COLORADO

Center of Excellence for Advanced Technology Aerial Firefighting

Department of Public Safety

Satellite Messenger Evaluation for Wildland Fire Management

CoE-17-005.1

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Executive Summary

Wildland firefighters frequently operate in remote areas and are often a significant distance away from their supervisors or other nearby units. Additionally, wildland firefighters typically communicate with voice radios operating in analog mode, which does not facilitate location tracking or other digital situational awareness. One technology proposed to overcome these limitations and provide GPS location tracking and messaging for firefighters is satellite messengers. The Center of Excellence for Advanced Technology Aerial Firefighting (CoE) was requested to conduct a study of these devices to analyze their utility for firefighters. This study illustrated the technical specifications of two consumer-grade satellite messengers, the SPOT Gen3® and the Garmin inReach® (formerly known as the DeLorme inReach), and provided information on service options and costs. The study also assessed the capabilities of the SOS feature common to both devices and employed field trials to evaluate the performance of the devices in various types of vegetation and terrain.

The CoE found that the SPOT device provides a one-way flow of information from the device user to others using predesignated email addresses, text messages, or website access. This device requires programming ahead of use to designate the time interval for location tracking, as well as the content of the three types of messages it can send. The inReach device provides a two-way flow of information, with others able to communicate with the device user via email, text message, or website.

The SPOT device successfully transmitted a test SOS message from a meadow with a clear view of the sky, which then led to the Colorado Division of Fire Prevention and Control Duty Officer being notified of the SOS within 3 minutes. The SOS testing scenario was on a prescribed pile burn under the control of the area interagency fire management unit and the plan was for the Duty Officer to contact the interagency dispatch center regarding the SOS and have them establish radio contact with the unit in distress. Unfortunately, the phone system at the dispatch center was down during the test and no notification could be made. The CoE recommends that for mission-critical applications like wildland fire, the SOS feature be tied directly into relevant computer-aided dispatch systems—a complex requirement for interagency centers that frequently host firefighters from off-unit and from a variety of agencies.

To determine the utility of the satellite messengers for personnel tracking, six field trials were conducted—two each in minimal, moderate, and heavy forest canopy. For each level of

canopy, one test was conducted in rolling terrain and one in rugged terrain. These tests sought to establish the rate at which the location of a firefighter walking the perimeter of a simulated 100-acre fire with both devices set on a 5-minute tracking interval would be known to a supervisor watching in real-time via an Internet connection.

The CoE determined that both devices can transmit location information successfully with minimal delays when used under minimal and moderate forest canopies. However, under a heavy forest canopy the devices experienced difficulties. The SPOT device failed to transmit 20% of points and the inReach device took more than 5 minutes to transmit 50% of points (and during one test, failed to transmit 35% of points). The CoE recommends shortening the tracking interval when operating under heavy forest canopies to increase the odds of successful transmissions and cautions against relying solely on these devices to achieve situational awareness for firefighters operating under heavy forest canopies.

Introduction

Many wildland fires in Colorado and other western states occur far from populated areas. Voice communication is typically available to firefighters in backcountry areas through radios or satellite phones. However, no other digital radio technologies are employed on a widespread basis on wildland fires. One consequence of this situation is that the locations of firefighters on the ground are not tracked digitally. Instead, firefighters self-report their movements over voice radio to their supervisors using descriptions of location and terrain, which are often inaccurate or hard to understand. When fires exhibits extreme behavior, voice radio communications become chaotic and the locations of fire crews becomes difficult to determine. In a true emergency, firefighters must attempt to clear the radio frequency of all other traffic and broadcast their location to potential rescuers. This leads to a reactive approach to location tracking; in other words, there is a possibility that firefighters will wait until they are in serious trouble before alerting supervisors to their situation.

One possible solution that has been proposed to mitigate the lack of location accountability for firefighters is the use of satellite messengers. These devices can enable firefighters to send messages and they also track the location of personnel without using cellular or conventional radio networks. Instead, the devices utilize a GPS receiver to capture the location of the user and a satellite radio to transmit the location and other data through a satellite network to servers on the ground, from which the data can be viewed on a variety of web platforms. To date, the primary users of these devices have been members of the civilian outdoor community; however, military and civil government agencies have begun experimenting with integrating these devices into their operations.

The Colorado Division of Fire Prevention and Control's (DFPC's) Center of Excellence for Advanced Technology Aerial Firefighting (CoE) is statutorily mandated to evaluate new and existing technologies for integration into tactical fire scenarios (24 C.R.S.). Additionally, the CoE is directed to make the results of its research available to stakeholders, including fire managers. In the case of satellite messengers, the CoE fulfilled this mandate by evaluating several facets of this technology and preparing this report on our findings.

Literature Review

The existing literature on satellite-based personal tracking devices consists mostly of reviews in popular press that are intended for consumers. More detailed published articles or scholarly works on the subject as applied to wildland firefighting are sparse and originate primarily from the U.S. Forest Service's (USFS's) Missoula Technology & Development Center. The June 2007 issue of the USFS Technology & Development Program's *Safety and Health Tech Tips* (Etter 1) discusses several devices available at the time to fulfill the need for emergency communications in remote areas. The article begins by explaining that both the Occupational Safety and Health Administration (OSHA) and USFS require that personnel working in remote locations have emergency communications capabilities at all times.

The article provides an overview of the technologies and devices available to satisfy the requirement for emergency communications imposed by OSHA and USFS. The hardware available at the time was larger and offered a smaller feature set, but the basic limitations and operating principles were similar to current devices. The article recognizes that duplex communication was a desirable function, but that simplex devices could sometimes successfully transmit a message where duplex communications could not be maintained. Also discussed is the influence of canopy and terrain on the ability of the devices to successfully transmit messages. The author notes that in the most challenging location selected for testing, a west-facing drainage under dense canopy in the Sierra National Forest, only 1 transmission out of 24 was successful. Tests at the remaining sites resulted in a greater chance of successful transmission.

In December 2008, the USFS Technology & Development Program published an evaluation of the SPOT Gen3® satellite messenger (Trent and Miller 1). The testing was conducted in three locations, with canopy coverage ranging from "open" to "heavy." An item of particular interest to anyone planning to use the SPOT as an emergency device is that—in addition to all of the drawbacks of a simplex device—the percentage of "Help" messages transmitted successfully during testing dropped dramatically as canopy coverage increased, with only 46% and 31% success rates in medium and heavy canopy, respectively. The SPOT device also proved to be quite sensitive to the orientation of the device—a vertical orientation resulted in low rates of successful transmissions.

After the 2012 fire season, the USFS released a lessons learned report (Hoffman et al. 1) on the Garmin inReach® devices (formerly known as DeLorme inReach devices). The report followed a study in which 45 USFS employees dispersed throughout the country were provided with inReach devices. Broadly, the results showed that users valued having access to topographical maps on the devices and the location data the devices provided, as well as having the ability to verify whether an emergency message was transmitted successfully. Users' confidence in the device was undermined by battery-life issues.

USFS's September 2013 publication, "The DeLorme inReach Pilot: A Closer Look at Duplex Satellite Emergency Notification Devices," consolidates and updates the information available in the previous USFS publications on the subject (Hoffman and Miller 1).

One of the primary motivating factors behind the USFS's deployment and studies of satellite messengers was OSHA's regulatory requirement to provide for emergency communication capabilities for workers deployed in remote locations (Etter 1). In response to OSHA requirements the USFS promulgated an internal policy regarding a "check-in and check-out" program (USFS 50-53), which mandates that unit leaders establish check-in and check-out procedures to ensure accountability. The policy requires that the procedures developed by unit leaders specify required communications equipment, but no guidelines are provided about the minimum capabilities or reliability standards of the equipment. The OSHA requirements referenced by USFS consist of the "General Duty Clause" in the Occupational Safety and Health Act of 1970 (29 U.S.C.). Section 5(a)(1) of the Act states that employers are required to provide a place of employment that "is free from recognizable hazards that are causing or likely to cause death or serious harm to employees." Given the general language, it is rather difficult to determine if any of the devices examined would actually meet any specific policy or regulatory mandates. USFS's recommendations appear to be a reasonable solution to vague regulations—in effect providing a practical, if imperfect, solution to an ambiguous problem. Because regulations leave room for interpretation (Musick), USFS research and guidance provide a useful tool for those in the wildland fire community and others who face the challenge of ensuring the safety of workers in remote locations.

More detailed requirements from OSHA would help both employers and device manufacturers ensure that capabilities provided by commercially available devices are appropriate. Such requirements could be defined by the frequency of successfully completed communication, maximum permissible search radiuses based on anticipated speed of movement, or even a standard based on the best commercially practical technology. This study looks at the latest developments and evaluates them in the context of those gaps.

Device Capabilities

Two types of devices were evaluated by the CoE. The first was the SPOT Gen3®, which can send one-way messages over the Globalstar satellite network. Since SPOT Gen3®'s have sending capability only, it is not possible to obtain delivery confirmations for successful messages. To increase the probability that messages are successfully delivered, the SPOT sends multiple copies of the same message (SPOT).

The SPOT Gen3® device can send the following types of messages:

- An SOS message that triggers a search and rescue response
- A "Help" message that delivers a preset distress message and the device's location to designated contacts
- A customized preset message that is input into the SPOT website prior to a trip
- A message stating that the device user is "OK," which is sent to designated contacts
- Tracking points sent at preset intervals that show the device's current location

Figure 1—SPOT Gen3®

The second device that the CoE evaluated was the Garmin inReach®. At the time of data collection this device was made by DeLorme, but the product has subsequently become a Garmin brand. The inReach SE was evaluated in this study. The inReach can send two-way messages over the Iridium satellite network, which provides delivery confirmations for successful messages. In addition, text messages can be sent to firefighters in the field (Garmin).

The inReach device can send the following types of messages:

- An SOS message that triggers a search and rescue response, though in this case the search and rescue coordination center can customize the response based on a text messaging with the device user
- Preset or customized messages sent via a virtual keyboard, or the inReach device can pair with Apple or Android smartphones and allow users to control all features of the device, including text input through their smartphones
- Tracking information at preset intervals

Figure 2—Garmin inReach® SE

Device Costs

The cost of using the SPOT or inReach messengers depends on the exact usage scenario of the devices. To simplify the explanation of overall costs, certain assumptions were made. These assumptions are stated in the text below.

Garmin offers both personal and professional service plans for the inReach, with this analysis conducted on the professional plans. The various options for professional plans are differentiated from each other based on the number of text messages that can be exchanged per month, the frequency that tracking points can be transmitted, and various add-ons. Table 1 references Garmin plans for unlimited messaging and 10-minute tracking or 2-minute tracking.

SPOT devices utilize the same plan for personal or professional usage. Pricing for the SPOT messenger depends on the desired frequency of location updates, but is otherwise fixed. The default plan provides a 10-minute tracking interval. An upgraded plan, the "unlimited" option, allows users to select a 2.5-minute interval.

The substantial difference in cost reflects a difference in the devices' capabilities. The SPOT is a one-way-only communicator, capable of sending out a preset message or a distress signal. The user has no way of verifying whether a message or distress signal was transmitted successfully. Conversely, the inReach device allows true two-way communication, even if it is not quite as convenient as we have come to expect from phones or computers. The value of being able to send out more information, along with a distress signal, should not be underestimated. Equally important is the ability to broadcast a message to field personnel who are beyond the reach of other communication methods.

Table 1—Estimated Costs of Satellite Messengers (Rounded to Nearest Dollar)

	Garmin inReach® SE	SPOT Gen3®
Hardware cost	$300	$150
Anticipated typical use annual cost: 10-minute tracking interval	$780	$200
Anticipated typical use annual cost: ~2-minute tracking interval	$1200	$300

Test of SPOT Gen3® SOS Function

Background

A key feature of satellite messengers is the SOS function, which is intended to be a means to indicate a life-threatening emergency from anywhere on the planet. Both the SPOT and inReach devices have an SOS function. Each device contains a special button that is protected against accidental triggering, but when deliberately pressed will collect and transmit the device's GPS coordinates to a private emergency operations center called the GEOS International Emergency Response Coordination Center. This center is located in a secure facility and is staffed 24/7 by search and rescue specialists. When an SOS activation is received by the center, staff members attempt to confirm an emergency by contacting the device owner and predesignated emergency contacts over the phone. If an emergency is confirmed, or if contact with those parties cannot be made or is inconclusive, the GEOS center will determine jurisdiction for a search-and-rescue response and contact the appropriate local dispatch center to initiate a rescue.

While both devices have an SOS function, only the inReach device can facilitate a two-way text message conversation with the GEOS center—allowing the center staff members to more precisely determine the nature of the emergency and what rescue resources are needed. Additionally, the inReach will confirm that an SOS message was successfully delivered. The SPOT device only transmits the location of the device to GEOS and, due to the simplex nature of the device, there is no confirmation that the SOS message was successfully transmitted. To address this risk, the SPOT continuously transmits an SOS message until the device's batteries run out. Both devices allow the user to input two phone numbers for the device owner via a secure website and require two emergency contacts that GEOS can reach out to in the event of an activation.

Narrative

In late 2015, the need to test the SOS function as part of the CoE satellite messenger evaluation was identified. Both messenger devices have this feature, which is designed to facilitate a rescue in the event of a life-threatening emergency. The SPOT device was selected for testing due to its more limited ability to transmit SOS information. In early February 2016, preparation for an SOS test began. A priority for the test was to evaluate the process of passing information regarding an SOS activation to DFPC and interagency personnel with responsibility for coordinating an initial rescue attempt. The ultimate goal was to get the location of the activation to staff at the interagency dispatch center, who would then plot the location of the SOS, determine the appropriate repeater, and contact the field unit by radio to confirm an emergency.

The GEOS International Emergency Response Coordination Center was contacted and agreed to participate in the test of the SOS function, with the condition that the test date and time were provided to their dispatchers in advance and a test request form was completed. The DFPC Duty Officer, DFPC Engine 6221, and the Grand Junction Interagency Dispatch Center also agreed to participate in the test. The decision was made to conduct the test during a prescribed pile burn to achieve as much similarity to an SOS on a wildland fire as possible, while avoiding the risks and uncertainties associated with testing during an actual wildland fire.

A plan was established that once burning conditions were verified and the pile burn began, calls would be made to the GEOS center, DFPC Duty Officer, and Grand Junction Dispatch to inform them that the test would occur in the next several hours. Only the GEOS center was informed of the specific time planned for the test. These calls were made on the morning of February 9, 2016, at the start of the pile burn.

Figure 3—Overview of Test Site

The testing site was located in the White River National Forest immediately adjacent to the Wildernest Subdivision in Summit County, Colorado. The test site was comprised of gently rolling, hilly terrain. The area had been clear-cut, with small stands of aspen and single coniferous trees present. The test itself was conducted approximately 30 feet away from aspen trees, but was otherwise removed from the forest canopy and with a clear view of the sky. Weather conditions were clear throughout the test.

Figure 4—Intended Notification Sequence

When Grand Junction Dispatch was contacted by phone on the morning of the test, they advised that their phone system was undergoing upgrades and would be briefly offline in the late morning. GEOS had been informed that the test would occur at approximately 1400, so the phone system upgrade was not initially a concern. Early in the afternoon, attempts were made to contact Grand Junction Dispatch by phone, but a busy signal was encountered each time. Dispatch was contacted by radio and advised the test participants that they no longer had an estimated time for the phone system to come back online, though they offered to provide a cell phone number to reach the center.

Figure 5—Author at the Test Site

The decision was made not to utilize the cell phone number since the DFPC Duty Officer would not be aware of this number; as such, the test was delayed while periodic attempts were made to call the normal dispatch center phone number. By 1500, the phone system was still not online and the decision was made to circumvent Grand Junction Dispatch and have the DFPC Duty Officer contact the author directly when the SOS activation had been received. Contact with the DFPC Duty Officer was made and the change in plan was communicated.

The SPOT device was placed on a log elevated approximately 3 feet above the ground and an arm's length away from the author. The SOS button on the SPOT device was pressed at 1458 and contact with the DFPC Duty Officer was established at 1505. The DFPC Duty Officer relayed instructions from GEOS on how to reset the SOS function on the device and the test was concluded. Grand Junction Dispatch was informed over

Figure 6—SPOT Transmitting the SOS

radio that their participation in the test was no longer needed and resources demobilized from the pile burn shortly thereafter.

Results

As a result of the phone system outage at Grand Junction Dispatch, the results of the study do not reflect the additional time and communication link that would have been observed with dispatch's involvement. Instead, the author received details of the activation from the DFPC Duty Officer, including the unit identification and the latitude and longitude of the activation. Ideally, if dispatch had been available and had received this information, they would have been able to plot the SOS location and determine the appropriate repeater to hail the unit. If an emergency was confirmed, or the unit failed to establish contact, a rescue operation or incident-within-an-incident could be initiated.

Table 2—Chronology of SOS Activation

Time	Minutes After Activation	Action
1458:00	0	SOS button pressed
1458:40	.67	SOS activation message logged on SPOT website
1501	3	DFPC Duty Officer contacted by GEOS
1505	7	Duty Officer contacted study author

Seven minutes elapsed from the time the SOS button was pressed to the time that the DFPC Duty Officer notified the study author of the activation. It is likely that additional time was expended above what would have been seen in a true SOS activation, as GEOS provided the DFPC Duty Officer with instructions on how to reset the SOS feature on the device—a step that would not have occurred during a true emergency.

The GEOS monitoring center provided geographic coordinates of the SOS activation to the Duty Officer in degrees-minutes-seconds format. The SOS activation could also be viewed from the SPOT website, with the location described in decimal degrees. These two locations were compared to the "true" location of the device, which was captured using the BackCountry Navigator app and GPS on the author's smartphone. The decimal degrees coordinates obtained from the SPOT website were found to be 12.48 feet north of the true location. The degrees-minutes-seconds coordinates that

Figure 7—Locations Captured During Test

were relayed from GEOS were found to be 41.81 feet southwest of the true location. It should be noted that the phone and SPOT GPS chips are subject to error; however, when the SOS location captured by the SPOT is viewed over an aerial photo of the test site, it appears to be the most accurate location and is the only point that is centered over the pile where the test took place.

Discussion

The SOS function on the SPOT device performed as expected, with the message reaching SPOT's servers in less than 40 seconds. Under heavy forest canopy, it is possible that the first SOS message would not successfully reach a satellite, but the device would continue to send SOS messages until the batteries died. If the distressed party could move, they should seek out an area of lighter canopy or a meadow, which would increase the odds of a successful delivery.

The GEOS monitoring center handled the SOS activation quickly and professionally, placing a phone call to the DFPC Duty Officer within 3 minutes of the SOS button being pressed. The coordinates that GEOS provided over the phone to the DFPC Duty Officer were within 42 feet of the location of the device, leaving little uncertainty as to the location of the distressed party. Each device allows the user to input custom text on the companion website that GEOS can access in the event of an activation. GEOS has advised that they read this custom text before attempting to reach the emergency contacts, so directing them to immediately call a duty officer or dispatcher may further reduce the processing time.

Operational challenges arose in this test once the DFPC Duty Officer had been contacted by GEOS. While the Colorado Department of Public Safety does operate statewide dispatch centers for law enforcement and initial notification of State Fire Management Officers, all other wildland fire dispatching of State resources is handled by the six interagency dispatch

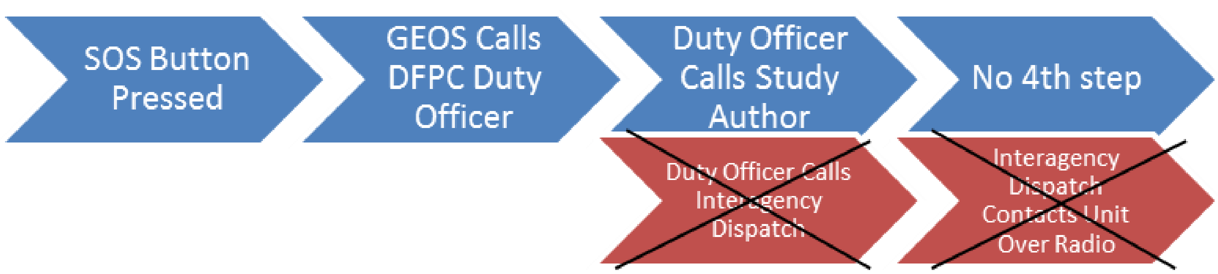

Figure 8—Actual Notification Sequence

centers that operate in Colorado. DFPC is a partner with each interagency dispatch center and could coordinate with these centers to deploy satellite messengers operationally. However, each device can only have two emergency contacts listed, thus requiring a central point of contact to determine the appropriate interagency dispatch center to contact and coordinate a response. It is important to note that since the interagency dispatch centers are not designated public safety answering points (PSAPs), the GEOS center would not know to contact an interagency center for search-and-rescue assistance. The exceptions to this are colocated centers found in large national parks and in California.

While Geographic Area Coordination Centers are designed to coordinate the allocation of resources across interagency dispatch center lines, they are not necessarily staffed 24/7 and should not be relied upon to respond immediately to an SOS activation. Therefore, the DFPC Duty Officer is the best choice to serve as a statewide contact for SOS activations triggered by DFPC employees. However, this individual will have to contact the appropriate interagency dispatch center by phone to initiate a response. The extended downtime of the Grand Junction Interagency Dispatch Center's phone system on the day of the SOS test illustrates the risk of relying on multiple phone-based hops to relay an SOS message. The interagency dispatch centers do not have the hardened phone systems seen in "911" PSAP dispatch centers staffed by local governments and, while the interagency dispatch center offered to provide us with a cell phone number to contact them during the downtime, this approach carried its own risk since an alternate cell phone number would not necessarily be known by the DFPC Duty Officer.

The SPOT device currently provides only GEOS as the SOS response system. However, the inReach allows enterprise account users to deactivate GEOS and use an alternate system for responding to SOS activations. Garmin provides an application programming interface that allows developers to access the raw SOS activation information from Garmin and program a custom SOS tool, thus facilitating two-way communication to the inReach device and plotting the location of the emergency. Automatic processing that determines the appropriate interagency dispatch center for each activation and notifies dispatchers on their console would eliminate the delays and risks of relying on a single statewide point of contact for SOS activations. The Interagency Dispatch Implementation Project, coordinated by Wildland Fire Information and Technology, is seeking to standardize the computer-aided dispatch (CAD) systems at interagency dispatch centers and may be able to build this type of SOS functionality into a future CAD system.

On the day of the test, however, the phone system outage at the interagency dispatch center prevented the testing of the full sequence of events that would need to take place to confirm the emergency and initiate an incident-within-an-incident. While GEOS could find the local PSAP and initiate a response with local search-and-rescue authorities, the CoE believes it is important to find a solution that immediately notifies the interagency dispatch center. An interagency center will be more familiar with the incident the device user is assigned to and will be able to track down the nature of the emergency and the necessary response more quickly than a local PSAP.

Device Performance Test

Introduction

A major goal of the CoE's study on satellite messengers was to provide recommendations to wildland firefighters and incident commanders regarding the viability of the use of messengers to track and communicate with fire crews. To achieve this goal, we conducted field trials on the devices to gauge their performance under conditions likely to be encountered on a wildland fire. We sought to determine (1) if the devices can be expected to function under heavy forest canopies and in rugged terrain, and (2) how frequently the location of a firefighter carrying a satellite messenger would be known and how up-to-date that location would be under different environmental conditions.

Stationary tests of satellite messengers have been conducted by other organizations in the past and we sought to build on that work by conducting mobile field tests. By hiking with the devices in various conditions, we sought to identify combinations of vegetation and terrain that cause the devices to fail. We also sought to provide results in a visual format that would be familiar to wildland firefighters.

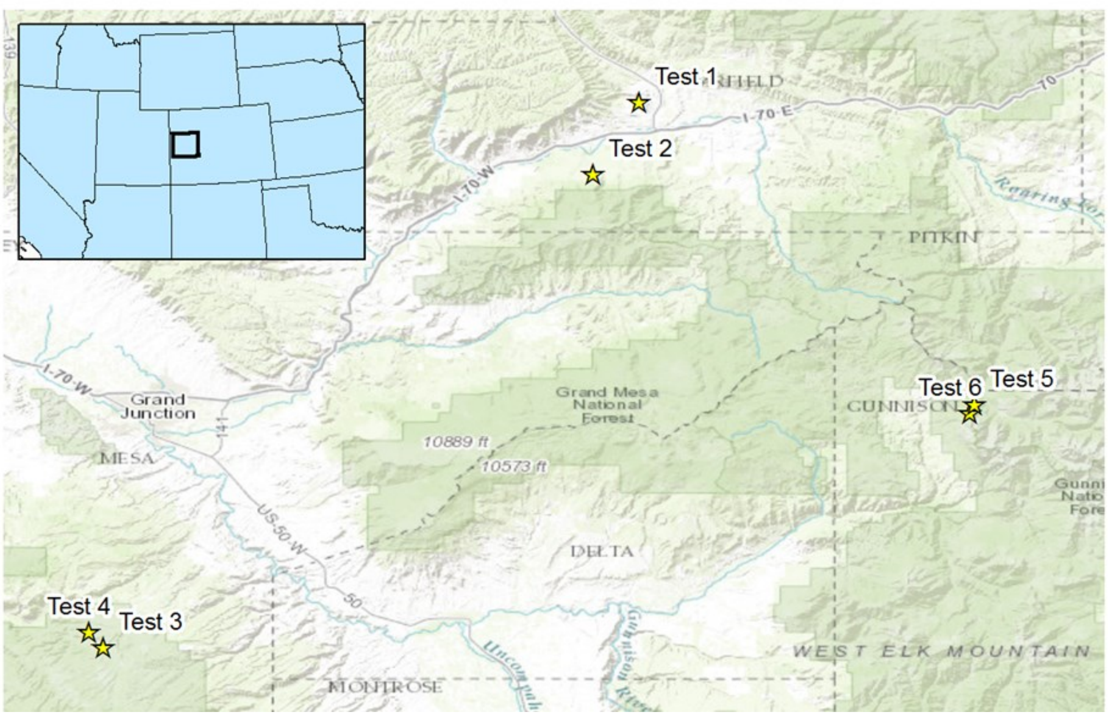

Figure 9—Device Performance Test Locations

Methods

Field tests of the satellite messengers were conducted in September 2016. Following a beta test to confirm the testing methodology, a total of six field tests were conducted. Since the goal of the testing was to evaluate the performance of satellite messengers under conditions likely to be encountered on a wildfire, we conducted tests in a variety of vegetation and topographic conditions. Tests were conducted under minimal, moderate, and heavy forest canopies and in rolling and rugged terrain.

Test 1 was conducted in the Hubbard Mesa area north of Rifle, Colorado, in sagebrush and light piñon-juniper woodlands. Test 1 took place in gently rolling terrain, with the entire route consisting of dirt roads and established trails. Test 2 was conducted on the Houston Mountain Fire southwest of Rifle, which was controlled at the time. This test took place in heavy piñon-juniper woodlands, though the testing party walked along the perimeter of the fire with one foot in the black (which was devoid of foliage). Test 2 took place on a steep hillside with occasional small draws.

Test 3 was conducted on the Uncompahgre Plateau in continuous ponderosa pine/Gambel oak forest in gently rolling terrain. Test 4 was also conducted on the Uncompahgre Plateau in a mix of sagebrush, ponderosa pine, Gambel oak, and aspen. The testing team ascended a ridge and descended into a steep and narrow draw to complete Test 4.

Tests 5 and 6 took place in the Raggeds Mountain Range near Chair Mountain. Test 5 was conducted in heavy spruce/fir forest with extensive deadfall. Test 5 was conducted in a wide bowl with moderate slopes. Test 6 was also conducted in heavy spruce/fir forest, though this stand was younger and less dense than in Test 5. Terrain in Test 6 was very rugged, with the testing party travelling along steep slopes, descending into an avalanche chute, and traversing across several spur ridges to complete their route.

To standardize the testing process, each test was designed to simulate an approximately 100-acre fire. The test route was mapped out ahead of time to ensure that the area would meet size, forest canopy, and terrain requirements. The objective of each test was to hike the perimeter of the simulated fire and allow the devices to transmit the hiker's location. At least two researchers traveled around the perimeter of the fire, with an additional researcher remaining at the start/stop point. Logistics for the tests were coordinated by VHF voice radio.

Table 3—Vegetation and Terrain Found at Test Locations

Test 1: Minimal forest canopy; rolling terrain 	**Test 2:** Minimal forest canopy; rugged terrain 
Test 3: Moderate forest canopy; rolling terrain 	**Test 4:** Moderate forest canopy; rugged terrain 
Test 5: Heavy forest canopy; rolling terrain 	**Test 6:** Heavy forest canopy; rugged terrain 

The satellite messengers and other radios were consistently placed in a General Services Administration (GSA) fireline pack for each test. The antennas for the satellite messengers were oriented toward the sky in accordance with the manufacturer's directions. Both satellite messenger models were configured prior to the test to send tracking points every 5 minutes. Other radios were spread out as much as possible on the pack to minimize interference; however, since firefighters will typical carry VHF or UHF radios, a relatively standard configuration was used. A Nexus 6 smartphone remained in the researcher's pocket throughout each test and was used to capture a GPS track of the true testing route using the Android Team Awareness Kit app, as well as to interface with a goTenna as discussed in the appendix.

Figure 10—Location of Equipment During Test

Upon completion of each test, the tracking points from the satellite messengers and the tracklog from the smartphone were stored digitally and loaded into ArcGIS for analysis. Canopy closure, canopy bulk density, Scott and Burgan fuel model, slope, and aspect data from LANDFIRE 2012 were calculated for all of the tracking points and for all LANDFIRE pixels that intersected the GPS track.

The satellite messengers send tracking points on a schedule and, by comparing the times that points failed to send to the GPS tracklog, we determined the locations where the devices failed, the distance between satellite messenger tracking points, and the off-track distance from points to the GPS track. Since inReach devices will send delayed data points with a time stamp showing when the GPS point was captured—not when the point was received by the tracking system—a web server running during the tests appended a time stamp to the incoming inReach data. This documented when the tracking point was actually available and allowed for calculation of the delay in sending inReach tracking points.

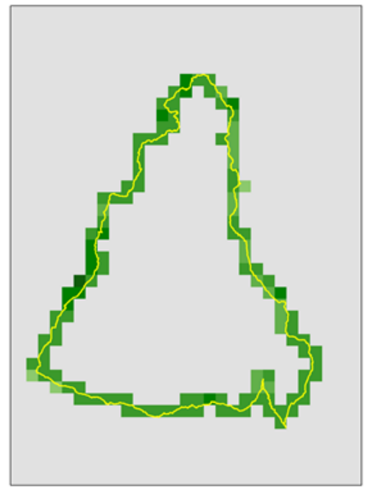

Figure 11—Calculated Values for Canopy Cover Along Test 5 Track

A review of the satellite messenger data showed that only a handful of points from each device were missing. As a result, missing points were plotted by hand—by finding gaps of 10 minutes or more in the satellite messenger data indicating that one or more points was not received. Once the gap and specific time of a missing point had been identified, we looked in the GPS tracklog file to find a point recorded by smartphone GPS that corresponded or was within a few seconds of the missing satellite messenger point. We created a new GIS layer and dropped a point at each location where the satellite messenger failed to send a tracking point, and then calculated vegetation and terrain attributes at each of these points. Standard deviation was calculated to ensure that a good cross reference of fuel model canopy, bulk density, slope, and aspect was used. Correlation was also determined to see if there was any connection between each type and whether a point was missed or not.

Results

The GPS tracklog collected by the mobile party's smartphone provided basic statistics on the test sites and vegetative data was calculated when LANDFIRE layers were overlaid on the track. This data was intended to validate the desired methodology of testing the satellite messengers on 100-acre simulated fires in minimal, moderate, and heavy forest canopies and in rolling and rugged terrain. We were largely able to meet these criteria. On average, the study-site size was 103.58 acres, with a perimeter of 2.57 miles. When considering terrain where forest canopy levels remained the same, each time we found that the rugged terrain showed significantly higher average and maximum slope values than the rolling terrain.

Forest canopy as measured by LANDFIRE layers for canopy closure and canopy bulk density also largely met the criteria of increasing from minimal to moderate and heavy. The exception was Test 2, which was intended to have minimal canopy but actually had canopy closure and canopy bulk density values similar to the moderate or heavy canopy tests. However, much of this vegetation along the test route had been consumed by a recent wildfire. For much of this test, at least one-half of the surrounding vegetation had been completely consumed by fire, creating more open vegetation conditions than was reflected by the LANDFIRE data.

Between all six tests, the SPOT device successfully transmitted 87 tracking points and the inReach device successfully transmitted 88 tracking points. Both devices failed to send 8 tracking points during the field tests, resulting in a 91.6% success rate during all tests. However, most of the inReach points were cached on the device for several minutes before it could establish satellite reception to send the tracking data. We considered that tracking points that were delayed by more than 5 minutes (the tracking interval set on the device) were invalid, as they represented less than the most accurate location of the mobile testing party. When these points were excluded, the number of successfully transmitted inReach points was revised down to 72 points, a success rate of 81.1%.

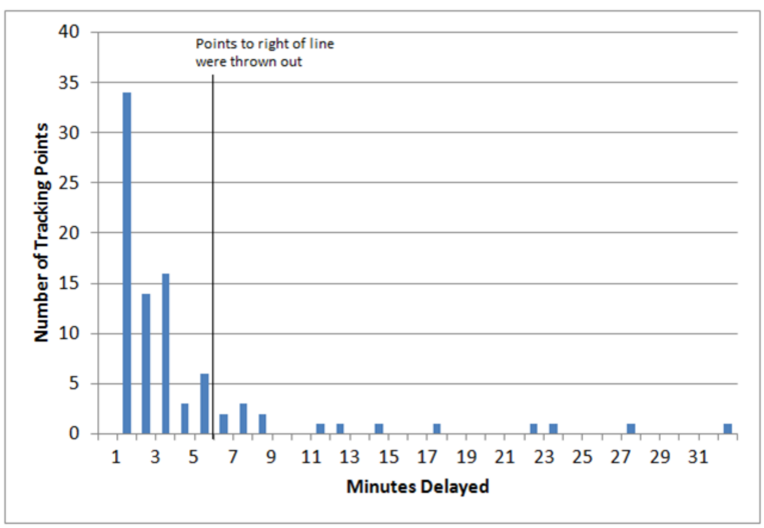

Figure 12—inReach Tracking Point Delay Histogram

Table 4—Statistics on Device Performance Test Sites

	Forest Canopy	Terrain	Area (acres)	Perimeter (miles)	Avg Slope (degrees)	Max Slope (degrees)	Avg Canopy Closure (% closure)	Max Canopy Closure (% closure)	Avg Canopy Bulk Density (kg/m^3) *100	Max Canopy Bulk Density (kg/m^3) *100	Test Duration (mins)
Test 1	Minimal	Rolling	115.23	2.2	3.67	10	0.46	25	0.35	19	37
Test 2	Minimal	Rugged	86.97	3.58	10.93	17	31.28	45	23.32	38	98
Test 3	Moderate	Rolling	105.88	2.33	2.75	8	42.52	65	8.49	45	48
Test 4	Moderate	Rugged	149.89	2.7	5.47	23	26.26	65	6.91	45	51
Test 5	Heavy	Rolling	79.55	2.14	8.85	18	54.26	75	10.73	22	100
Test 6	Heavy	Rugged	83.97	2.49	19.83	30	51.42	75	10.15	22	117
		Average	103.58	2.57	8.58	17.67	34.37	58.33	9.99	31.83	75.17
		Minimum	79.55	2.14	2.75	8.00	0.46	25.00	0.35	19.00	37.00
		Maximum	149.89	3.58	19.83	30.00	54.26	75.00	23.32	45.00	117.00
		Standard Deviation	26.55	0.53	6.32	8.16	19.89	19.66	7.52	12.19	33.67

Regression testing was used to view the correlation between vegetation and terrain at each tracking point location and whether a point was missed or not. The correlation coefficient can be between −1 and 1, close to each end indicating a stronger correlation. We correlated fuel model canopy, bulk density, slope, and aspect against a 1 if the point was captured or 0 if the point was missed. The average correlation coefficient is −0.009238535, meaning that there is virtually zero correlation between all test data and whether a point was missed or not. The strongest correlation coefficient was with canopy closure, but it was still only −.2227. Generally, for a correlation to be considered positive a coefficient stronger than $^{+}/_{-}$ .95 is needed.

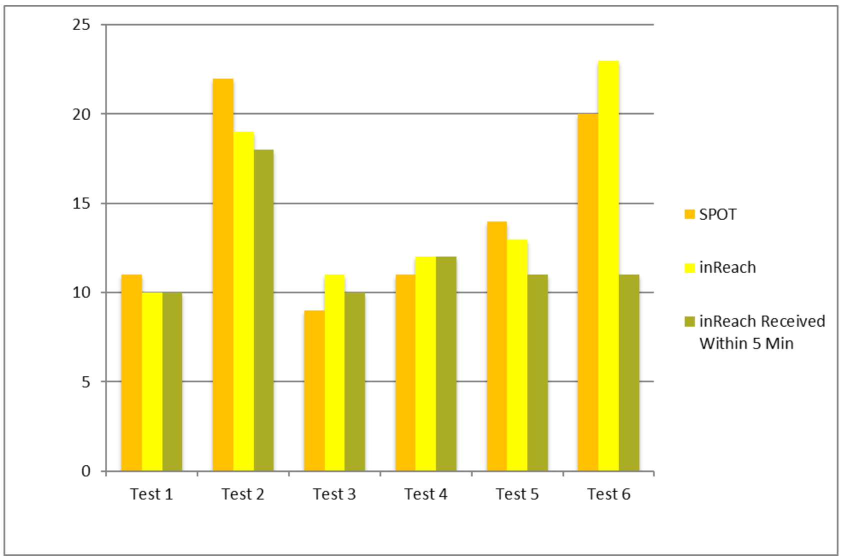

Figure 13—Absolute Number of Tracking Points Received per Test

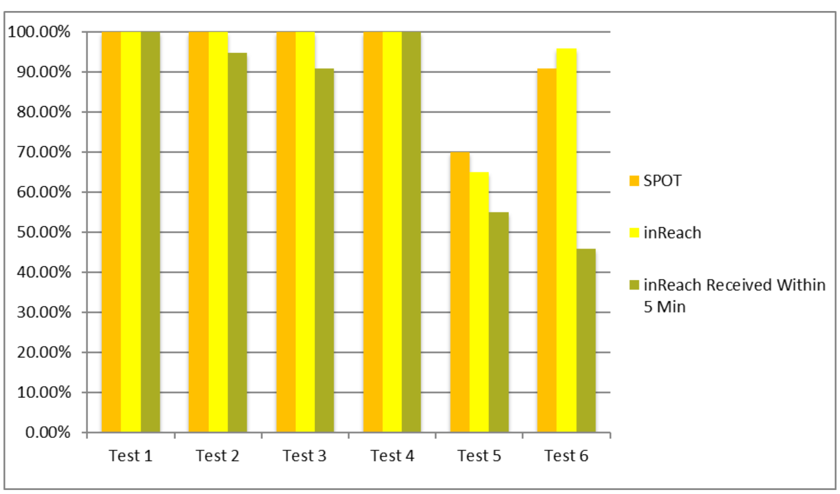

Figure 14—Percentage of Tracking Points Successfully Transmitted

Discussion

The SPOT device presented a relatively simple case for analysis as it utilizes a basic methodology for transmitting tracking points, so its data from the field trials neatly fell into two categories. During the minimal and moderate forest canopy tests, the SPOT successfully transmitted all tracking points. However, during the heavy canopy tests the SPOT encountered situations where it was unable to successfully transmit tracking points to the satellite network.

While the SPOT device simply broadcasts tracking points with no confirmation of successful transmission, the inReach device is able to verify that a point is received by the satellite and will follow a protocol if satellite reception is unavailable. This protocol presented a barrier to the study, but also increased the utility of testing the inReach in a mobile environment. If the device lacks satellite reception to transmit a tracking point, it will save that point to the device's internal memory and send it later when the device regains reception. However, when the point eventually sends it is assigned the time it was collected rather than the time at which it was successfully transmitted.

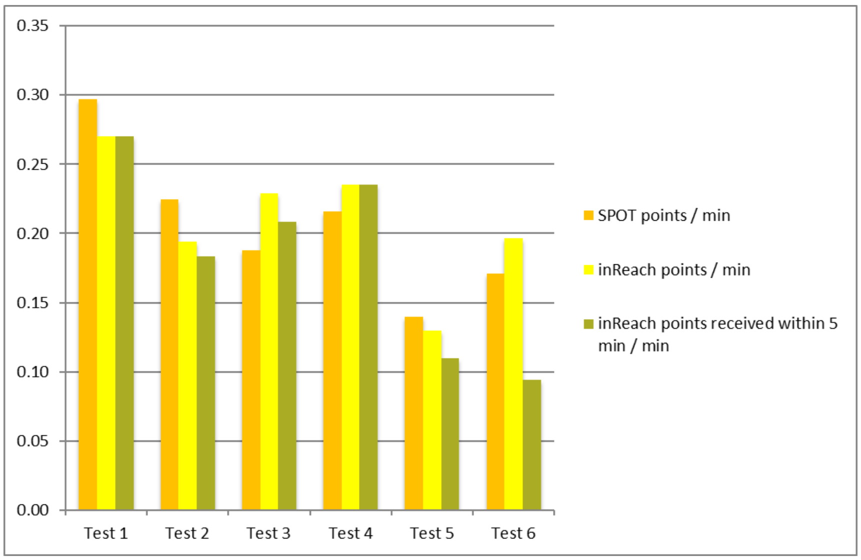

Figure 15—Tracking Points Successfully Transmitted per Minute

The end result is that when looking back in time at a completed hike, all of the tracking points will display in their proper order and as having been received at the proper time. However, in reality the tracking points from an inReach are typically delayed by a minute or two, and in some cases points may not be successfully transmitted for several minutes. While these delays are typically not problematic for recreational users, they are for professional applications—such as wildland fire management, in which near real-time location tracking is desired. The specified tracking interval of 5 minutes is actually relatively sparse. That means that a crew may move a fair distance between points. If a point is delayed (as was often the case during testing), the actual location of the firefighter may be quite different than the last reported point.

During the course of this study, we eliminated 18% of the tracking points transmitted by the inReach device because they were more than 5 minutes delayed. Few delayed points were encountered during the light and moderate forest canopy tests, but the heavy forest canopy tests had significant delays. Indeed, during Test 6 over half of the tracking points generated by the inReach were delayed by more than 5 minutes. Our data showed that multiple inReach tracking points can be transmitted at the same time; during the heavy forest canopy tests, multiple points were commonly cached to the device before satellite reception was established. Anecdotally, it appears that tracking points built up as we traveled through areas of dense forest and were transmitted in bulk when we passed through meadows, roads, or other areas where the forest canopy abated for a time.

There were also cases during the heavy forest canopy tests when inReach points totally failed to send due to a continuous lack of satellite reception. This was most severe in Test 5, in which only 65% of the tracking points were transmitted. At the conclusion of Test 5, we allowed the inReach to face the sky for 5 extra minutes at the start/stop point to see if it could send the points that were cached to the device. At the end of the 5 minutes, it had not established satellite reception and we turned the device off, marking all the points remaining on the device as having failed to send.

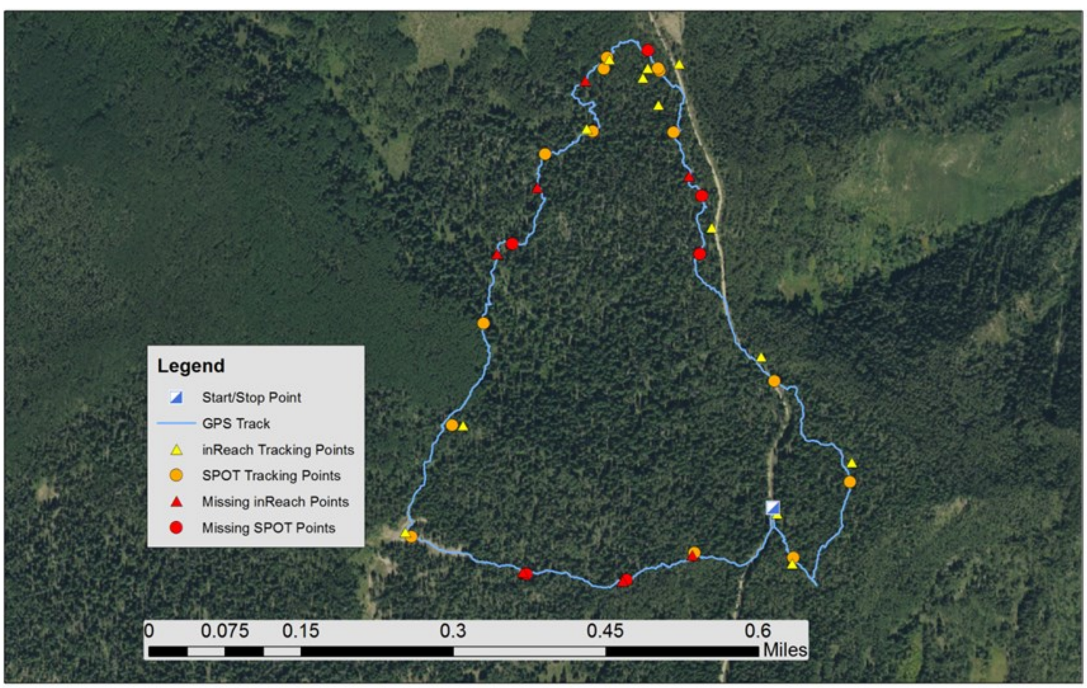

Figure 16—Spatial Depiction of Tracking Data Collected During Test 5

Recommendations

Use of the satellite messengers for mission-critical applications should only be attempted if robust protocols are developed to ensure that dispatchers or supervisors can be immediately notified of an SOS activation. These protocols must accommodate firefighters who are traveling off-unit and engage the SOS feature while outside their home dispatch area. This need was illustrated during the SOS test, in which the phone system for the interagency dispatch center was down, preventing them from being informed of the activation by the DFPC Duty Officer. Reliance on multiple phone calls to notify dispatchers of an SOS activation proved to be a cumbersome and ineffective solution. Ideally, a system that directly interfaces with the CAD application used in dispatch centers should be developed to ensure that dispatchers are notified of an SOS activation immediately.

Firefighters operating in areas with minimal to light forest canopies should feel confident that their location is being transmitted, provided that they are following the manufacturer's instructions. However, firefighters operating under heavy forest canopies are cautioned that the devices' performance may become significantly degraded. Firefighters who want location tracking enabled in areas with heavy forest canopies could try shortening the tracking interval on their devices to increase their odds of successful transmission. However, no strategy can completely mitigate the loss of reception that occurs under heavy forest canopies. The ability of supervisors or dispatchers to view the locations of their firefighters using the Internet should also be considered prior to deployment. Beyond merely the ability, administrators should also consider the utility of supervisors viewing the locations of their resources. A supervisor watching the location of firefighters from afar may be unable to intervene effectively if they observe firefighters entering a dangerous situation.

However, a supervisor physically at the fire and observing the locations of their firefighters may be able to effectively intervene by redirecting fire crews over voice radio. This scenario requires the supervisor to have Internet access and the ability to view the firefighters' locations on a website. While certainly not impossible, this scenario will likely require too much of the supervisor's attention or require Internet connectivity that is not present at backcountry fires. Note that at the time of data collection, inReach devices allowed users of enterprise plans to view the locations of other inReach devices, though additional data charges would be incurred to take advantage of this feature. Administrators should determine in advance how the devices will be deployed on a fire, how the locations of firefighters will be viewed, and what communication tools will be used to redirect firefighters if needed.

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Appendix—goTenna and ATAK Device Performance Testing

Introduction

The Center of Excellence for Advanced Technology Aerial Firefighting (CoE) took advantage of the field test of satellite messengers to test an additional system that uses terrestrial radio communication to provide situational awareness. This system consisted of the goTenna, a data-transmitting radio compatible with mobile devices, and the Android Team Awareness Kit (ATAK) situational awareness app. The CoE previously tested the goTenna in a line-of-sight environment, but this was the first test we conducted with the device in areas with intervening foliage and terrain.

The goTenna is a 2-watt VHF radio that is capable of transmitting short bursts of data over Multi-Use Radio Service (MURS) band frequencies. The MURS band is currently used by civilian and business voice radios, so to coexist with this traffic the goTenna uses a cognitive approach—meaning that the radio listens for traffic on several channels and transmits only when it detects that a channel is clear. The goTenna uses Bluetooth to connect with smartphones and tablets running iOS and Android and end-users interact with the device using a goTenna-provided app or other apps that participate in the goTenna software development kit.

In March 2016, the CoE tested the goTenna in conjunction with other data and voice radios in a line-of-sight environment (CoE 1). We found that the goTenna was capable of sending both text messages and GPS locations across long distances. The goTenna was able to transmit these files up to 9.6 miles with suboptimal antenna positioning, and successfully transmitted files out to 16.3 miles when the device's antennas were aimed perpendicular to the line-of-sight between radios to maximize signal propagation. We did not conduct testing beyond 16.3 miles, so it is possible that the goTenna is able to transmit data across even greater distances when in an environment with clear line-of-sight.

The goal of the test documented here was to evaluate the goTenna in environments lacking line-of-sight due to vegetation and/or terrain. We specifically sought to test the ability of the goTenna to send tracking points at regular intervals in a manner similar to the satellite messengers—a feature that was not tested during the previous line-of-sight test. To test this feature, we used a newly developed plug-in enabling the goTennas to work with the ATAK app.

ATAK was developed by the U.S. Air Force Research Laboratory to provide situational awareness to markets within the U.S. Department of Defense, as well as Federal, State, local, and nongovernmental agencies. Specifically:

> ATAK focuses on improving the situational awareness of small units at the tactical edge. [Situational awareness] at the tactical edge means knowing where you are, where the rest of your team is, and having a variety of ways to communicate with your team (and, if feasible with reach-back, to operation centers) (Usbeck, et al. 2).

Figure 1—Example of ATAK in Use

ATAK has three main components: mapping, real-time data transmission, and mission-specific tools. The app can stream or download mapping tiles from the U.S. Geological Survey, the National Agricultural Imagery Program, and many others, or users can load GeoTIFF and similar formats onto their devices. The app can also display shapefiles and KML files. ATAK displays the GPS location of all other app users on the network in real-time and can provide real-time spatial data and video from aircraft and unmanned aerial systems overhead. The app also allows users to place and share points, lines, polygons, routes, images, and many other types of data. A variety of other tools and plug-ins provide additional functionality to ATAK users.

Methods

The goal of this test was to evaluate the ability of the goTenna to transmit location information generated by the ATAK app in a non-line-of-sight environment. We conducted field tests of the goTenna concurrently with the satellite messenger field tests since we were interested in observing how changes in vegetation and terrain affected the goTenna. We sought to make the testing environment similar to situations that may be encountered on wildland fires by manipulating the testing sites and locations of testing parties. We also intended to compare the amount and quality of tracking data generated by the goTenna to the data generated by the satellite messengers.

We tested the goTenna during each of six satellite messenger tests. These tests were conducted in Western Colorado in combinations between minimal, moderate, and heavy forest canopies and rolling or rugged terrain. As the goTenna is a terrestrial radio, we required two parties to form a link that we could test. We chose to simulate a link between a stationary incident commander or field supervisor and a mobile firefighter. We staged the incident commander on the perimeter of simulated 100-acre fires at the start/stop point of the test, with the mobile testing party walking the perimeter of the simulated fire. During Test 2, which took place on the site of the Houston Mountain Fire, the incident commander was staged where the incident command post (ICP) was set up during the actual fire response and the mobile party walked the perimeter of the fire.

Figure 2—ICP goTenna Location in a Tree During Test 6

The mobile testing party strapped the goTenna to the exterior of a standard GSA fireline pack, with a Bluetooth link providing connectivity to ATAK—which was running on a smartphone in the researcher's pocket (this instance of ATAK also provided the true GPS track of each test). A variety of techniques were used to position the goTenna at ICP, though in all cases the goTenna was placed away from the human body and elevated at least 5 feet above the ground. The incident commander goTenna was at various times placed on top of the cab of a pickup, attached to an antenna tower, and stuck in a tree. At ICP, a Bluetooth connection linked the goTenna to a smartphone or tablet running ATAK, which collected the tracklog of successfully received goTenna tracking points from the mobile party.

The version of the goTenna plugin for ATAK utilized during the test was automatically configured to broadcast a tracking point every 20 seconds. Any other device within range of the broadcasting goTenna can receive these tracking points; if a point is not successfully transmitted to another device, there is no recourse other than to wait another 20 seconds for the next tracking point to be transmitted. In this way, the architecture of the goTenna plugin is similar to the SPOT satellite messenger, which also broadcasts data at regular intervals with no confirmation that a message has been successfully transmitted. The goTenna plugin for ATAK can also broadcast custom text messages to all other devices within range, but we did not test this feature as part of our field evaluation.

Figure 3—Tracking Data Being Collected at ICP Location During Test 5

During all tests, the incident commander and mobile party remained in voice contact by VHF radio, which proved crucial on at least two occasions in which the incident commander noticed that the data link had failed and directed the mobile party to restore the link by resetting the goTenna or ATAK. During Test 2, the link failed and could not be restored during the remainder of the test, leading to a premature conclusion of that test.

After each test concluded, we saved the tracklogs from the mobile and stationary testing parties. GPS points from the mobile party were generated dozens of times a minute by their copy of ATAK and this data was considered to be the true GPS track of the test. The movement of the stationary party was not captured; rather, we captured the track of the mobile party from the perspective of the stationary party. This track was composed exclusively of points transmitted from the mobile to the stationary party by goTenna; as such, the track depicted how a firefighter’s movements would appear to an incident commander or stationary field supervisor if both parties were using ATAK and a goTenna.

The process of plotting the locations where the goTenna failed to send a tracking point was more challenging than the equivalent process with satellite messengers, as the goTenna produced so much additional data that manually plotting these locations was deemed impractical. Instead, an automatic process was developed to identify gaps between tracking points of 40 seconds or more, which indicated missing goTenna tracking points. These times were compared in Microsoft Excel to all of the points that comprised the internal GPS tracklog. A GPS track point was not necessarily available at the exact second that a goTenna tracking point failed to send, so a 2-second search radius was employed to match missing goTenna points to GPS tracklog points. Any missing goTenna tracking point that occurred between 2 seconds before and 2 seconds after a GPS track point was automatically matched to that tracklog point, which allowed us to plot the locations where the goTenna failed. We selected a 2-second search radius to ensure that the plotted location would be reasonably accurate, as the time difference between missed goTenna point and nearest GPS track point increases as the accuracy of the plotted position decreases. We were able to plot the locations of 234 of the 308 missing goTenna points—a 76% success rate.

Results

Between all six field tests, we successfully transmitted 830 tracking points from the mobile testing party to the stationary incident commander. We identified 308 instances in which the goTenna failed to transmit a tracking point, leading to an average success rate of 72.93%, with success rates for each test shown in Figure 5. While the success rates are lower for the goTenna than for satellite messengers, the higher frequency at which the goTenna transmits tracking points leads to a greater number of tracking points being received per minute than is possible with the satellite messengers (as shown in Figure 6). As discussed in the Methods section, we were able to plot the locations and create GIS attributes for link distance, distance between tracking points, vegetation, and terrain for 234 of the 308 missing points.

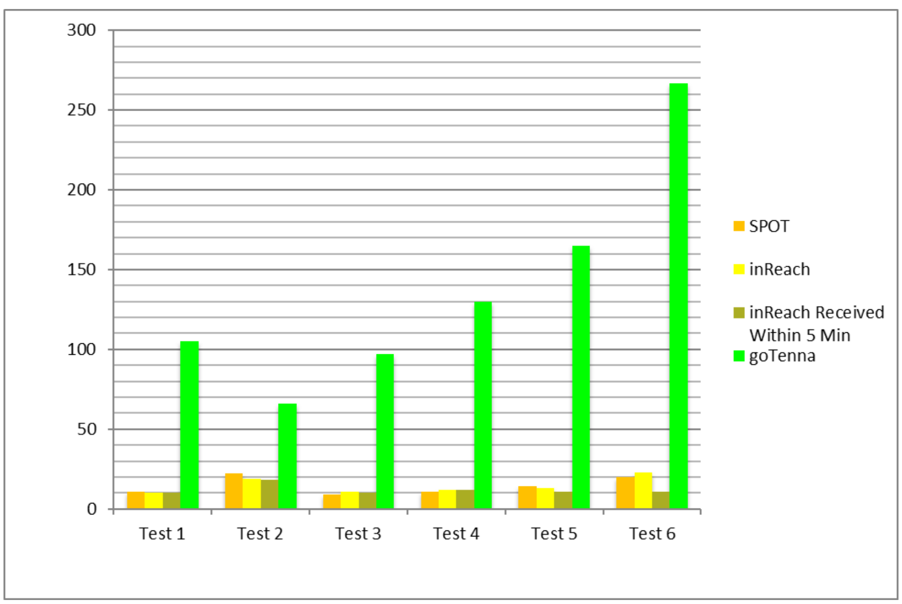

Figure 4—Absolute Number of Tracking Points Received per Test

Regression testing was used to assess the correlation between each environmental variable as measured at each tracking point

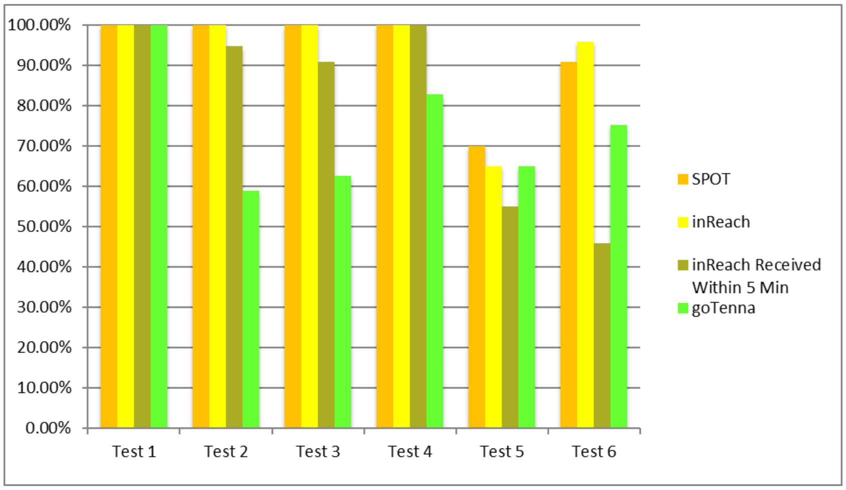

Figure 5—Percentage of Tracking Points Successfully Transmitted

location, and the success of the transmission at that location. The correlation coefficient can be between −1 and 1, close to either end dictating a stronger correlation. We correlated fuel model canopy, bulk density, slope, and aspect against a 1 if the point was successfully transmitted or 0 if the point was missed. The average correlation coefficient is −0.057294862, meaning that there is virtually zero correlation between all test data and whether a point was missed or not. The strongest correlation coefficient was with distance from ICP, but it was still only −0.26198415. Generally, for a correlation to be considered positive a coefficient stronger than .95 is needed.

The average distance of a link that successfully transmitted a tracking point was 432 meters (1417 feet), while the average distance of an unsuccessful link was 615 meters (2017 feet). While this relationship was not statistically significant, we did find individual cases (i.e., Test 3) in which there was clearly a threshold link distance beyond which the odds of a successful link dramatically decreased. Viewshed, which is the predicted ability of the two parties to see each other given the terrain, was also a statistically insignificant factor toward the success of the link. However, again this appears to have

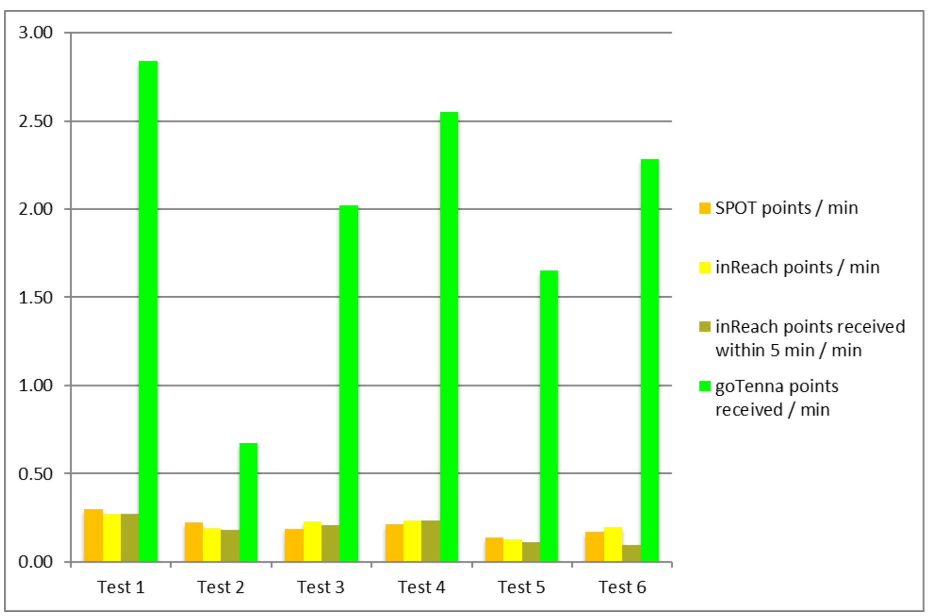

Figure 6—Number of Tracking Points Transmitted per Minute

some predictive power toward a successful link since 337 of the 830 successfully transmitted points were in a viewshed, while only 29 of the 234 unsuccessfully transmitted points were.

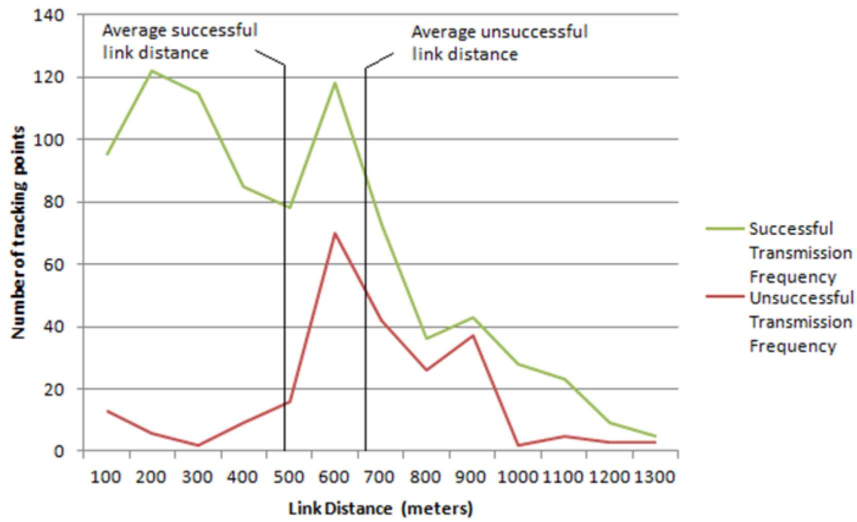

Figure 7—Histogram of Distances for Successful and Unsuccessful goTenna Transmissions

Discussion

The goTenna paired with ATAK presents a very different communications strategy than the satellite messengers. The goTenna relies on a terrestrial, near-line-of-sight data link to nearby goTennas, while the two satellite messenger products rely on a satellite link and provide their products to a server. While we could test the satellite messengers simply by hiking with them in differing types of vegetation and terrain, to test the goTenna we had to be conscious of the distance and obstacles associated with the radio link we were attempting to form between testing parties.

The location tracking capabilities of the goTenna have a clear application on wildland fires—to ensure that the locations of firefighting units are known to field supervisors and adjacent units. As a result, we sought to simulate links that would exist on wildland fires. Indeed, our testing scenario consisted of a firefighter walking around the perimeter of a 100-acre fire and communicating via goTenna with a field supervisor/incident commander who remained stationary at a point on the perimeter of the fire. This scenario occurs frequently on wildland fires when crews walk around the fire to map it, check for flare-ups/spot fires, or deliver supplies to crews on the fireline.

In theory, the goTenna—which broadcasts its location every 20 seconds—will send 15 times more location points than a satellite messenger configured to send its location every 5 minutes. However, during our tests we found that the goTenna actually successfully transmitted approximately 9.5 times as many location points as the satellite messengers. In addition, the satellite messengers sent data via satellite to a website that was unavailable to the incident commander due to lack of Internet connectivity at the test site. Therefore, the goTenna actually provided real-time tracking, whereas the satellite messengers did not.

An unplanned event occurred during Test 5 that helps to demonstrate how this technology could prove beneficial on a wildland fire. Midway through this test, the goTenna fell off the pack and was inadvertently left behind. When the goTenna was dropped and left behind, the Bluetooth link to ATAK was lost and the mobile party stopped transmitting tracking points. The incident commander party noticed this and alerted the mobile party via voice radio. When it was discovered that the goTenna was not on the backpack, the stationary party gave the coordinates of the most recent tracking point to the mobile party over the voice radio, and the mobile party then plugged the coordinates into their copy of ATAK and began to navigate toward them. The mobile party found the goTenna on the forest floor within 30 feet of the point they were navigating toward. Based on this experience, we believe that the goTenna could help firefighters locate each other while in the field, even if a firefighter became incapacitated and their goTenna stopped transmitting (provided that the rescue team could access the last known location using the ATAK app).

Our testing methodology consisted of fires averaging 103 acres in size and our simulated goTenna link distance averaged 431 meters (1414 feet), with a maximum successful link distance of 1,249 meters (.77 miles). Certainly there will be situations during wildland fires in which the size of the fire and the required link distance will far exceed those values. In addition, the current goTenna can only transmit data point-to-point and once the link is

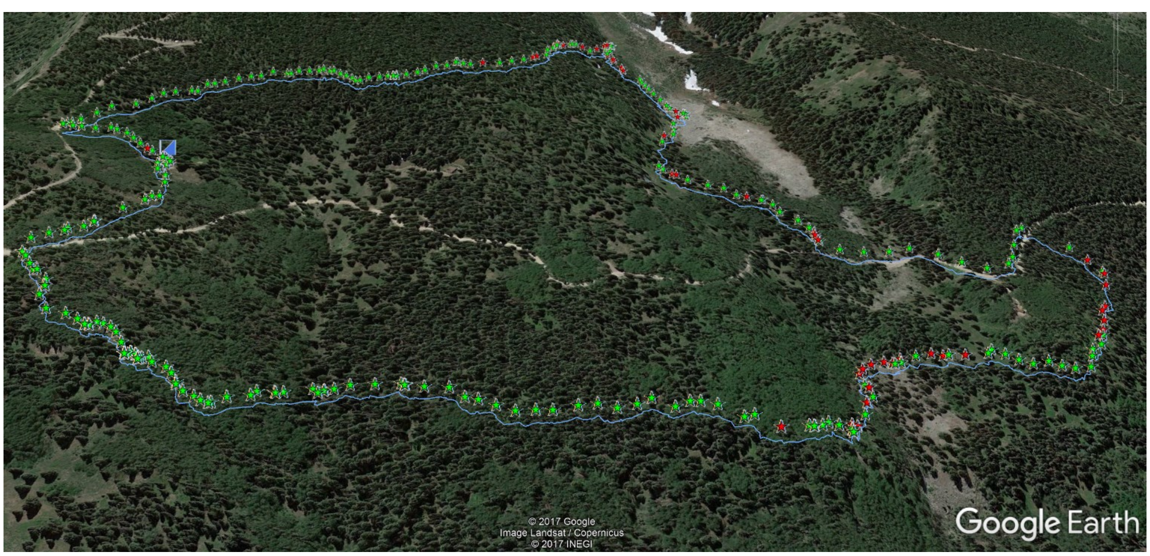

Figure 8—Three-Dimensional Depiction of Results from Test 6 (Successful Transmissions in Green; Failed in Red)

broken, there are no other options than to move the two parties closer together until the link is reestablished.

However, goTenna is slated to release a next-generation device designed for professional use that will address the limits of the current goTenna in two ways. First, the next-generation goTenna will feature a 5-watt radio (compared with the current version's 2-watt radio) and an adapter to accommodate high-gain external antennas. Second, the next-generation goTenna will feature mesh networking, which allows multiple goTennas to forward messages until they reach their ultimate destination(s). In simple scenarios, a mesh-networking radio acts as an automated repeater to forward a message across a distance or around an obstacle that would otherwise prevent a direct point-to-point link. In more complex scenarios, several mesh-networking radios—both on the ground and in aircraft—work together to ensure that data can flow to all points on an incident. This approach negates the need to deploy a central high-power repeater.

The CoE intends to test the ability of this next-generation goTenna to (1) demonstrate radio signal propagation in a point-to-point environment, and (2) construct a mesh network between several radios. We are interested in the ability of a mesh network to integrate with aircraft and pass messages across long distances and around obstacles, as well as in the number of devices and amount of data traffic that can be accommodated into the mesh. Coupled with upgrades to the goTenna plugin for ATAK, the CoE's long-term plan is to evaluate the ability of this system to transmit location reports, text messages, fillable form responses, and spatial data (consisting of points, lines, and polygons) across a mesh network composed of firefighters in the air and on the ground.

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