LOWTRAN 6 atmospheric model [6,7]. The system spectral bandpasses were calculated to provide uniform degradation to both bands with increasing atmospheric water vapor content. The bi-spectral fire detection algorithms rely on a ratio of the two spectral bands. The analysis suggests that the bands listed in Table 1 will provide very uniform transmission loss, without narrowing the bands too much, and therefore reducing sensitivity.

The required sensitivity was calculated with a model developed for the Firefly project at JPL. Due to the very small size of a hot spot, detection requires a relatively small IFOV combined with sensitivity. The sensor must detect a 1 square foot hot spot (at 600° C) at altitudes of 10,000 feet. Hot spots of very high temperature are distinguished from warm terrain features by their spectral characteristics. A threshold (or multiple thresholds) is implemented at a standardized output signal level, Signals above the established threshold standard are considered fire targets. Mapping large fires requires sensitivity in the LWIR band, to allow identification of terrain features by the operator.

Both detection and mapping missions are accomplished at a variety of aircraft altitudes and speeds. The extreme requirement on sensor V/H (the velocity to height ratio) comes from the low altitude mapping mission, at 2000 feet altitude and 120 knots. The scanner V/H is sufficient to allow for 50% overlap on successive scans, which allows double detection of small fires and rejection of spurious noise spikes. The scanner V/H is sufficient to meet the requirements over the range of aircraft operational conditions. The primary interface to the remaining portion of the system is through the airborne Signal Processing Subsystem.

6.2. Navigation Subsystem

The airborne Navigation Subsystem measures the aircraft position, attitude and heading for real-time determination of vectors to objects in the infrared imagery. The subsystem consists of a Global Positioning System (GPS) receiver for determination of aircraft position, and gyroscopes for aircraft heading and attitude determination. In addition, pressure altitude is measured for comparison and check of the GPS receiver.

For attitude measurements, rate gyros are used and integrated to generate angular motion as is shown in Figure 3. For initialization, and for offsetting rate gyro DC errors, a pendulum is used and combined through a servo loop with a slow (> 60 sec) time constant. The integration process and servo loop are implemented in firmware using a 16 bit microprocessor which samples the signals each 10 milliseconds. The use of a microprocessor in this situation enables the entire process to be integrated using standard off-the-self computer hardware. No special electronics will be necessary, thereby minimizing maintenance requirements, and allowing for easy reproduction of the system. Attitude accuracy is expected to be 0.5°.

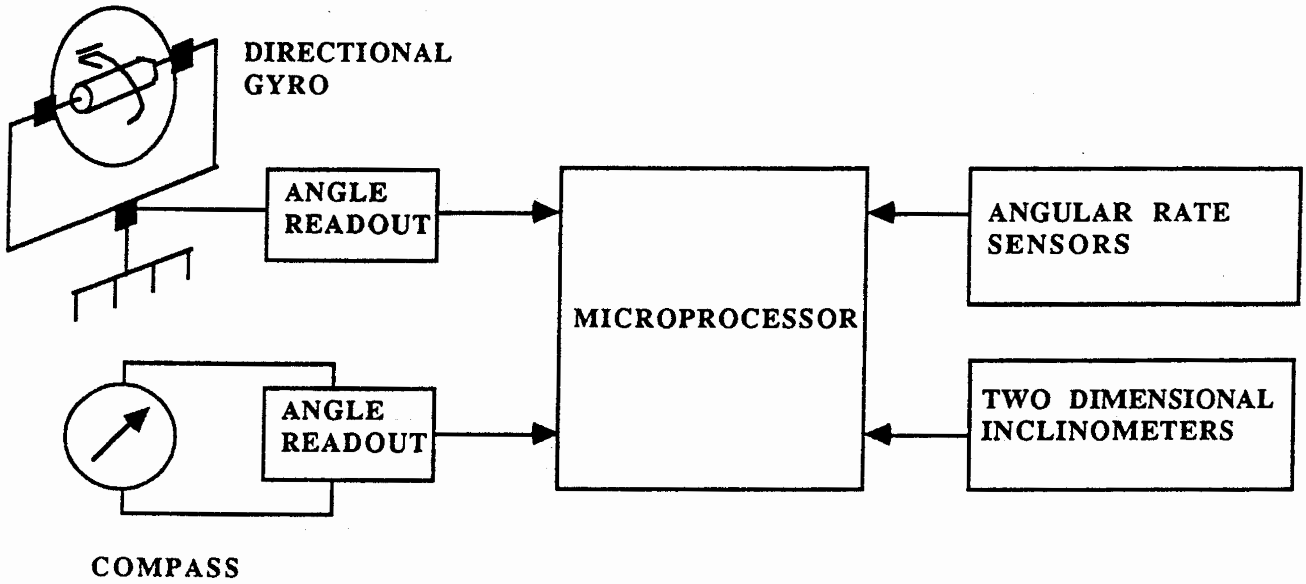

Figure 3. Gyro Configuration Simplified Block Diagram

Heading measurements will be taken with a directional gyro and north seeking compass as shown in Figure 3. A servo loop will be implemented by combining the two outputs through differing time constants. Initially, both instruments will be read to define an arbitrary offset as determined by the start up condition of the gyro. The gyro will then serve as the primary output for heading. To correct for gyro drift, a servo loop will be implemented by differencing the gyro (plus offset) and the compass. The servo filter will be slow (> 60 seconds) to properly average out short term compass errors caused by airplane lateral accelerations. The servo correction will then be implemented by varying the gyro offset. A microprocessor will be used to implement the servo function. Heading accuracies are expected to be 1.0°. Continuous outputs from these instruments are interfaced to the airborne Signal Processing and Data Processing Subsystems.

6.3. Signal Processing Subsystem

The airborne Signal Processing Subsystem is responsible for the real-time processing necessary to prepare the imaging sensor output. This includes the image combination of both IR wavebands, sensor calibration, fire identification in the image, and recording of the combined imagery.

The Signal Processing Subsystem consists of a specialized microcomputer, video processing electronics, video monitor and video recorder. The subsystem accepts the dual channel sensor data from the Sensor Subsystem, digitizes and mathematically combines them to produce quantized levels of thermal brightness values. The dual band data is combined in a manner which minimizes the possibility of false alarms caused by warm background objects (< 600° C) and solar reflection. The Signal Processing Subsystem also interfaces with the Navigation Subsystem and Data Processing Subsystem. The brightness values which are determined to identify a fire or hot spot are tagged with navigation and ancillary sensor data for georeferencing by the Data Processing Subsystem.

Video processing will utilize digital video processors which are designed to allow the sensor output to be either digital or analog video. All of the video electronics will be fully compatible with standard monitors and displays. Pipeline architecture processors will be utilized for internal processing of the dual band sensor data. The pipeline structure allows steps of the sequential process to be performed in parallel and allows for the execution of complex computations with a speed commensurate with video imagery data rates (10 Mega pixels per second). After completed processing of the imagery, video encoders will reproduce the processed video signal from the digital data.

The Signal Processing simplified block diagram is shown in Figure 4. Frame grabbers will be used to input the two channels of line-scanner data for digital or analog input. The data is stored separately in two image buffers. The next sequence in the pipeline utilizes a lookup table to generate the combined image (including thresholded image which identifies fire areas and brightness), and the original long waveband image for operator imagery display. Separate image buffers will store this data as 1024 x 1024 pixel images. The operator imagery is then generated by displaying the long wave band in monochrome, with a red overlay indicating fire areas. Additionally, the thresholded data is also routed to a convolution filter which performs two minimum/maximum operations to eliminate noise spike false alarms, and reduce the data quantity for transfer to the data processing subsystem computer. A parallel data path from the frame grabber image buffers also allows brightness histogram processing for line-scanner calibration.

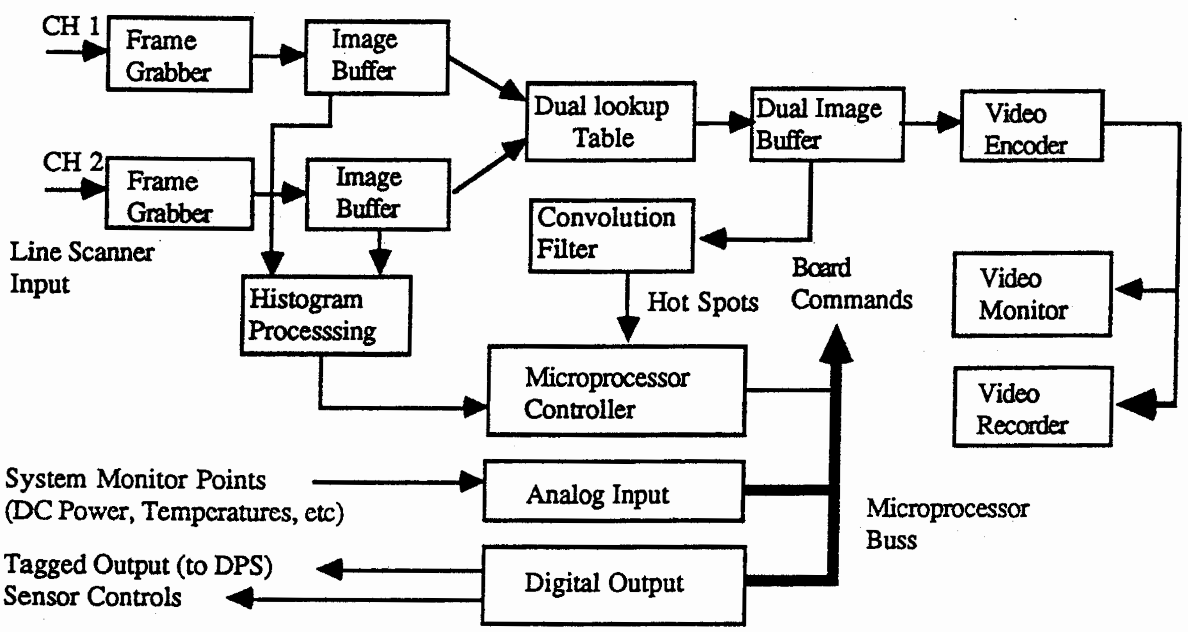

Figure 4. Airborne Signal Processing Block Diagram

6.4. Data Processing Subsystem

The Data Processing Subsystem accepts the tagged fire and hot spot data and generates graphical data sets in order to compute the ground position of each point. In addition, this subsystem provides the primary control interface between the aircraft unit and the system operator. The subsystem's georeferenced graphical output represents the fire perimeter, and is sent to the Telecommunications Subsystem for transmission to the Ground Terminal Subsystem.

The Data Processing Subsystem consists of the computer, data storage, operator terminal, and software that is needed to georeference the tagged fire and hot spot data. The Data Processing Subsystem collects fire location information from the Signal Processing Subsystem and registers it for plotting onto a standard United States Geological Survey map projection. As the fire data is received, the subsystem will request navigation information from the Navigation Subsystem to determine the aircraft position and orientation at the time the data was collected. This allows calculation of the true latitude/longitude coordinates for construction of the fire perimeter and hot spots map plot. At the request of the operation, these plots will be transmitted to a ground terminal for plotting.

The operator interface will display the plot of the fire data as data is received and processed. The interface will allow the operator to annotate (that is add text or other markings to high-light landmarks) and transmit the current plot to the ground terminal. The operator can also use the interface to configure the Firefly system, for example, switch the currently displayed channel between channels A and B, or change the automatic recalibration interval.

The subsystem software will provide the above functionality by continuously monitoring operator inputs and the Signal Processing Subsystem for fire data. Upon receiving fire data, the software will:

- Gather current navigation information from the Navigation Subsystem.
- Scan the data for boundaries between different fire levels.
- At each boundary, determine the true latitude/longitude location of each boundary using navigation information and elevation data of the area.
- "Scroll" the currently displayed to make room for new data.
- Add the boundary information to the current plot.

The Data Processing Subsystem will allow the operator to request a freeze frame of the currently displayed scanner data. Upon receiving a request from the operator, the freeze frame will be digitally sent from the Signal Processing Subsystem to the Data Processing Subsystem to be displayed with the fire plot overlay on the freeze frame. At this point, the operator can annotate the plot to high-light landmarks visible in the scanner image. The annotated plot is then transmitted to the ground terminal.

6.5. Telecommunications Subsystem

The Telecommunications Subsystem has components at both ends of the telemetry link, in the aircraft and the ground terminal. These consist of telemetry modems, transceivers and radios. The telecommunications equipment will provide a standard serial computer interface at both ends to eliminate the need for manual operation. This will allow automatic data transmission and error checking when radio frequency line-of-sight conditions exist.

6.6. Ground Terminal Subsystem

The purpose of the Ground Terminal Subsystem is to generate plot output of the Firefly fire data. The subsystem consists of telecommunications equipment, a microcomputer, plotter and power conditioning equipment. The Ground Terminal Subsystem will be a portion of the Forest Service Incident Network (InciNet). InciNet is designed to interface with all Forest Service communication equipment by using standardized communication protocols and software. The computer is the primary interface to the ground operator for initializing the unit and reporting status.

7. CONCLUSIONS

The Firefly system will meet or exceed the Forest Service user needs for an advanced wildland fire detection and mapping system. The design concept provides flexibility by allowing the incorporation of both present and developing technologies in a future follow-on development phase. The system will make possible the acquisition and integration of requisite information into a high resolution, user-friendly system, which will perform fire mapping and detection on a near real-time basis. The system will support potential non-fire, multiple-user reconnaissance missions through the incorporation of additional detectors in the IR and microwave spectral range.

8. ACKNOWLEDGEMENT

This paper represents one phase of research performed at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Forest Service, U.S.D.A. under a contract with the National Aeronautics and Space Administration.

9. REFERENCES

1. McLeod, Ronald G., et al., A Feasibility Study: Forest Fire Advanced System Technology (FFAST), JPL Pub. 83-57. Jet Propulsion Laboratory, Pasadena, CA., September 1, 1983.

2. Enmark, Harry, Fire Logistics Airborne Mapping Equipment (FLAME) Final Report. (JPL Internal Document) Jet Propulsion Laboratory, Pasadena, CA., April 23, 1984.

3. Nichols, J. David, Forest Fire Advanced System Technology (FFAST) Task Definition Phase Final Report. (JPL Internal Document) Jet Propulsion Laboratory, Pasadena, CA., July, 1988.

4. Warren, John R., and Wilson, Ralph A., Airborne Infrared Forest Surveillance - A Chronology of USDA Forest Service Research and Development. USDA, Forest Service, General Technical Report INT-115, Washington, D.C., August 1981.

5. Nichols, J. David, and Warren, John R., "Forest Fire Advanced System Technology (FFAST) Conceptual Design Study," Airborne Reconnaissance X, Paul Henkel, Francis R. LaGesse, Editors, Proceedings SPIE 694, pp. 2-9, 1987.

6. U. S. Air Force Geophysics Laboratory, "LOWTRAN-6," AFGL-TR-83-0187, Hanscom Air Force Base, MA., July 29, 1983.

7. "PC Tran Version 2," Ontar Corporation, Brookline, MA., June 1987.