MITRETEK TECHNICAL REPORT

# Aircraft-to-Satellite Links Suitable for Transmitting USDA Forest Service Infrared Forest Fire Data

## Screening and Feasibility Study

**April 2003**

NATIONAL INTERAGENCY FIRE CENTER
Boise, Idaho

RSAC


MTS™ Mitretek Systems

**Center for Science and Technology**
**Falls Church, Virginia**

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# Aircraft-to-Satellite Links Suitable for Transmitting USDA Forest Service Infrared Forest Fire Data

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**April 2003**

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Prepared for:

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Salt Lake City, Utah

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# Abstract

Mitretek performed a screening and feasibility study of the capabilities of military and commercial satellite communication systems to send data from infrared sensors carried on Forest Service aircraft to a ground interface point accessible to data interpreters. We could identify no military systems that are capable of or likely to be available to support the Forest Service operations. However, we identified existing commercial systems that have advanced to the point that available data rates can handle some, and possibly all, of the data transmissions that are required. The degree to which these commercial satellite systems can support the Forest Service needs depends on how much the raw data can be reduced by selection and compression before transmitting from the aircraft and on the acceptable length of the transmission time.

Mitretek recommends the following:

- Implement a communications system based on the INMARSAT commercial satellites.
- Investigate acceptable methods that could be used to select or compress the data sets produced by the infrared sensor system.
- Conduct a thorough end-to-end design.
- Use the performance of military unmanned aerial vehicles as a reference point for comparison to the performance provided by the commercial systems.

# Acknowledgments

Significant contributions to this study were made by Wesley Center, Principal Staff; Mohammed Zaatari, Principal Staff; Rajiv Khanna, Senior Principal Staff; and Michael Caloyannides, Ph.D, Senior Fellow.

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Section 1

# Introduction

The USDA Forest Service uses an aircraft-borne infrared (IR) sensor instrument, called the Phoenix System, to obtain data over wildland fires that are used by interpreters on the ground to prepare a map of the burning and smoldering area. To deliver the IR and associated data to the on-ground personnel for interpretation, the aircraft must land so that the data media can be hand-delivered or the aircraft must make a low pass over a designated drop location so that the media can be dropped to the ground for pickup. The Forest Service is looking for a satellite communication system that could be used on the current Forest Service aircraft to deliver the IR and associated data electronically via satellite to the ground so the aircraft can cover more fires per night and the ground personnel can have more time to evaluate the data. Mitretek Systems has conducted a screening and feasibility analysis of currently available military and civil satellite communication systems that can meet the Forest Service requirements using current Forest Service aircraft.

## 1.1 Mission Requirements

The Forest Service currently uses a Cessna Citation Bravo and a Beech King Air 200 aircraft based in Boise, Idaho, as the airborne platforms for the Phoenix IR sensing system. IR data are usually gathered at night at an altitude of 8,000 to 12,000 feet above ground level. Data may be gathered over as many as 8 to 10 fires in several states in a nighttime operating period of six hours. The time required to gather data over a fire depends on the size of the fire and can range from 10 minutes or so for smaller fires to as much as one hour or more for extremely large fires. The aircraft may operate throughout the United States over most of the year.

The Forest Service needs a communication system to send the data collected by these airborne systems all the way to the ground-based interpreters, but this study focused on the aircraft-to-ground link via a satellite.

## 1.2 Communication Requirements

Mitretek met in person and held telephone conferences with personnel from the National Interagency Fire Center and contractors who were familiar with the performance of the Phoenix sensor, the data sets created on the aircraft, and the application of those data sets to create the maps of the fire areas.[1,2,3] Our understanding of the significant parameters of this system is based on these discussions. We list below the parameters we believe to be important to the communications system design.

- The scanner operates at 200 scan lines per second and produces 1728 bytes per scan line.

- The output of the scanner is assembled into a GEOTIF file at a data rate of approximately 2.8 Mbps.
- At 200 to 240 knots aircraft ground speed, the scanner provides an overscan of more than 4:1, which could be combined in the aircraft.
- A log file is also produced on the aircraft at about 14,000 bytes per scan line.
- The log file is relatively new and it probably could be reduced by selection of data subsets, possibly to only 10 percent of its full size.
- The GEOTIF file could also be reduced by selecting or compressing the raw data, but users are concerned about possible loss of data due to these processes and would require extensive testing before they would be willing to accept any form of compression.
- The "average" pass over a fire lasts between 5 and 10 minutes.
- It would be acceptable to transmit the data from the aircraft over a time period considerably longer than the period in which it was recorded and therefore at a significantly lower rate of transmission.

Based on these parameters, Mitretek calculated that full rate transmission of the image and log files in real time would require a communications link with a data rate of about 25 Mbps. However, since these data will be formatted to fit geographically accurate maps of the scanned area, the overscan produced by the sensor must be eliminated before this fit can be made. If the data reduction can be made on the aircraft and the transmission period can be extended to include flight times between passes over the fires, we calculate that the communications link might only need to support a data rate in the range of 75 to 100 kbps (Appendix A).

## 1.3 Critical Communications Factors

Mitretek's analysis of the communications capabilities provided by military and civilian satellite systems has found that the most critical factor for all systems using aircraft is the antenna used to transmit to the satellite. The antenna has to be mounted on the aircraft and must be pointed towards the desired satellite throughout a wide range of aircraft maneuvers without causing interference to other satellites that may be in nearly the same direction from the aircraft. The antenna must also fulfill its function without significantly degrading the aerodynamic properties of the aircraft. The ability to fit a suitable antenna on the existing Forest Service aircraft was therefore a major factor that was considered during Mitretek's investigations.

The second most critical factor is the data rate that the communications system is required to carry. The maximum rate for any system in use today is set by the transmit power available from the ground (or aircraft) transmitter and the sensitivity of the satellite receiver. It is therefore a matter of some importance to determine the amount of data that must be transmitted and the time period in which the transmission must occur.

Section 2

# Analysis of Military Systems

Mitretek conducted a survey of military satellite communications systems to identify those systems with the potential to meet the communications requirements for transmitting the IR data from current Forest Service aircraft. The survey started with unclassified sources for the initial screening and survey to help focus our efforts on useful areas that could require access to classified data sources. However, following a review of these unclassified sources and discussions with military personnel, Mitretek determined that military satellite systems are either not capable of meeting or unlikely to be available for Forest Service needs, as discussed below, and no classified sources were investigated. It is possible that our investigation missed some factor that is only discussed in classified material, but Mitretek believes this is very unlikely.

## 2.1 Military Satellite Systems

The military satellite systems in use today can be divided into three categories by the frequency band in which they operate. They are designated UHF (Ultra High Frequency), SHF (Super High Frequency), and EHF (Extremely High Frequency).[4,5] Satellites using SHF are also designated as the DSCS (Defense Satellite Communications System). (Note that these designations have also been used as identifiers of the satellites themselves, but recent upgrades have combined the frequency bands provided on a single military satellite. However, the characteristics of the frequency bands have remained unchanged.)[5]

Most military satellite communications are at data rates either much greater or much less than the rates needed for the Forest Service task, and most of the high-rate communications are intended to be transmitted by a large uplink antenna at a fixed location. Mitretek determined that all the UHF systems were at data rates far too low—typically 75 to 4800 bps—to support the Forest Service communication needs.

We also determined that the EHF systems are unable to support the Forest Service communication needs, although they used bandwidths nominally able to transmit the data rates necessary. We found that most of the EHF systems use spread-spectrum techniques for low probability of intercept and to reduce the level of interference they could induce in satellite receivers other than the one intended to receive these transmissions. The actual throughput data rate is therefore too low to support Forest Service needs except for reserved channels used for broadcast types of services. While the broadcast data rates are much greater than what is needed for the Forest Service, the systems in place all seem to require large antennas for the uplink and are only able to use small antennas for receiving the downlink—the reverse of what is needed for the Forest Service link.

This leaves the SHF systems as the only remaining possibility that may be able to support the Forest Service needs. Military systems in the SHF band are all designed to operate with the DSCS and equivalent NATO satellites. They are tasked to provide wideband and anti-jam communications in support of strategic and tactical requirements. Large, medium, and small earth stations are defined for this system, which are designated as AN/WSC-6(V) plus another digit to identify antenna size and other variables. The smallest of these earth stations can transmit data at 384 to 512 kbps, which is compatible with the transmission rate the Forest Service would need. Unfortunately, from the Forest Service point of view, the smallest of these terminals use an antenna that is 8 feet in diameter. Any smaller antenna would produce unacceptable interference into other satellites that share the SHF band. Operation from aircraft near the size used by the Forest Service is therefore not possible.

It is also significant to note that the DSCS satellites[5,6] provide only six channels with bandwidths from 50 to 85 MHz, while the published maximum throughput data rate per user is only about 3 Mbps, even from the large-size earth station. This implies the system design includes spread-spectrum operation for maximum anti-jam and low probability of intercept. While this type of operation provides important advantages for military operations, it greatly reduces the communications capacity these satellites can provide and ensures the capacity that is available can only be used by high priority military users. It is also possible that the wide bandwidth of the channels could be shared among multiple users, but this would allow only a small usage of spread-spectrum techniques. The high-security but low-data-rate usage is considered more likely.

## 2.2 Military Unmanned Aerial Vehicles

The Mitretek investigation of military systems included research of two well known Unmanned Aerial Vehicles (UAV) called Predator and Global Hawk.[7] We found that both of these aircraft use a physically steered dish antenna to link to commercial Ku-band satellites at the data rates required. Although this antenna is quite small (approximately one foot in diameter on the Predator UAV), the pointing mechanism requires a relatively large aperture to point the antenna in all the necessary directions.

For these two aircraft types, the airframe design was, in part, built around the antenna requirements. Several tens of square feet of fuselage on these aircraft are constructed from a radome material through which the radiation to the satellite can pass with minimal attenuation. Since the radome material has relatively low structural strength, we expect that significant additional strength must have been required for that portion of the fuselage surrounding the radome. The design trade-offs that were chosen for these UAVs are only possible because there is no cockpit. A similar design for a piloted aircraft would have to greatly restrict the antenna pointing angles or have a very large bulge for a protruding radome. Any radome of that type would also likely require structural modification of the aircraft fuselage because some of the original strength members would most probably have to be removed to prevent obstruction of the antenna sight lines. Therefore, fitting an antenna of this type to the Forest Service aircraft would be a difficult and expensive task.

Mitretek also noted that the published maximum speed of the Predator UAV of 117 knots is much less than the 402 knots that is the maximum published for the Cessna Citation Bravo. This would greatly restrict the area that could be covered in a single night by this UAV. A new version of this UAV is reported to have a cruise speed of about 120 knots, but its maximum speed was not stated. Even this speed would cause a significant reduction in its range of coverage.

We also noted that the Global Hawk UAV has a published speed of 454 mph, a range of over 16,000 miles, an endurance of 42 hours, and a service ceiling of 65,000 feet. On this aircraft, the antenna size is listed as 48 inches in diameter and is able to support communications through a Ku-band satellite at up to 50 Mbps, well above the rate necessary for the Forest Service application. The price of a Global Hawk has been quoted as $35-48 million and the smaller Predator costs about $4.5 million, each with its complete military sensors and communications package installed.

The capabilities of these UAVs seem to exceed the Forest Service requirements in some areas and not meet them in other areas. However, they have proven their ability to fulfill missions that are basically similar to the Forest Service mission, are known to be able to carry a range of different sensors, so it is possible some suitable configuration could be arranged with their manufacturers, should the Forest Service choose to follow that course. At the very least, these vehicles could serve as a benchmark, against which other possible communications systems can be compared.

## 2.3 Military Use of Commercial Satellites

During discussions with military personnel, Mitretek determined that military satellite communications systems often use commercial satellites as well as, or instead of, military communications satellites.[5,7,8,9] Some of the military and civilian personnel with whom we discussed the Forest Service needs stated that this mainly occurred because there is not enough capacity on the military satellite systems to handle the required traffic.[4,5] Several of our military contacts made a special point to tell us that this lack of capacity is a severe limitation to military operations and that they believe it would be extremely unlikely that any non-military user would be granted access to any military satellite system, especially if an alternate commercial system is possible.[8,9]

One of the suppliers of commercial systems stated they had provided several of their systems to military customers.

We also note that the Predator and Global Hawk UAVs use commercial Ku-band satellites for their communications link.[5,7]

## 2.4 Military Satellite Availability

Several of the military contacts and contractor personnel[8,9] with whom we discussed the Forest Service needs stated that all military satellite systems were badly overloaded and unable to meet the needs of the military users. We believe this is due, in part, to the use of anti-jam and low probability of intercept techniques, which do not allow the same high-rate data throughput as would be possible on commercial satellites. These features are of great importance to many military operations, but they reduce the overall communications capacity available in a given bandwidth.

The military uses a seven-level system to prioritize uses of all of their satellite systems. Non-DOD users are listed on the seventh (lowest) level. We were also told that users with low priority are often interrupted by higher priority users while communications were in progress. This is not to say that the Forest Service would have to accept the current scheme, but that to change this system so the Forest Service could reliably schedule their transmissions would be a significant undertaking, and we expect to do so would take agreements and coordination among the highest levels of each agency. As stated above, the personnel we spoke with believed that it would be highly unlikely that Forest Service access would be granted since commercial systems are probably available.

**Section 3**

# Analysis of Commercial Systems

The Mitretek survey of satellite-based commercial services that could support the Forest Service communications needs found that there are essentially two basic types of systems currently available. One system transmits using L-band frequencies near 1.5 GHz. All the satellites that use this band are owned and operated by Inmarsat. The other basic type of system transmits on Ku-band frequencies, near 14 GHz. Communication satellites that use this frequency band are operated by many satellite service providers, such as PanAmSat, Intelsat, Loral, and Americom.[6] Table 3-1 provides a comparison of some relevant parameters for these two systems.

**Table 3-1. Summary of Commercial L-band and Ku-band Satellite Communications Systems**

| Parameter | L-band System | Ku-band System |
|---|---|---|
| Satellite spacing | 40 – 120 degrees of longitude | Minimum 2 degrees of longitude |
| Up-link frequency range | 1.6265 – 1.6605 GHz | 14.0 – 14.5 GHz |
| Down-link frequency range | 1.530 – 1.559 GHz | 11.7 – 12.2 GHz |
| Antenna location | Side of fuselage | Top of fuselage |
| Operational antenna size (approximate) | 36 (l) x 12 (h) x 3 (t) inches | 70 (l) x ? (w) x 10 (h) inches |
| Number of antennas required | Two | One |
| Maximum current data rate | 128 kbps | 128 kbps |
| Predicted near-future data rate | 432 kbps | 2 – 5 Mbps |
| Aircraft certified for antenna | Cessna Citation Series (not BRAVO) | Boeing 747, Airbus A-340 |

Note that the summary in Table 3-1 is the result of a relatively brief survey and may not include other possibilities that may also be available or may become available in the near future. We consider this a developing market, and the equipment available could change quickly but will depend, in part, on the health of the commercial airline industry, which is the main market for these systems.

One of the major differences between these two systems and between them and the military UAV systems is the size of the antennas required on the aircraft. The wide spacing of the Inmarsat satellites[6] permits the use of a much simpler antenna that is easier to construct and mount to an aircraft, and we are sure this has been done. A full system would only need to be adapted to the Forest Service aircraft. All other components have been proven in actual service.

The Ku-band systems require an antenna that is physically larger and more difficult to construct and mount to an aircraft. We are sure the military solution has been put into practice, but are not certain that the commercial version has made it past the demonstration phase.

## 3.1 L-band Solution

Inmarsat, a global mobile satellite communications service provider, offers a commercial service that can be utilized to meet the Forest Service requirements for the distribution of infrared sensor data from aircraft overflights of wildland fires. Inmarsat provides the space segment capability for the system, including interaction with all Inmarsat LES (Land Earth Stations) operated by independent telecommunications companies around the world. This space segment constellation provides full coverage of the United States (and also most of the rest of the world) using L-band frequencies.

Inmarsat builds its market relationships to end users like the Forest Service through an Inmarsat Partner and Service Provider (IPS). The IPSs utilize the Inmarsat family of satellites to offer installation and integration services for the aeronautical satellite communications systems. Mitretek established a contact with three IPSs for this task (see Table 3-2).

**Table 3-2. Inmarsat Partner and Service Vendors Contacted**

| Company | Web Address | Mailing Address | Telephone |
|---|---|---|---|
| LandSea Systems, Inc. | www.landseasystems.com | 509 Viking Drive<br>Suite K, L & M<br>Virginia Beach, VA 23452 | 757-463-9557 |
| LAC Avionics, Inc | http://www.lacavionics.com | San Jose Jet Center<br>1250 Aviation Ave<br>San Jose, CA 95110 | 408-295-4144 |
| DataLine, Inc | http://www.dataline.com | 2551 Eltham Ave<br>Suite O<br>Norfolk, VA 23513 | 757-858-0600 |

During three teleconferencing sessions, these IPSs described the capabilities of the Aero High Speed Data (HSD) aeronautical communications systems. The system components are as follows:

- Two high-gain side-mounted, conformal, and electronically steered phased array antennas. The antenna assemblies are installed on the aircraft exterior. The antenna dimensions are approximately 3 ft x 1 ft with a thickness of approximately 3 inches.

- A radio frequency (RF) unit that interfaces to the antenna system. The high power amplifier (HPA) varies its gain so that the satellite always receives the same constant power level at the output from its antenna. As the plane moves, the HPA adjusts its power levels to compensate for antenna gain variation. The RF unit also provides a bi-directional 128 kbps data channel that interfaces to a mobile router system.

- The mobile router system adapts the RF unit output to the end user (i.e. Forest Service) terminating equipment such as the computer that handles the transfer of sensor data.

LandSea Systems and LAC Avionics had experience with antenna installations on aircraft similar to the two aircraft types owned by the Forest Service (Beech King Air 200 and Cessna Citation). One of the vendors expressed some problems with installations on some Cessna planes, but they may come up with a slightly better curvature line for the antenna configuration by the time of the Forest Service installation (within a year time). As for the Beech King Air plane, their fuselage does not have a constant radius, but installations can be worked out to fit the airframe, based on their experience. In all cases, it is Mitretek's belief that the planes need to be re-certified with the new installation. The RF unit and the router are mounted inside the cabin of the airplane.

DataLine stated they had installed similar systems on C-130 and C-17 aircraft using hatch-mounted parabolic antennas instead of the phased array antenna used by the LandSea Systems and LAC Avionics. They also said they had used the 128 kbps link with compression on video and text files, achieving an effective throughput data rate of approximately 512 kbps.

The current INMARSAT service is available in a circuit switched mode in which a connection is established between the aircraft and the ground station before a file transfer process is initiated. With the new service release in 2005 for the Inmarsat 4 satellite, an always-on connection will be available. There is also a shared service available for applications involving short bursts of data for which the service is charged in terms of data volumes sent or received and not minutes of usage. With the requirement for transmitting large files, Mitretek recommends the circuit switched service for the Forest Service to guarantee service performance and channel allocation when a file transfer process is initiated. LandSea Systems and LAC Avionics mentioned that upgrades may be available to data rates capability up to 432 kbps in 2005. The new data rate will be compatible with the antenna technology and only the RF unit will need to be interchanged.

Rough order of magnitude costs were provided by LandSea Systems and LAC Avionics. They estimated the system cost including antennas, RF Unit, and Router to be around $300K, not including installation charges that will vary with aircraft type and existing equipment. The IPSs wanted to have a more thorough review of the Forest Service planes before they provided an installation cost estimate. The cost currently is $13 per minute for the 64 kbps service and $26 per minute for the 128 kbps service for Inmarsat airtime charges.

The Inmarsat satellites are the only satellites authorized to use L-band frequencies[6] for this type of service, so Inmarsat is able to keep large angular separations between its satellites. This has greatly simplified the antenna requirements and allowed service to be offered through the phased-array antennas described above with relatively wide beam width. As a result, antennas with small size, low weight and drag, and relatively low cost can be used, which are expected to be suitable for installation on the Forest Service aircraft.

## 3.2 Ku-band Solution

Connexion by Boeing[10] has been experimenting with an in-flight system that can provide airborne communications capability to Boeing airplanes. The cabin is equipped with a server/router and an RF unit in the interior of the plane. On the exterior of the plane, a phased array antenna is currently working with leased Ku-band commercial satellites. Reported data rates are 3 Mbps (downlink) and 128 kbps (uplink) to and from the aircraft. The phased array antenna requires a very extensive structural modification of the aircraft (747-400). It is not a matter of bolting it on top of the fuselage and drilling a hole. Numerous large holes have to be drilled plus some portion of the metal fuselage itself has to be replaced. The recertification effort is quite massive, unless you are the aircraft maker (Boeing) in which case the process is much more routine and streamlined. It is also reported to have some technical shortcomings. An alternative design with a gimbaled dish antenna is currently proposed, but the aircraft that the USFS currently operates (a Cessna Citation Bravo and King Air 2000) are too small for this type of antenna system. In the future, Boeing states there is a possibility of developing a product for heavy general aviation aircraft (like Gulfstream IVs, Vs, and similar type aircraft from other manufacturers), which unfortunately still would be too big for USFS aircraft.

We also spoke with Tenzing Communications Inc,[11] which is associated with the European aircraft maker AIRBUS. Tenzing only offers a suite of ready-to-deploy in-flight email and text messaging systems for AIRBUS fleets or equivalent. For these systems, they are not currently offering the complete end-to-end system including the RF unit and antennas. They are continually developing and employing the RF technologies for the future but were non-committal at this time about dates.

**Section 4**

# Conclusions and Discussion

**Conclusion 1.** There are no current military satellite systems that are both capable and available to support the Forest Service mission.

*Discussion:* The DSCS series of satellites has the capability needed to support the necessary links but transmission from an aircraft would require an antenna too large to fit on the Forest Service aircraft, and also (it seems) unsuitable for use on military aircraft. Also, we found these satellites are very heavily used for military missions, and the current system of priorities would place the Forest Service usage at the bottom of the list for access. Mitretek has not attempted to find out what it would take to change the priority the Forest Service would be allocated, but we think it likely it would require action by people high in each agency. None of the other military satellite systems in use appear to support the type of links needed for the Forest Service mission.

**Conclusion 2.** The military use commercial communications satellites to support links of the type needed by the Forest Service, such as in military UAVs. The military aircraft and the communications equipment they carry could be acquired by the Forest Service but using these systems may be impractical at this time.

*Discussion:* Obtaining these systems in a timely manner may not be possible because of current military demand. Obtaining permission to operate UAVs for the Forest Service mission may not be possible. The set of sensors carried by military UAVs are not suitable for the Forest Service mission, and the effort to integrate the existing Forest Service sensor into the UAV or to obtain a replacement if needed would require additional time and money. Adapting aircraft of the size used by the Forest Service to accommodate the communications equipment used in military UAVs may not be practical; even much larger aircraft would require major structural changes to fit antennas of similar size to those used on the UAVs.

**Conclusion 3.** The commercial satellite communications services currently available can provide data transmission at rates up to 128 kbps from aircraft in flight, which exceeds the rate necessary to send the minimum volume of data for the Forest Service mission. Higher rates are proposed for the future, but predictions of the time at which they will become available are not certain since air travel usage is much less than was predicted two years ago, a significant factor in this commercial market.

*Discussion:* If any of the commercial services discussed in this paper are to be considered as possible candidates to fulfill the Forest Service mission needs, some method must be used to reduce the volume of data that needs to be transmitted. This could be done by selecting a subset of the available data, such as by removing the overscan or by passing the full data set through a compression program before transmission and a compatible expansion program after reception. A combination using both methods is also possible.

Note that the entire overscan has to be removed before the data can be displayed or the display will not be geographically correct. It is not obvious how easy it would be to do this on the aircraft, but if it can be done, the result will be a considerable reduction in the required data transmission rate. (See the calculations in Appendix A.) The overscan removal does not involve any compression, so no expansion is required at the receiving location. Therefore, this process would be more desirable because it would be less likely to lose significant data points compared to compression.

In a worst-case situation, the 128 kbps rate would allow the first set of files created during a flight to be transmitted while other files from other fires are being recorded. This rate would therefore be able to provide some benefit even under worst case conditions, and the potential exists for the full desired capability if either of the data selection, data compression, or increased data rate options are shown to be acceptable, either separately or in combination.

Section 5

# Recommendations

Mitretek offers the following recommendations for consideration by the Forest Service based on our analysis of the information obtained in this survey and feasibility analysis.

**Recommendation 1.** The Forest Service should start to develop and implement a communications link using the HSD L-band Inmarsat commercial system in the circuit switched mode.

*Discussion:* The Inmarsat system is currently operational, providing similar service to other users. It provides a minimally sufficient data rate, and several potential vendors are readily available to supply and install the external aircraft antennas and the internal radio equipment. There are plans to increase the satellite data rate to 432 kbps and overall satellite capacity by 2005, which will make the system a better fit to the Forest Service needs. If this proposed rate increase is not available at the time the Forest Service is able to implement the system, it will still be possible to transfer some of the wildfire overflight files from the aircraft to the ground station at whatever data rate is available. The aircraft antennas that would be used for this system are considered a good fit for the Forest Service Cessna Citation Bravo, and that minimal, if any, changes would be needed for the existing antennas already in use on this aircraft. The match between the antennas and the aircraft would be more difficult for the Beech King Air 200, but this is considered a reasonable possibility.

**Recommendation 2**. The Forest Service should investigate methods for selecting subsets of the data in the log files and the capabilities of various compression algorithms and then test the performance and acceptability to users of the actual GEOTIF and log files.

*Discussion*: Since the data will be displayed in a geographically accurate format, all overscan must be combined to fit the true spatial extent of the land from which the image was made. If this is done on the aircraft, the data transmission rate would be reduced by a significant amount without using a compression process that could (potentially) distort some data points. The files could be compressed if this selection process is not sufficient or impractical.

Candidate algorithms could be tested on a single, independent “test” computer and the results compared directly with the original files. These tests could include both selection and compression algorithms and could be performed independent of all other components of the system. The tests could be made using any of the existing files from prior overflights or new files as they are created during new overflights. The results would be applicable irrespective of the choices made for any other part of the system. This process could create a high level of confidence for the end users of the data that the system could be trusted, before they actually had to use the system for a real fire.

**Recommendation 3**. The Forest Service should start a thorough design of an end-to-end communications system capable of transferring the wildfire overflight files to at least two Internet-based file servers that could be accessed by appropriate personnel.

*Discussion:* An end-to-end design should include consideration of all factors that could influence the delivery of accurate and complete data to the final users. This should include error control and correction or re-transmission, network security and accessibility (both physical and electronic), availability and redundancy, plus the overall system optimization.

For example, an optimized communication system could use a new computer program to intercept the data being sent to the existing file-creation program. The new program would be able to format and transmit the files in small pieces so transmission can start as soon as the overflight has started. This intercept program would need to be closely integrated with the existing file creation program, with the communications program, and with a program to re-create the original files at an internet file server.

**Recommendation 4**. Mitretek also recommends that the capabilities of the existing military UAVs be investigated, including possible modifications that may be available to best suit them for the Forest Service mission.

*Discussion*: The capabilities of the UAVs could be tabulated and used as a reference to which other systems could be compared. Even though the actual vehicles themselves seem unlikely to provide a cost effective solution to the Forest Service needs, their performance parameters could be compared on an item-by-item basis to the performance that might be offered by competing contractors. This could provide a useful metric against which the cost/benefit of a particular system could be judged.

**Appendix A**

# Supporting Calculations

## A.1 Infrared Detector Operation Calculations

Scan rate = 200 per second
Field of view = 120 degrees (±60 from nadir)
No of pixels per line = 1728
Digitized at 8 bits per pixel (= 1 byte per pixel)

Aircraft height (AGL): 10,000 ft preferred (±2,000 ft, or more if necessary)
Aircraft nominal speed over fire: 200 – 240 knots

Pixel Size at Nadir:
120 degrees / 1728 pixels = 0.0694 degrees per pixel
At 8,000 ft, pixel size at nadir is 8000 * Tan (0.0694) = 9.7 ft (diameter)
Aircraft Speed:
240 knots = 240 * 1.1508 mph = 276.2 mph
= 276.2 * 5280 / 60 / 60 = 405 ft/sec = 405 / 200 = 2 ft per scan line
Therefore, the corresponding overscan is 9.7 / 2 = 4.8:1

At 12,000 ft, pixel size at nadir is 12000 * Tan (0.0694) = 14.5 ft (diameter)
200 knots = 200 * 1.1508 mph = 230.2 mph
= 230.2 * 5280 / 60 / 60 = 338 ft/sec = 338 / 200 = 1.7 ft per scan line
Therefore, the corresponding overscan is 14.5 / 1.7 = 8.5:1

At the outer edge of the scan, i.e., at ±60 degrees, the overscan will be a factor of 1.7 times greater, 8.2:1 to 14.4:1. To achieve true geographic registration of the data sets, all overscan must be removed before the IR data is plotted on a map.

Scan Width:
At 8,000 ft, scan width is 2 * 8000 * Tan(60) / 5280 = 5.2 miles
At 12,000 ft, scan width is 2 * 12000* Tan(60) / 5280 = 7.9 miles

## A.2  Data Creation Rate Calculations

Scan lines per second * pixels per line * bits per pixel

= 1728 * 8 * 200 = 2.8 Mbps

Dave Chamberlain stated the total file creation rate is 15,900 bytes per scan line

= 15900 * 8 * 200 = 25.4 Mbps

Log file data rate = 15900 – 1728 = 14172 bytes per scan line

If the Log file to be transmitted can be reduced by a factor of 10, by selecting a subset of the available data, would produce about 1420 bytes per scan line. The data rate would be:

= 1420 * 8 * 200 = 2.3 Mbps

and the total of the IR and Log files would be about 5.1 Mbps

If the overscan were eliminated on the aircraft before transmission, by choosing (for example) the hottest reading in each overscan pixel subset, the resulting image file would be reduced by a factor of about 8 (or more) and the maximum data rates would be:

= 1728 * 8 * 200 / 8 = 346 kbps and the log file would become:

= 1420 * 8 * 200 / 8 =  284 kbps

The total data rate would then be:

= 346 + 284 = 630 kbps

This rate could be reduced further, if the scan width were standardized, for example at 4 miles.

## A.3  Data Transmission Rate Calculations

Since there will always be some time between each overflight of sequential wildfires in a particular flight, the aircraft-to-satellite-to-ground data transmission rate can be less than the data creation rate. If the transmission can be twice as long, the rate can be half as fast. For convenience, the following table lists the required transmission rates for times from two to eight times the creation rate.

Data transmission rate = Creation rate / Transmission rate factor

| Creation Rate | Transmission Rate Factor | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| 5.1 Mbps | 2.55 M | 1.70 M | 1.28 M | 1.02 M | 850 k | 729 k | 638 k |
| 630 kbps | 315 k | 210 k | 158 k | 126 k | 105 k | 90 k | 79 k |

The required transmission rates are shown in Mbps or kbps.

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