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PHOENIX – THE NEW FOREST SERVICE AIRBORNE INFRARED FIRE DETECTION AND MAPPING SYSTEM

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1 ABSTRACT

For several years, the USDA Forest Service has been making advances to the airborne thermal infrared imaging capabilities for wildland fire detection and mapping. The new Phoenix system represents the first time that a high productivity, digital, geo-corrected product is available for tactical fire intelligence and mapping. In conjunction with government and private-sector developers and suppliers, a complete system has been developed tailored to the unique requirements of the wildland fire fighting community. Beginning with the 2003 fire season, two Phoenix systems were deployed in the United States for wildland fire detection and mapping missions. Included is an explanation of the imagery itself, the advanced GPS/inertial measurement unit and the resulting geo-corrected products, an operational orientation concerning the use of Phoenix and integrating Phoenix products into the incident command structure, and proposed future enhancements.

2 HISTORY

Research by the Forest Service into the use of thermal infrared technology for wildland fire suppression efforts started in 1962, when a study concluded that infrared systems could make a significant contribution to wildland fire fighters. In 1963, initial system analysis identified several infrared fire detection requirements [1]:

1) rapid access to imagery
2) larger total field of view
3) better optical resolution
4) increased temperature sensitivity
5) more precise air navigation

In 1966, the Forest Service placed the first infrared fire mapping system into operation. A 1971 final report also concluded that:

"… forest fire detection is not a simple thermal mapping job. To be effective, this system must find the fire targets when they are very small and distributed over vast land areas. The fire targets must be precisely located to be of any use to fire suppression efforts." [2, page 3]

This has been an underlying principle throughout the evolution of infrared systems within the Forest Service.

2.1 Systems Evolution

All Forest Service infrared systems for large area fire mapping prior to Phoenix have been analog systems, relying on analog electronics to shape, filter, amplify, and process the incoming signals. The products have always been some form of strip chart imagery, whether etched on film with emulsion or printed on paper. The ability to combine multiple signals for fire detection allowed various forms of marking the strip charts to highlight specific points and areas that were identified as exceeding some user-defined threshold [3]. Limited capabilities were available in some cases for recording the signals and saving them for future use.

With the advances in line scanner technology and the advances in electronic components, the infrared systems likewise advanced in capability. A very real concern has always been for being able to maintain the operational status of the components of these systems, and that has been a driving force for Phoenix.

3 REQUIREMENTS

The primary users of the airborne infrared imagery products are the Infrared Interpreters (IRIN) who

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support the Situation Unit Leader in the Incident Command Structure at a wildland fire incident location. Because this information is vital to the intelligence decisions made during the early morning hours, IRINs typically perform their duties at night after the imagery has been delivered. Their input is then used by decision makers to shift forces and adjust fire attack strategies for that day's activities.

The Infrared Interpreters' primary objective is to analyze thermal infrared imagery and to provide intelligence information concerning the wildland fire's current state. Some of the specific items produced include delineating the fire perimeter, identifying the active fire front, identifying isolated hot spots, estimating the success of any backfire operations, calculating acreage burned, and producing summary maps. To produce these maps, IRINs typically utilize multiple products, such as the USGS 7.5 minute quad maps, terrain data, features data, and infrared imagery. As capabilities expand and needs change, many of these products are used in digital form. The products can be integrated into GIS tools and their results can be made available via the Internet.

Uncorrected line scanner systems require IRINs to mentally remove distortions from imagery, match features to other data, and interpolate positions. The reality of interpreting is that there is frequently limited access to other data sources, a very short time frame, and the users must have confidence in the products for most effective use.

Typically, for an IRIN to do the job, they need imagery of the areas surrounding heat sources, which establishes context and situational awareness. They need identifiable features, such as roads, trails, hills, valleys, water, and vegetation variations. They also need visibly identifiable heat sources, which requires both accurate fire detection and target discrimination marks, being strip chart edge marks and image highlights.

The primary requirements of systems to support IRINs have always been to support the ability to distinguish land features, see relative placements of hot spots and fire boundaries, and locate areas geographically. For operational use, systems must also utilize components that can be maintained, and be easy to use, which reduces user training and workload.

For these systems, there are two user groups: the Infrared Technicians onboard the aircraft who operate and maintain the equipment, and the IRINs on the ground who utilize the products that are created.

3.1 Sensors and Platforms

Remote sensing of the Earth from satellites has been ongoing for many years and for many purposes. When trying to match existing satellite capabilities to wildland fire suppression, there is a certain niche that can be filled. One problem, though, is that current satellite capabilities fall short of the tactical mapping needs of the firefighting community. Currently, spatial resolution is too coarse for wildland fire intelligence purposes. Satellites that can provide daily imagery typically provides pixels that are 1 km in size and this does not provide the necessary spatial resolution. Satellites with better spatial resolution are still not adequate for tactical needs and they do not have the re-visit interval necessary to produce daily products.

At the other altitude extreme, many advances have been made in uncooled Forward Looking Infrared (FLIR) units and hand-held units, as well as digital cameras with infrared filters used in low altitude airplanes and helicopters. While these capabilities also fill a certain niche, they typically provide small-area thermal mapping rather than large-area fire detection. Their area of coverage is too limited to be of much use to the tactical fire intelligence and mapping communities for incidents over 1,000 acres in size.

While thermal imaging airborne line scanners have been around since before the first Forest Service system was researched in 1963, they support both the large field of view and area of coverage issues. In addition, they provide the optical resolution necessary to perform small-spot automatic fire detection. In the Forest Service mid-altitude aircraft that typically fly at 2,400 to 4,300 m above ground level, the line scanner systems are able to detect and identify hot spots on the order of 15-20 cm, while viewing a breadth of 8-14.5 km[1].

The Phoenix system is currently flown aboard either a Cessna Citation Bravo jet (Figure 1) or a King Air 200 turboprop aircraft. With a typical air speed of 200 knots and a height above ground of 3,000 m, an area of 6,515 hectares can be covered in one minute with an overall resolution of 6.3 m/pixel. This roughly equates to imaging an entire USGS 7.5 minute quad sheet in just over two minutes. Within this area, Phoenix automatically detects fire spots that are 15-20 cm in size. This coverage area is 40.5 sq km per minute.

[1] At 3,048 m above ground, a 1.25 mRad detector will see a nadir spot that is 3.8 m in diameter while viewing a width of 10.6 km. A 15-20 cm hot spot can be detected across the entire line.

Phoenix provides the capability to acquire and process this data and to create the imagery in hardcopy and digital formats in real-time.

Figure 1 – Cessna Citation Bravo showing modifications to accommodate a line scanner.

4 PHOENIX CAPABILITIES

At the core of the Phoenix system are two thermal infrared detectors that are utilized to provide outstanding thermal detectability. With one detector in the 3-5 µm band and the second in the 8-14 µm band, the full potential of thermal imaging for wildland fire can be realized. As described by the Planck function, the shorter wavelength detector is more sensitive to radiation of higher temperatures and the longer wavelength detector is more sensitive to lower temperatures. This latter band is used to generate the background imagery, while the former detector typically sees the heat associated with wildland fire. It is the combination of these bands together that determines whether a single spot exceeds a user-defined threshold to be identified and marked on the imagery as fire. The digital processing of the kA-B analog function used in earlier systems is well known within the Forest Service infrared community. This dual-band capability is the key to removing false fire detection resulting from sun glint on reflective surfaces, hot rock outcroppings, and other non-fire thermal sources.

The Phoenix system utilizes a Kennedy Optics style RS-25 line scanner. The scanner spins at 4,000 rpm, and with its triangular mirror, produces 200 scan lines per second with a 120-degree field of view. With detector sizes of 1.25 mRad, the entire 120-degree field of view requires 1,676 samples, with no in-scan oversampling.

$$\frac{120\deg * \frac{(2\pi)rad}{360\deg}}{0.00125 rad / sample} = 1676 sample \qquad (1)$$

It is important to note that these 1,676 samples are taken from equal angular increments of rotation of the mirror and not from equidistant projections onto the ground. This is exactly the cause of much distortion in line scanner imagery, since each sample projects to a different sized spot on the ground. It is important to distinguish between an angular sample and that sample's projection to the ground.

To obtain these 1,676 samples for a single 120-degree field of view scan line, the Nyquist Sampling Theorem states that an analog-to-digital converter must sample the signal at slightly more than twice this rate. At 200 lines-per-second, each line takes 0.005 seconds, so the sampling rate must be at least 670,400 Hz.

$$2 * \frac{1676 samples}{0.005\sec} = 670{,}200 Hz \qquad (2)$$

With analog anti-alias filters at 500 kHz, the sampling rate is increased to 1.008 MHz for both channels. The samples are digitally filtered and down-sampled to produce scan lines of 1,680 samples for each channel. Just for comparison, audio CD players and digital audio streams can be sampled and played quite acceptably in stereo at 48 kHz and DVD audio discs typically run at 192 kHz.

The Phoenix airborne signal processing is performed on a Digital Signal Processor (DSP) within the airborne PC and is considered a hard-real-time component, since all of the processing for each individual scan line occurs within the same 5 msec acquisition time frame. This processing includes digital filtering, automatic fire detection, quantization, and transfer to the PC, which then removes the distortion, produces the hardcopy strip charts, and logs the data to files.

Several improvements that the Phoenix system has added to the infrared systems capabilities are to:

1) remove distortion from imagery, providing Level 2 rectified imagery in real-time,
2) enhance visualization by use of 3D and terrain, map grids, and to scale and orient imagery,
3) provide overviews of flight passes, and

4) provide products in digital formats, which can be input to GIS tools and can be distributed on the Internet.

4.1 Output Formats

The goal of Phoenix is to produce products that are useful for the IRINs, but also to accommodate multiple situations in fire camp scenarios. While the ultimate capability is to have images downloaded to a fire camp to be integrated with other digital basemap data for easy interpretation and mapping, not every fire camp situation may support that option. Especially in early stages, there may not even be computer access or there may not be ready access to other digital data. In these scenarios, Phoenix is able to fill the need by providing the hard copy strip charts. The Mission CD-ROM provides the images and data for review, even on a low-end laptop, without requiring any network access.

Phoenix products are:

1) Roll corrected hardcopy strip charts.

2) Level 2 fully rectified hardcopy strip charts, which includes correction for aircraft position and attitude and line scanner geometric distortion, but not removal of distortions caused by terrain.

3) High resolution GeoTiff image files of roll-corrected and fully rectified strip chart imagery, containing both geographic position and orientation information, for integration with GIS software.

4) Lower resolution JPEG files of strip chart imagery, for downlink to the ground.

5) National Elevation Dataset (NED) file for geographic area covered by the mission, used for orthorectification.

6) Level 3 orthorectified GeoTiff image files that do remove distortions caused by terrain.

7) Virtual Reality Modeling Language (VRML) files of level 3 orthorectified imagery for display and manipulation in 3D within a web browser.

8) Log files of captured data.

All of the data files are written to a Mission CD-ROM onboard the aircraft for delivery to the IRINs on the ground, in addition to the hardcopy strip charts. HTML files are automatically created based on the collected data to provide a simple user interface to the content of the CD-ROM, including an overview image of all flight lines (Figure 2) using Scalable Vector Graphics (SVG). The lower resolution JPEG image files, which are considerably smaller than the source GeoTiff files, are transmitted to the ground to provide "quick-look" review and heads-up digitizing capabilities in near real-time.

System analysis and additional processing can be conducted on the log files, as they contain all navigation and signal data for each scan line passed from the DSP to the PC.

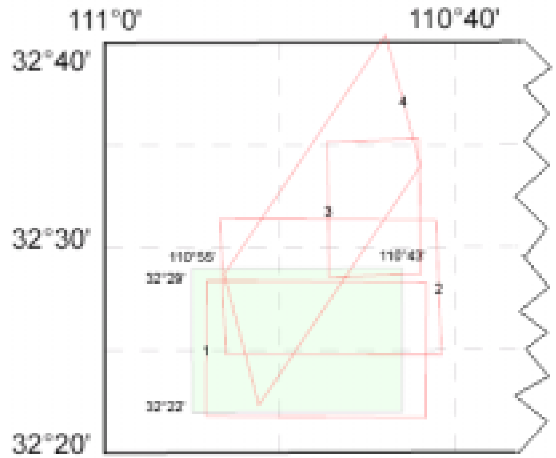

Figure 2 - SVG Mission Overview

The mission overview image shows the relative placements of each flight line, resulting in both GeoTiff image files and hardcopy strip charts. Within the overall geographic area of interest, the green box shows the boundary from the scanner order request. Each pass is shown in red with the pass number in the center of the beginning of the pass. From this figure, the first pass was made from West to East across the scanner request boundary at the southern end of the entire mission area. Pass 2 was further to the North, overlapping the previous pass by about 50% and going from East to West. Pass 3 was further to the North with no overlap with pass 2 and went from West to East. Pass 4 went in a southwest direction crossing over areas of the previous 3 passes.

The pilots and the Infrared Technicians determine the flight lines over an area of interest, whose original coordinates are provided by the IRINs on the incident through a scanner request, but they do not necessarily limit themselves to the requested boundary. Their objective is to fly where the fire is, even if that is outside the requested box. The mission overview image provides necessary feedback from the IR Techs to the IRINs to show the area covered in relation to the area requested.

An additional intended benefit of creating these overview images is to increase the ability of the users to correlate multiple strip charts and to simplify the comparison of data between flight lines.

With the digital image files, it becomes quite simple to rotate the image by the flight line heading, so that North will appear at the top of the rotated image. In the following figures, one can see a rotated IR image and the corresponding topographic area.

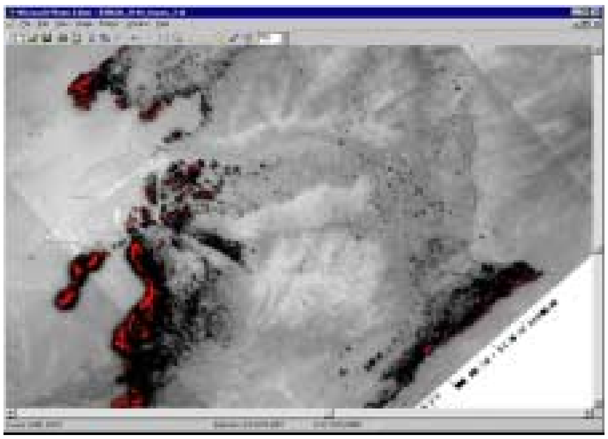

Figure 3 - Aspen Fire Infrared

Figure 4 - Aspen Fire Topo

Feature comparison between the IR and the topo map becomes straightforward and the placement of the fire boundary and hot spots can be made easily, either manually or digitally. While several areas triggered the fire detection (shown in red), surrounding areas are still seen as burned (shown in black). Isolated hot spots will show as red fire pixels with little or no surrounding black area.

5 SAMPLE IMAGERY

The strip chart in Figure 5 was collected with only roll-correction applied during acquisition and processing. The effects of aircraft position and attitude variations have not been corrected, nor have any distortions from the wide field of view scanner geometry, usually known as S-bend and the bow-tie effect. Roll correction is always applied in order to keep the center of the scan line to be looking straight down from the aircraft.

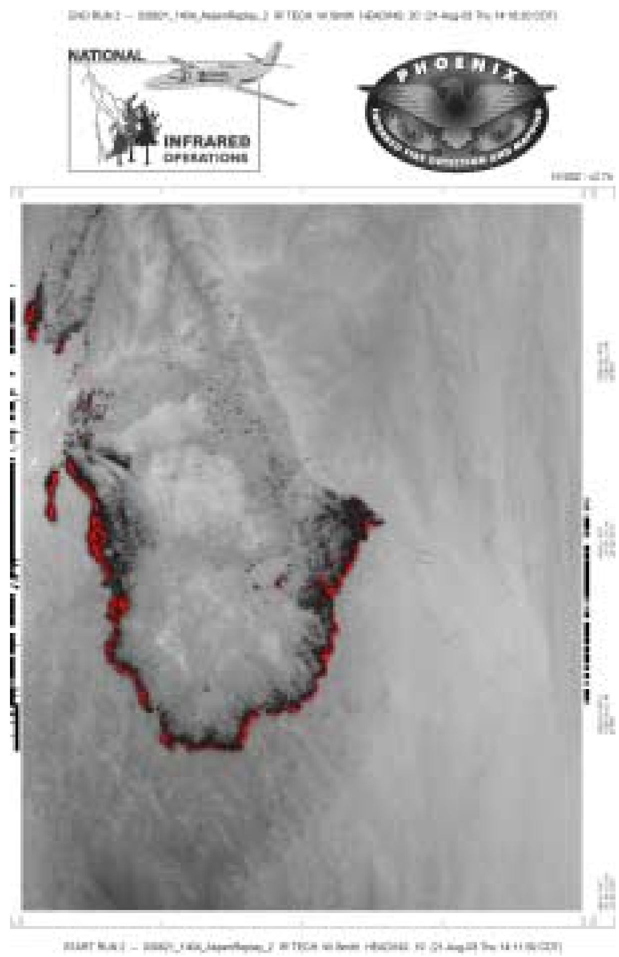

Figure 5 - Phoenix Roll-corrected Strip Chart

Fire spots that exceed the user-specified threshold are marked in the image as red pixels and are marked at the edge of the strip chart with a tick mark that corresponds to the quarter of the horizontal image line where the spot occurs. On the hardcopy strip chart, which is a grayscale product, the detected fire spots are a dark black, which is distinguishable from the surrounding gray.

When the Level 2 corrections are applied for aircraft position and attitude and the geometric distortions from the line scanner, the strip chart is produced as in Figure 6. In this image, every image pixel represents the same amount of ground, and every pixel in every scan line is added to a grid of that size. While still not accounting for radial offsets due to variations in the terrain, the fully rectified image is considerably better, in terms of size, scale, shape, and orientation of the area. The fire detection and marking in both images is the same.

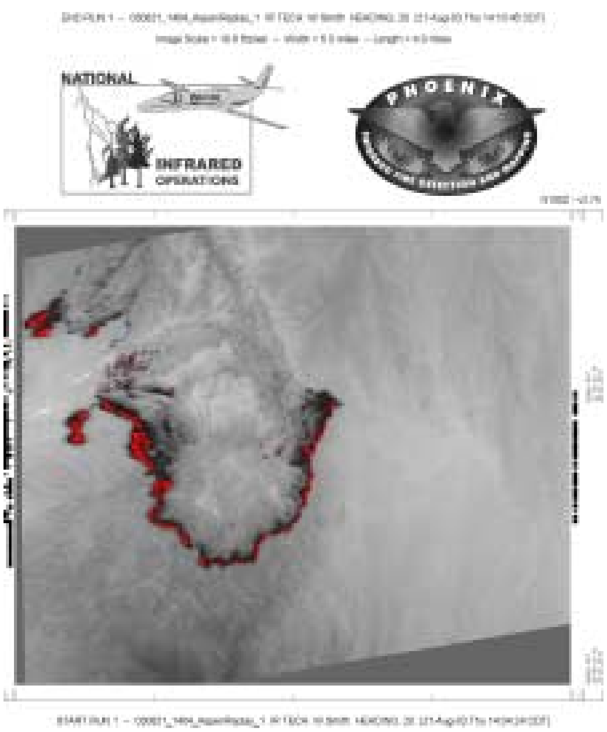

Figure 6 - Phoenix Fully Rectified Strip Chart

One important aspect to this imagery is that the fire spots are presented within the context of the surrounding imagery. While suggestions have been offered to extract the fire detections and present those separately, these processes typically remove them from the surrounding context. In order to provide real value to the IRINs and to promote confidence in the products, the context of the entire image is maintained.

This brings to light another important aspect of the Phoenix system, and that is that the system has evolved and been developed within the Forest Service and with the close involvement of the end users, being both the airborne Infrared Techs and the ground-based Infrared Interpreters. Their daily use and need for infrared products has been a key component in the effective implementation of the Phoenix system.

Beyond the extraordinary capabilities of the Phoenix system itself, having grown within the user community adds to its usefulness for wildland fire suppression efforts.

6 PARTICIPANTS

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U. S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.

Infrared systems for wildland fire suppression activities continue to require

1) dual-band thermal infrared detection,
2) real-time generation of digital mapping products,
3) COTS hardware, and
4) a growth path for upgrades and evolution.

In cooperation with the USDA-FS National Interagency Fire Center (NIFC) and the National Infrared Operations unit (NIROPS), each additional participant provides specific expertise.

The US Army Aviation and Missile Command's (AMCOM) Aviation and Missile Research, Development, and Engineering Center (AMRDEC), at Redstone Arsenal in Huntsville, Alabama, provides technology support for infrared sensor capabilities, guidance and navigation systems, and real-time processing. AMRDEC develops guidance, navigation, and control systems, utilizes digital map products, and integrates and tests hardware and software for real-time systems. Their support relationship with the Forest Service started in 1994, and their goal and purpose was to leverage relevant technology and experience.

Computer Sciences Corporation (CSC) provides experience in supporting government customers and performing information technology systems development, real-time software development, and the integration of hardware and software for highly specialized systems. Their support relationship with the Forest Service through the AMRDEC started in 1995.

Applanix Corporation, of Ontario, Canada, was used as the source for the POS/AV system, which provides precise position and orientation information for airborne vehicles by combining GPS data with an inertial measurement unit (IMU).

Innovative Integration, of Westlake Village, California, was used as the source for the high-speed analog-to-digital converter and the Digital Signal Processor (DSP), which resides on a PCI bus inside the airborne PC.

ICS Advent, of San Diego, California, was used as the source for the airborne PC, which currently contains a 2.0GHz Pentium 4 processor running Microsoft Windows 98, which is used for compatibility with the DSP interface drivers from Innovative Integration.

Ocean Data Equipment Corporation, of Providence, Rhode Island, was used as the source for the TDU-850 thermal strip chart printer, which interfaces to the airborne PC through a standard parallel cable. It provides a 256 gray shade capability in 8.5 inch lines that are 1,728 pixels wide.

All of the Phoenix hardware components are commercial-off-the-shelf (COTS) items, which mean they are available through normal retail purchasing. This was a requirement so that spare parts, backups, and field replacement could be performed with a minimum of downtime. The hardware is mounted in a custom rack that fits all of the Forest Service infrared aircraft, currently a Cessna Citation Bravo jet and a Super King Air B200 turboprop. It can also be installed in leased aircraft.

Figure 7 - Phoenix Line Scanner and Hardware Rack

Figure 8 – Phoenix operator display station shown aboard aircraft.

7 FUTURE ENHANCEMENTS

Future enhancements to the Phoenix system will involve all aspects of the data flow including sensors, on-board processing, GPS and IMU navigation sensors, display, and data delivery. The timing for these individual efforts will depend on the state of the technology and how economically and reliably they can be integrated into the total system.

Current enhancement efforts involve integrating the processing with different line scanners, specifically different models of Daedalus line scanners, which are currently used both by the Forest Service and by the Infrared Operations Group based in Melbourne, Australia. They are part of the Department of Sustainability and Environment for the State of Victoria and are actively involved in developing their own digitally enhanced infrared systems and with adapting the Phoenix technology for their needs.

Several different RF downlink systems are being evaluated for downlinking the digital imagery directly to incident personnel. A system that is currently showing progress involves the 2.4 GHz band as a means of downlinking in excess of 2.0 MB/s. Work continues with NASA Goddard Space Flight Center and their contractors for this effort.

Additionally, the full value of Phoenix digital data has yet to be exploited. All of the current image files are produced from a single flight line, and work is underway for integrating multiple flight lines into a single image. The output formats will be updated to be compatible with advancing GIS software.

8 REFERENCES

[1] Project Fire Scan Fire Detection Interim Report, USDA Forest Service Research Paper INT-25, 1966.

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[3] Warren, John, "Advanced Fire Sensing and Locating Systems", Proceedings of the 4th Forest Service Remote Sensing Applications Conference, April 6-11, 1992, ASPRS, ISBN 0-944426-89-1.