Demonstrating UAV-Acquired Real-Time Thermal Data over Fires

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Abstract
Project FiRE (First Response Experiment), a disaster management technology demonstration, was performed in 2001. The experiment demonstrated the use of a thermal multispectral scanning imager, integrated on an unmanned aerial vehicle (UAV), a satellite uplink/downlink image data telemetry system, and near-real-time geo-rectification of the resultant imagery for data distribution via the Internet to disaster managers. The FiRE demonstration provided geo-corrected image data over a controlled burn to a fire management community in near-real-time by means of the melding of new technologies. The use of the UAV demonstrated remotely piloted flight (thereby reducing the potential for loss of human life during hazardous missions), and the ability to “linger and stare” over the fire for extended periods of time (beyond the capabilities of human-pilot endurance). Improvements in a high-temperature calibrated thermal imaging scanner allowed “remote” operations from a UAV and provided real-time accurate fire information collection over a controlled burn. Improved bit-rate capacity telemetry capabilities increased the amount, structure, and information content of the image data relayed to the ground. The integration of precision navigation instrumentation allowed improved accuracies in geo-rectification of the resultant imagery, easing data ingestion and overlay in a GIS framework. We present a discussion of the feasibility of utilizing new platforms, improved sensor configurations, improved telemetry, and new geo-correction software to facilitate wildfire management and mitigation strategies.

Introduction
Large-scale wildfires occur frequently throughout the United States every year. The “fire” season begins in late winter in the southeastern U.S. (initially in Florida) and transitions both northward into the Appalachian states and westward. The severe fire season transitions into the southwest, north through the Rockies, west to the Pacific Northwest, then south through California, culminating in late fall/early winter fire events in southern California. This extended fire season taxes the resources of local, state, and federal agencies mandated to monitor and mitigate these events. During the extensive burning seasons throughout the United States, pilot aircraft employing thermal imaging systems are deployed by some state agencies (California Dept. of Forestry; CDF) and by the National Interagency Fire Center (NIFC; Boise, Idaho) to collect large volumes of data over fires spread from Canada to Mexico, and from the Rocky Mountain Front to the Pacific Ocean. Large fires, such as the Yellowstone conflagration in 1988, the Cerro Grande, New Mexico fire in 2000, the western Montana fires of 2000, and the Colorado and Arizona fires of 2002, burdened these remote sensing data-gathering crews, and taxed both the resources and the stamina of these personnel.

Through cooperative endeavors between agencies, a team of investigators have embarked on a research and technology demonstration utilizing UAVs and advanced sensor and data distribution technologies focused on improving the information gathering over wildfire disaster events. The rationale for exploring the development of the platform, payload, data telemetry and geo-rectification procedures was to greatly increase the timeliness of the data stream for utility in fire mapping, to reduce potential risks to pilot and system engineers, and to provide improved and more accurate information on fire conditions than is currently realized. The culmination of those efforts resulted in the UAV-FiRE demonstration.

The Uninhabited Aerial Vehicle (UAV) First Response Experiment (FiRE) was created in 2001 to demonstrate the utility of integrating remotely piloted aerial platforms, advanced thermal imaging, cost-effective satellite data telemetry systems, and image geo-rectification for rapid data dissemination of a disaster event in near real-time (Figure 1). The primary focus of the FiRE demonstration was to utilize the unique features of an unmanned aircraft as a data-gathering platform to test the feasibility of long duration missions to support wildfire management activities. Although UAVs are currently expensive to operate, the purpose of the demonstration was to showcase their feasibility for future operational data gathering. Within the next
few years, as operational costs decrease, UAVs will prove to be an effective alternative platform for long-duration data gathering missions. UAVs and the improved data telemetry technologies described in this paper offer vast improvements in platform range capabilities (ability to cover continental-scale areas), timely delivery of data, and improved quality of information to the disaster manager. The employment of a multichannel thermal imaging payload also offers improvement over the current use of forward looking infrared (FLIR) systems and single-channel thermal systems with poor (or non-existent) high temperature calibration, narrow FOVs, and low spatial and radiometric resolution. Improvements in on-board and ground-based image geo-correction technologies also allow vastly improved data integration capabilities and speed.

The success of the FiRE project was the result of a collaborative effort between government agencies and private industry. NASA-Ames Research Center organized the project and the enhancement and development of the AIRDAS scanner as well as the integration of all the components needed for the demonstration. Ames cooperated closely with General Atomics Aeronautical Systems, Inc. (GA-ASI) who developed, built, and flew the ALTUS® II UAV airborne platform. System integration was accomplished at the GA-ASI Flight Operations Facility in El Mirage, California. The telemetry system, provided by Remote Satellite Systems, Inc. of Santa Rosa, California, was modified by NASA-Ames and integrated by GA-ASI into the ALTUS® II UAV fuselage. All geo-rectification procedures and data handling were coordinated and performed with Terra-Mar Resource Information Services of Mountain Ranch, California. Disaster managers from the U.S. Forest Service (USFS) and the State of California Resources Agency participated as technology reviewers and provided feedback on the resultant fire data.

Figure 1. FiRE Demonstration Concept Plan. Thermal infrared image data collected from a payload operating on a UAV is telemetered over-the-horizon through an orbiting communications satellite to a data command center. At the data archive center, the imagery is processed in near real time, archived, and also distributed to the World Wide Web for use in disaster visualization and mitigation response.

Background
Fire imaging from remote platforms can be divided into two distinct categories: strategic and tactical. Strategic observations are those that provide a regional view of fire occurrences. Tactical observations are those that provide detailed, frequent, and repetitive views of specific fire events. Satellite systems such as AVHRR have been used to provide strategic views (Matson and Dozier (1981), Matson et al. (1984), and others) but are ineffective for repetitive, timely observations of fires due to orbit cycles, design characteristics, and data relay (days, weeks to months after the fire). While the Forest Service and other agencies utilize satellite data to provide an overview of fire distribution at regional scales, they rely on the use of airborne platforms as tactical systems to provide continuous coverage and rapid data accessibility over individual fire events. The ability to change aircraft position, altitude, and data acquisition time makes them essential for real-time fire fighting and management decisions. This paper will focus on the use of improved tactical airborne remote sensing systems.
The development of Fisheye Fire & Resource Analyst System (AIRDAS) was driven by the need for rapid payload data delivery, NASA-Ames shifted development to aircraft telemetry systems (Ambrosia, 1990). Low-bit data rates (4.8 Kbps) were employed successfully for a number of years in the 1990’s. This procedure necessitated dialing into a ground station via command and control telemetry, and the AIRDAS payload remotely from a ground station via command and control telemetry, required modification of the instrument control software and all functionality performed by a systems engineer.

The fifth goal, to globally distribute data to the Internet and disaster managers. The first goal of the FIRE demonstration was to successfully integrate and fly the AIRDAS scanner on a UAV platform. The ALTUS® II UAV payload integration of the AIRDAS was performed at the CA-ASI Flight Operations Facility in El Mirage, California during late summer of 2001. The second goal, to operate the AIRDAS payload remotely from a ground station via command and control telemetry, required modification of the instrument control software and all functionality performed by a systems engineer.

The third goal, to provide satellite data communications telemetry, required modification and integration of a satellite phone antenna system onboard the ALTUS® II UAV. The telemetry system provided a communication and data link to the INMARSAT (International Mobile Satellite Organization) satellite system.

The fourth goal, to provide improved geo-rectification of fire image data, required customized image correction software provided by Terra-Mar. The software required inputs from the platform, and payload navigation information collected in conjunction with the AIRDAS image data.

The fifth goal, to globally distribute the real-time corrected thermal imagery via the Internet, allowed the use of the resultant data both at an Incident Command Center (ICC) and at other facilities, including remote fire camps. An uncorrected image file and geo-rectified file were sent to a server at NASA-Ames and accessed via a web address.
The following sections describe the FiRE experiment components, the demonstration, results, and future directions for our research and development program.

**FiRE Demonstration**

**Overview**

The FiRE demonstration mission occurred on 06 September 2001 at the GA-ASI Flight Operations Facility in El Mirage, California. Disaster managers and fire management personnel viewed the FiRE demonstration and participated in an evaluation of the procedures and products. Integration of the payload and telemetry suite occurred during the week preceding the mission, and a full, end-to-end UAV/payload telemetry test flight was also performed the previous day.

The FiRE Demonstration controlled burn site was located at the GA-ASI Flight Operations Facility at El Mirage, California. The first phase of the FiRE project involved local flights over controlled burns in the vicinity of El Mirage. The fire location was moved to the GA-ASI facility to improve control of the burn (during high fire season on surrounding wildlands), and to better coordinate the project observers and fire managers. The ALTUS® II UAV was therefore limited to flights within the GA-ASI Flight Operations Range. The Flight Operations Facility at El Mirage is situated at 872 meters (2861 ft) elevation at 34° 37 /H11032 30 /H11033 north latitude and 17° 36 /H11032 21 /H11033 west longitude and has a 1525-meter (5000-ft) runway situated on a dry lakebed. The field is 30 kilometers (19 miles) northwest of Victorville, California and 47 kilometers (29 miles) east of Palmdale, California, in the Mojave Desert of San Bernardino County (Figure 2).

The demonstration burn was located approximately 50 meters (50 yards) north of the runway. The burn was created by a controlled ignition of a large supply of propane fuel fed through a series of vented feeder pipes. The feeder pipes were laid out in a linear pattern and extended approximately 35 meters. After the propane was ignited, vertical flame lengths reached approximately 3 to 5 meters. Pits containing fuel were disbursed around the propane feeder pipes (Figure 3). These fuel pits were ignited and provided added flame and thick black smoke, obscuring the flames, as would occur in a natural fire. The controlled burn was ignited immediately prior to the ALTUS® II rollout and takeoff and continued for the duration of the mission (over one hour).

A GA-ASI PREDATOR B® UAV was launched prior to the ALTUS® II to provide overhead video coverage of the mission. The video data were relayed to the Command and Control station and distributed via closed-circuit monitors to the attending disaster managers and audience. A piloted GA-ASI Cessna 182 aircraft was used for in-flight photography while the aircraft flew within the test range.

The controlled burn was ignited adjacent to the aircraft runway and the UAV was launched at 0800 (PDT). After attaining the planned data collection altitude of about 945 meters AGL (about 3100 ft), the ALTUS® II flew “racetrack” patterns in an east/west orientation over the controlled burn. This altitude provided a pixel spatial resolution of about 2.5 meters. The first data collection pass was made at 0822 (PDT).

**ALTUS® II UAV Description**

The ALTUS® II aircraft used for this demonstration is a derivative of the GA-ASI PREDATOR® UAV. The ALTUS® II builds on the proven technology of the PREDATOR® system with an altitude optimized propulsion and control system to create a UAV that is capable of high altitude, long endurance flight (Table 1). The ALTUS® II was developed under the NASA AeroSpace Enterprise, Environmental Research Aircraft and Sensor Technology (ERASt) program and is designed as a technology demonstrator for scientific research and commercial applications (Figure 4).
The ALTUS® II UAV is controlled via a command and control (C2) link that is separate from the data telemetry link. The C2 link is used strictly for flight and instrument operations. The aircraft can be easily disassembled, crated, moved, and reassembled rapidly (assembly in under five hours). This facilitates operations in remote areas away from base operations and provides rapid response for emergency situations. The remote operations for the UAV platforms are provided by personnel in a Ground Station C2 trailer, which is described in detail in the following section.

GA-ASI ALTUS Ground Station
Remotely piloted flight operations for the ALTUS® II UAV platform are performed on the ground at the GA-ASI Ground Station (Figure 5). The ALTUS® II and all GA-ASI aircraft are controlled by a portable common solid-state digital ground control station (GCS) through a C-Band line-of-sight (LOS) data link. The GCS is capable of direct control of the UAV and passing real-time payload data at ranges up to 280 km (150 NM). In addition to the LOS link, a high data rate Ku-Band satellite data link for routine over-the-horizon operations is available and has been used by the military. GA-ASI has also developed a high mobility ground control station and a portable ground control station that allows control of an unmanned aircraft to be passed to remote pilots at an advanced location. The pilot and co-pilot rely on aircraft attitude and positional information provided by the Litton LN-100G INS/GPS system as well as forward-looking video camera display (lower left), in conjunction with attitude and navigation information (lower right) to maintain the appropriate flight profile.

### TABLE 1. GENERAL ATOMICS-AERONAUTICAL SYSTEMS, INC. (GA-ASI) ALTUS® II UAV SYSTEM SPECIFICATIONS

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span</td>
<td>55.3 ft.</td>
</tr>
<tr>
<td>Wing Area</td>
<td>132 sq. ft.</td>
</tr>
<tr>
<td>Length</td>
<td>23.6 ft.</td>
</tr>
<tr>
<td>Height</td>
<td>9.8 ft.</td>
</tr>
<tr>
<td>Max Fuel Wt.</td>
<td>550 lb.</td>
</tr>
<tr>
<td>Payload Wt.</td>
<td>330 lb.</td>
</tr>
<tr>
<td>Max GTOW</td>
<td>2,150 lbs.</td>
</tr>
<tr>
<td>Propulsion/Fuel</td>
<td>Rotax 914-2T Dual Turbo; liquid-cooled four cylinders, Rated 100 HP @ 52,000 ft.</td>
</tr>
<tr>
<td>Performance</td>
<td>Max Altitude 65,000 ft.; Endurance: 8 Hours (at 60K), 18 Hours (at 30K), 24 Hours (at 25K); Max Speed 100 KIAS, Cruise/Loiter Speed 65 KIAS</td>
</tr>
<tr>
<td>Payload Specs</td>
<td>Size: 58&quot;L × 26&quot;H × 27&quot;W, (Adaptable); Max Wt. 300 lbs., Payload Power Available 1.8 kW</td>
</tr>
<tr>
<td>Shipping Size</td>
<td>319&quot;L × 48&quot;H × 57&quot;W</td>
</tr>
<tr>
<td>Navigation</td>
<td>Litton LN-100G INS/GPS (P-Code GPS)</td>
</tr>
<tr>
<td>Avionics</td>
<td>GA-ASI PCM, C-Band Line-Of-Sight RF, adaptable for Over-The-Horizon Operations</td>
</tr>
<tr>
<td>FTS</td>
<td>GA-ASI Rocket deployed parachute and NASA Flight Termination System</td>
</tr>
<tr>
<td>Landing Gear</td>
<td>Normal tricycle-type retractable landing gear.</td>
</tr>
</tbody>
</table>
looking real-time video camera data collected on the UAV and streamed to the pilot console via the same C2 link. The video, in conjunction with UAV positional information displayed on a moving map base, allows the crew to monitor the aircraft condition and location at all times.

**AIRDAS Imaging Payload**

The AIRDAS thermal scanner (Ambrosia et al., 1994) was flown on the ALTUS® II for the FIRE demonstration (Table 2; Figure 6). The AIRDAS was integrated on the ALTUS in late summer 2001, following system checkout flights on piloted aircraft. Integration was facilitated by the design elements of the UAV as a NASA scientific imaging platform. As such, only minor modifications were made to the platform to allow integration of the scanner. Significant software modifications were made to the AIRDAS operating system to allow remote control and operations by the payload engineer from the ground station. These modifications required the greatest time allocation for integration and mission performance.

The AIRDAS has been laboratory-calibrated to resolve fire intensities up to 973 K (700°C). Accurate higher temperature discrimination of the thermal channels is possible but is restricted by the peak temperature efficiency of the laboratory-calibrated thermal source in use (maximum at about 700°C). The NEAT of bands 2 and 3 is less than 0.5°C at 500°C. During AIRDAS science missions, where highly accurate temperature discrimination is required, a narrowing band-pass filter is employed for channel three. This filter narrows the channel to 3.95 to 4.05 μm, allowing for accurate temperature discrimination, but restricting the energy transfer to the sandwiched detector channel 4. This reduces the signal strength at channel four and precludes useful data in that thermal region. Integration of non-linear response pre-amplifiers for the near-infrared (channel 2) and thermal-infrared (channel 3) allows for a greater range of temperature discrimination than do standard linear calibrated pre-amplifiers. The pre-amplifiers allow for two distinct, non-linear temperature discrimination curves to be developed. For low temperatures (30 to 100°C), discrimination is approximately 1.0°C/count while, in the higher temperature portion of the non-linear curve (500 to 600°C), discrimination is approximately 0.2°C/per count in the mid-infrared thermal channel 3. This design allows for discrimination for low temperature earth ambient targets, and also discrimination of discrete temperatures emitted by a variably hot target.

For the FIRE experiment, discrete temperature variations were not necessary to convey the fire properties; therefore, images of relative fire intensity sufficed for data telemetry to the disaster managers. Therefore, the narrowing filters were not employed for the FIRE experiment. The fire data were portrayed as either single-channel grayscale images (channel 3 or 4) or as thermal-infrared-visible (RGB) color composites. Temperature variations were portrayed as varying shades of color in these image files.

Each of the specific AIRDAS bands provides useful information for fire analysis. The visible band 1 is suitable for monitoring smoke plumes as well as distinguishing surface cultural and vegetative features not obscured by smoke or clouds. Band 2 is suitable for analysis of vegetative composition, as well as very hot fire fronts, while still penetrating most associated smoke plumes. Band 2 is sensitive to fires and hot spots at temperatures above 573 K (300°C). Riggan et al., 1993). Band 3 (mid-infrared thermal) is specifically designed for estimating high temperature conditions. Band 4 is designed to collect thermal data on earth ambient temperatures and on the lower temperature soil heating con-

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**Table 2. AIRDAS System Configuration and Characteristics for Payload Operations Aboard GA-ASI ALTUS® II UAV**

<table>
<thead>
<tr>
<th>System Composition:</th>
<th>Texas Instruments® RS-25 thermal line-scanner optics; Non-linear detector pre-amplifiers; Sixteen-bit Digitizer; Dichroic filters for spectral channel separation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Computer:</td>
<td>Pentium® I Pro 233 MHz system; On-Board ETHERNET; SCSI; High-speed serial ports running QNX OS; Kingston® 18.0 GB removable hard drive storage device; Integrated Motorola® Chassis-Mounted GPS Receiver; Crossbow® DMU-FOG-VG Fiber-Optic Gyro, 2-axis</td>
</tr>
<tr>
<td>Weight and Power:</td>
<td>Scan Head: 95 lbs.; Control computer and peripherals: 70 lbs.; Requires 28V DC @ 20 amps</td>
</tr>
<tr>
<td>Sensor Parameters:</td>
<td>Quantization: 15-bit true (signed 16 bit) FOV: 108 degrees iFOV: 2.62 milliradians Scan Rate: 4–23 scans/second Digitized Swath Width: 720 pixels Spatial Resolution: 26 ft. (8m) at 10K ft. NEAT: Band 2 and Band 3: &lt;0.5°C @ 500°C Temperature Sensitivity: 1.0°C/DN / 0.2°C/DN (non-linear two-step pre-amp; below and above breakpoint) Thermal Calibration Temp: ~700°C</td>
</tr>
<tr>
<td>Spectral Configuration:</td>
<td>Channel 1: 0.64 - 0.71 μm 2: 1.57 - 1.70 μm 3: 3.75 - 4.05 μm (narrowing filter available) 4: 5.50 - 13.0 μm</td>
</tr>
</tbody>
</table>

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Figure 6. The AIRDAS system integrated into the GA-ASI ALTUS® II UAV payload pod. The scan head is located in the forward portion of the payload bay above the open port window, with the computer control rack immediately aft of the head electronics. Aft of the control computer is the Litton LN-100G INS/GPS. The forward looking video camera can be seen in the nose of the UAV, while the command and control communications antenna is located on the belly of the fuselage, aft of the payload bay and ports. The hatch cover for the payload bay (not visible) incorporates the NERA telemetry antennas on both sides of the airframe.
The AIRDAS contains an integrated Motorola® chassis-mounted Global Positioning System (GPS) unit and a Crossbow DMU-FOG-VC (Fiber-Optic Gyro-Vertical Gyro) two-axis gyro. The GPS data are integrated into the scanner output and provide encoded location information on aircraft position to the header file for each flight segment (scan line). The two-axis gyro sends encoded information on pitch and roll to the control system in order to allow for post-flight correction. A magnetic compass assists in determining heading, allowing for geometric correction. The barometric altimeter data are also incorporated in the header. The system accommodates additional serial interfaces to integrate other avionics navigation systems on airframes that acquire such information.

Significant software and hardware modifications were made to the AIRDAS system to allow UAV remote payload control from the ground control station (GCS). These modifications included streamlining the system health data from the on-board computer to the payload engineer’s computer on the ground. This allowed for real-time monitoring of payload performance, image area location, and spatial coverage.

Remote Operations of Payload

The AIRDAS payload engineer and all system controls were collocated in the GCS. Collocation enabled direct communication with the pilots and flight engineer, and access to the same forward- and downward-looking video data. A downward-looking video camera, placed in the nose of the ALTUS® II, provided real-time coverage information of the potential target area. By incorporating this camera view with the streaming GPS and moving map display, the payload engineer could monitor the UAV position and select the optimum flight profile (approach, altitude, and speed) for AIRDAS data capture.

The engineer initiated AIRDAS image data gathering after ascertaining the position of the UAV in relation to the target (fire) area. When the UAV passed over the approximate center of the fire target area (visible on the downward-looking video display), the engineer saved that AIRDAS image stream to a file. The AIRDAS image data were compressed from the signed 16-bit data and “remapped” employing a histogram equal probability distribution stretch to portray the appropriate fire information from each band. The resultant file was then jpg-compressed to 720 by 640 pixels by three bands (approximately 100 Kb) to reduce unnecessary data volume prior to telemetry. An associated navigation file of approximately 9 Kbs, composed of sensor profile and attitude data (pitch, roll, yaw, time, heading, etc.), was also captured and telemetered to a ground computer server along with the image file. The navigation files were used in AIRDAS image geo-rectification.

Following completion of a data collection pass, the resultant image and navigation file were saved for telemetry. The ALTUS® II UAV was then aligned with a heading necessary to transfer data via the telemetry antenna on either side of the fuselage. During that procedure, the payload engineer determined the appropriate INMARSAT satellite for data relay, and initiated a communications connection.

Airborne Data Telemetry System

The airborne data telemetry system was derived from a wireless mobile handheld telecommunications system that communicates through the INMARSAT series of geo-stationary satellites. The NERA World Communicator M4 is a portable satellite terminal offering ISDN functionality and a pure digital interface (NERA website URL: http://www.nera.no/index.html, last accessed 07 August 2002). The NERA antennas were selected for integration simplicity, cost, and adequate functionality. The M4 was designed primarily for the mobile remote satellite voice and data communications market. The M4 functions as a “suitcase phone” with a modem, phone handset, and folding, lightweight antennas (Figure 7a). The INMARSAT system currently operates at 64Kbs, sufficient for the FIRE project data telemetry activities.

The AIRDAS scene data and navigation file were sent from the AIRDAS control computer to the NERA system onboard the UAV. Data were telemetered through a pair of phased array antennas mounted into the skin of the ALTUS® II fuselage, pre-positioned (in elevation) to acquire signal lock with an appropriate INMARSAT geo-stationary communications satellite. A custom fairing was built to accommodate the satellite communications antennas mounted on both sides of the UAV airframe (Figure 7b). These opposing antennas allowed the aircraft to fly in either direction to attain proper intercept angles. Orientation of the aircraft flight direction was optimized to attain an antenna intercept angle of 90 degrees. Proper intercept angles were determined from known fixed locations of the nearest INMARSAT satellite in the constellation. For the FIRE demonstration, both the Atlantic Operating Region—West satellite located at 54° West longitude over the equator and the Pacific Operating Region satellite at 178° East longitude at the equator were used. Given the fixed location of the satellites, and the known location of the UAV, an appropriate antenna intercept angle was derived and used to obtain maximum bit rate throughput during data telemetry.

When signal strength was maximized (through an indication at the payload engineer’s workstation), a TCP/IP network connection was established and the image data were transmitted to either of the appropriate antenna panels. A switching mechanism was created to select the appropriate transmitting antenna remotely (depending on flight orientation and best signal strength intercept angle).

Ground Data Distribution Site

AIRDAS data and the associated navigation data file were transmitted via a File Transfer Protocol (FTP) login from the UAV through INMARSAT to a SUN SPARC workstation server located at the NASA-Ames Research Center, Moffett Field, California. The data were accessible immediately at the project website (http://geo.arc.nasa.gov/sge/UAVFiRE/).

Figure 7. (a) NERA Telecommunications M4 WorldCommunicator® portable satellite terminal phased array antenna. The antennas are approximately 340 mm by 774 mm by 12 mm (depth). The antenna communicates with the INMARSAT series of communications satellites at 1626.5 to 1660.5 MHz. Data throughput is 64 Kb with near future upgrades to +300 Kbs. (b) The antennas (one on each side of the UAV fuselage at the FIRE logo) were installed at an appropriate intercept angle for satellite communications. Data were relayed from the AIRDAS system through this antenna setup, through INMARSAT, and to a dialup server site at NASA-Ames.
Automated website page refresh updates were performed whenever a new image file set was received, updating information at the user’s monitor. Labels for the uncorrected images were provided automatically from the navigation file (such as date, time, etc.). The uncorrected jpg file allowed the disaster manager an opportunity to view the imagery in near real time (within two minutes of telemetry initiation).

**Image Geo-Rectification Process**

The image geo-rectification processing was performed on a Dual-Pentium III, 1.0 GHz computer. The image data and navigation file, housed at the NASA-Ames server, were accessed by the PC via FTP. The two files were then used to create the georectified data sets using the Terra Mar Data Acquisition Control System (DACS) software package. The DACS system was designed to receive ephemeris streams from airborne platforms and to rectify the associated image file in real time. The DACS system requires platform position (GPS), pitch, roll, heading, and altitude information in order to automatically project and geo-reference the imagery. The terrain-corrected, geo-rectified image files were generated using the navigational file (scan line acquisition time, aircraft altitude, GPS location, pitch, roll, yaw angle, and track), sensor attribute and configuration information (sensor scan angle and scan rate), and terrain data (USGS DEM data). The navigation data were used with the photogrammetric projective transformation equations (Wong, 1980) to project the imaged pixels to a ground location.

The aircraft orientation data provided the parameters necessary to compute the transformation coefficient matrix, which then was iteratively corrected for the ground elevation when a DEM was available, or was adjusted to a user-supplied average elevation (Buechel et al., 2001). Symbolically such as fire perimeter delineation, annotation notes, or geo-referencing tick marks may be added to the image as well. A spatial database, Terra-Mar’s Global Data Catalog automatically logged the image information, coverage, and original metadata for ease in referencing and retrieving incident imagery.

The rectified output file was saved in a tif format with an associated tfw file. Spatial resolution of the geo-corrected data was set at 2.5 meters, matching that attained by the AIRDAS at the platform altitude of 945 meters (3100 ft) AGL. The tif file was used to describe the geographic position, and contained a listing of variables such as the coordinates of the upper-left image corner, rotational characteristics, and pixel resolution. The common format of the tif and tfw files allowed import into compatible GIS or image processing systems. The total time required for these procedures (from sensor data acquisition, satellite uplink/downlink, geo-correction, and distribution via the web to the user community) was under 10 minutes.

The geo-corrected AIRDAS tif and tfw data were placed at a central web server and were accessed by the on-site fire managers or by the general public. Data can then be overlain with other digital data (DRG or DEM) and used in a GIS.

**Data Collection and Distribution**

During the FIRE mission, AIRDAS single-band and multiband color composite images were collected and relayed from the UAV through the telemetry link. The black-and-white images were composed of single-band data sets of either the mid-IR thermal channel (band 3: 3.60 to 5.50 μm) or the long-wavelength thermal channel (band 4: 5.50–13.0 μm). Color composites were also collected and relayed via the telemetry link. The color composites were composed of thermal, mid-IR, and visible channels of the AIRDAS scanner. Either of the two AIRDAS thermal bands were combined with channels 2 (1.57 to 1.70 μm) and 1 (0.61 to 0.68 μm) to compose the three-band color image (Plates 1 and 2). Five data collection passes were made over the fire site with data telemetry occurring on the completion of each pass.

Real-time quicklook imagery was viewed on the FIRE website by the fire managers immediately following telemetry. Concurrently, the image and navigational file were acquired from the server by the image-processing operator and integrated with the DACS software to create a geo-rectified image file. Image quality control was performed on the geo-rectified data sets to ensure data integrity prior to distribution to the fire managers and public. The image files were formatted to tif and associated tfw files and transferred via FTP to the NASA-Ames server and website. The DACS processing took approximately six minutes before data were sent to the FIRE website.

The ALTUS® II completed the FIRE data collection mission and landed at 0930 (PDT) (Figure 8). Within the one hour allocated for the FIRE demonstration, the ALTUS® II UAV had been launched, attained attitude, and made five passes over a controlled burn; and the AIRDAS payload data had been telemetered from the UAV to INMARSAT and back to the ground, and the data were geo-rectified and were distributed through the World Wide Web where they were made available to disaster managers around the globe.

**Results and Discussion**

The UAV FIRE demonstration was highly successful, exceeding many of the objectives of the program, yet the authors also note some technology upgrades that could have improved the demonstration. The successes and technological barriers that arose are discussed in the following sections.
Successes

From a UAV operating at an altitude of about 945 meters (~3100 ft) AGL, five fully geo-rectified fire status images from an imaging payload were collected, uplinked via a satellite telemetry system, and delivered to an Incident Command Center and over the World Wide Web. Our objective to deliver accurate geo-rectified data employing this methodology in less than one hour was achieved. Overall collection, telemetry, geo-processing, and delivery were achieved in less than ten minutes once the UAV was on station at the fire site. In a “real” fire event, time consideration for the aircraft to arrive at the site must be accounted for, although there are no significant speed differences in a UAV versus a manned, propeller-driven airframe. As UAVs attain higher speeds, they will compete with jet aircraft for on-fire travel time, but will also have the advantage of increased linger and on-station time over fires versus those possible by manned jet or propeller aircraft. The five images were obtained over a one-hour flight profile while the ALTUS® II UAV “lingered” in the airspace above the controlled burn site.

The GA-ASI ALTUS® II UAV proved to be a capable platform for this disaster support mission. The uniqueness of remotely piloted aircraft facilitates hazardous operations during critical data gathering conditions. With the ability to switch out pilots easily, the aircraft can remain on-station over a disaster event such as a fire for extended periods of time. This becomes critical in long-duration missions, or where monotonous, long-term data collection missions would stress an aircraft pilot. A UAV operates effectively under hazardous conditions (unstable air, large obscuring smoke plumes, and possible rugged terrain conditions) that pose risks to flight crews.

Integration of the AIRDAS scanning instrument into the ALTUS® II was facilitated by the configuration and capacity of the airframe payload and sharing of electronic and system command and control links for remote payload operation. The AIRDAS, having been optimized for fire and disaster-related imaging, was enhanced further with remote operations capabilities. These enhancements will enable integration on other UAVs in the future, simplifying the task of remote operations of the payload.

The NERA M4/INMARSAT data telemetry communications link was highly successful in this demonstration and will continue to prove itself as a useful telemetry system given planned bit rate upgrades and evolution of an improved and cost-effective airborne system. The antennas that were configured into the UAV payload fairing were designed originally for remote satellite telephony and data communications and were modified for this demonstration. Further refinements, including an inexpensive tracking antenna, are warranted and forthcoming. Data usage costs for the INMARSAT system are reasonable, with anticipated declining costs over the next several years. Satellite signal “lock-on” was achieved within specifications, although the use of the UAV platform necessitated designing moveable antenna mountings and aligning the platform for specific satellite signal intercept angles. This is another reason for exploring tracking antenna opportunities to use aboard aerial platforms.

Currently, INMARSAT communications are rated at 64 Kbs, although the actual throughput was approximately 45 Kbs, due to NERA file information being sent with the data stream. Larger bandwidth throughput upgrades (greater than 300 Kbs service by 2003/04) to the INMARSAT satellite system will enable greater data volumes and minimize file...
compression. The high bit rate, combined with tracking antenna configurations, should greatly enhance the ability to telemeter data from airborne platforms.

The NERA/INMARSAT telemetry system accommodated high data rates from the AIRDAS payload. This proved critical in providing multichannel color composite images of various spectral band combinations of AIRDAS. The multichannel color image data readily displayed the fire parameters, such as fire front, perimeter, and hot spots, allowing more rapid decision making on the deployment of resources to combat the fire. An increased data throughput (color multi-band images) will increase interpretability of fire (or other disaster) parameters by the disaster manager or the GIS integrator.

Barriers

Technological and procedural barriers were noted in the FIRE demonstration and are addressed here. The shortcomings were primarily in the available technology at the time of the demonstration or involved cost constraints.

A current barrier to the operational use of UAV technology is the Federal Aviation Administration (FAA) lack of a regulatory framework for UAV operations and certifications. These regulatory uncertainties precluded operating the UAV over a larger scale controlled burn in the nearby National Forest or on other State or Federal lands. The UAV industry is working closely with the FAA to develop the regulatory framework to allow UAVs unrestricted access in national airspace. These issues should be resolved in the near future, allowing expanded use of UAVs for commercial and disaster support activities.

Integration of the M4 antennas into the UAV fairing restricted the aircraft to distinct flight alignment vectors to maximize signal strength. In a large fire condition with numerous fire support aircraft in constrained airspace over the fire, enabling the UAV to specific flight paths may prove to be an unreasonable proposition. Valuable time was also lost between the image acquisition time and transmission of the data. A tracking antenna would allow continuous collection, communication, and data telemetry with INMARSAT without specific UAV flight orientations. This communications antenna system shows great promise as a telemetry link in the near future, and is being examined for integration on future UAV missions.

The use of an onboard differential GPS would increase the accuracy of the platform position, particularly the aircraft/sensor altitude calculation. Currently, altitude is determined from the barometric pressure altitude instrument on the aircraft. This information is not of sufficient accuracy to allow refined geometric/terrain correction of image data. With improved GPS and aircraft pointing vector information, very reliable geo-location (~1.0 pixel RMS) can be achieved. During this demonstration, geo-location RMS errors were approximately 3 to 4 pixels, sufficient to determine fire location.

Image geo-rectification error resides in the quality, detail, and rate at which the navigation information was saved and interpreted. Most of the variables and sensor/aircraft positional information were collected on a one-hertz (1.0-Hz; 1.0/sec) cycle, while the AIRDAS scanning configuration is 4 to 23 scans per second. Although navigation data are recorded for every scan line of sensor data, only every fifth scan line of navigation information was telemetered with the associated image. This was done to reduce the size of the navigation file. A planned improvement to this procedure is to transmit the navigation information for every image scan line, thereby increasing the geo-rectification precision.

Further image utility upgrades are being developed to portray fire information more efficiently on the collected AIRDAS data. These enhancements include on-board data compression (from the “raw” signed 16-bit data to 8-bit data) to efficiently portray the thermal and spectral range of the data. Other upgrades include development of various band combinations, and color enhancement procedures. The authors are working closely with personnel from the disaster community to improve customizable products for disaster managers that would enhance their value for real-time decision making.

During the FIRE demonstration, data were delivered to a NASA server and website for global distribution. This is not an optimum location for data storage or dissemination. The optimal solution would involve the establishment of a central “clearing house” for data from individual fire events. Distribution to multiple users at various Incident Command Centers located at the fire base camps or other locations can be coordinated by an appropriate disaster agency. This would allow the base camp to be mobile, and allow access to the data provided by wireless remote modem connection to the central data server. This functionality would decrease the need for full on-site (fire camp) data collection and processing and centralize these processes at an appropriate location.

**Final Remarks and Future Focus**

The FIRE project successfully demonstrated the potential to utilize UAVs and remote sensing data gathering to support disaster management strategies. The capability of UAVs to safely acquire and disseminate data during hazardous conditions could significantly enhance the disaster management community’s ability to monitor and mitigate a broad range of disasters. Development and refinement of remote payload operations enhances the use of those payloads on UAVs and other platforms where weight and volume precludes the use of an onboard systems engineer.

Rapid development of satellite communications (telemetry) played a significant role in the FIRE demonstration. The ability to telemeter accurate multispectral imagery to any location in the world frees the disaster manager from being “on-site” at the event. Data distribution can therefore be handled at an appropriate disaster facility, allowing multi-agency wide area network access with rapid download and distributed without the need for multiple ground stations and support crew to retrieve the data. Individual fire event data can be distributed to the responsible on-site management team. With rapidly increasing data-bit rates, large, multiband data streams can easily be telemetered from any aircraft to anywhere on the globe. Our success at integrating telemetry equipment on the ALTUS® II UAV platform, and the potential to integrate new tracking antenna systems, will greatly advance the field of rapid data delivery. With an increasing bit-rate/decreasing-cost ratio, the next challenge will not be in data delivery, but in the ability to interpret all the information relayed to the manager and to make rapid, informed decisions during a major disaster such as a wildfire. Improvements to the image quality of the delivered product will be foremost in the next phase of these activities. Disaster managers and GIS specialists will have to play a key role in defining the variables they need to make more informed decisions during a disaster event.

Although the AIRDAS system has been used extensively for data collection over fires, this was the first integration of the system on an unmanned platform. Integration of this or any other imaging instrument was easily accomplished, given the design purpose of the UAV as a reconnaissance platform. If an operational UAV/fire-imaging payload were required by disaster agencies, integration time and ability to rapidly deploy would be similar or faster than those same constraints posed by manned aircraft.
The FIRe project team is focused on the further advancements of UAV, payload, telemetry, and information processing for disaster management. The team is planning a large-scale demonstration of enhanced disaster management capabilities using the ALTAIR® platform (Table 3) in 2003. The ALTAIR® is a scientific variant of the GA-ASI PREDATOR B® UAV for use by NASA and other organizations. The ALTAIR-FIRE project will demonstrate 24-hour coverage of fires throughout the western United States. This long-duration mission will allow a fire management organization to request multiple AIRDAS thermal-IR digital data acquisitions over numerous fires spread throughout an area stretching from Mexico to Canada and the Pacific Ocean to Colorado. The +6437-km (+4000-NM) endurance of the ALTAIR will allow lingering over many of these potential fire events. Data will be transmitted via a high data rate (500 Kbs) commercial Ku-band satellite (SATMEX 5) communications datalink system to a fire data management facility. All data will be geo-rectified in near real time and will be GIS-compatible. This long-duration, large-area coverage demonstration mission will exceed the capabilities currently employed to capture tactical fires data over large regions. It is anticipated that the ALTAIR FIRE demonstration will lead to new technologies and procedures supporting anticipated UAV airspace operational and system certification standards.

The disaster management community is on the cusp of a great technological leap forward, enabled by advancements in airborne platforms (particularly UAVs), sensor and imaging systems, telemetry, and information processing and product delivery. The authors are committed to assisting and enhancing the development of these supporting technologies for use by the disaster management community.

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