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Application of the remote-sensing communication model to a time-sensitive wildfire remote-sensing system

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ABSTRACT

Remote sensing for hazard response requires *a priori* identification of sensor, transmission, processing, and distribution methods to permit the extraction of relevant information in timescales sufficient to allow managers to make a given time-sensitive decision. This study applies and demonstrates the utility of the Remote Sensing Communication Model (RSCM) to improve a tactical wildfire remote-sensing system to better meet the time-sensitive information requirements of emergency response managers in San Diego County, USA. A thermal infrared airborne remote-sensing system designed and operated by the United States Forest Service Pacific Southwest Research Station for active wildfire monitoring is documented and updated based on the RSCM. Analysis of the thermal infrared remote-sensing system in the context of the RSCM identified three configuration changes that can improve the effectiveness of the information produced when employed by wildfire incident commanders for suppression prioritization: (1) limit spectral sampling collection to a single waveband; (2) complete image processing steps on-board the aircraft; and (3) provide information on wildfire locations to incident commanders in the form of a static map.

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1. Introduction

Remote sensing holds significant promise to address the time-sensitive information requirements of hazard response managers (Joyce et al. 2009; Brucewicz 2003; CEOS 2005). The use of remote sensing to address time-sensitive information requirements, however, requires that acquisition, transmission, processing, and product dissemination methods be optimized to take place within time frames that permit response to the observed phenomenon (Bernsdorf et al. 2010; Lippitt, Stow, and Clarke 2014a; Stow et al. 2015). Given that research into the effective use of GIScience to inform hazard response has shown that all data sources, transmission channels, and processing flows must be determined *a priori* for hazard response managers to adopt the technology (Cutter 2003;

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Brucewicz 2003), remote-sensing methods appropriate to time-sensitive information requirements must be optimized *a priori.*

The Remote Sensing Communication Model (RSCM) provides a framework for the design and optimization of remote-sensing systems (RSSs) that maximize the effectiveness of information they produce with respect to a given user (Lippitt, Stow, and Clarke 2014a). It also provides a tool (i.e. capacity) for estimating the consequences of changes in RSS configuration on the timeliness of information delivery to a user. Here, the RSCM is applied to evaluate and recommend refinements for some uses of an extant wildfire RSS operated by the United States Forest Service (USFS). The USFS-operated Fire Imaging System (FIS) is described, evaluated based on the RSCM, updated based on evaluation results, and then original and updated FIS information timeliness estimates are compared to meet the two objectives of this study: (1) to assess the utility of the RSCM for the optimization of the FIS to meet the time-sensitive information requirements of wildfire response managers in Southern California and (2) to identify configurations of the FIS that better meet some of the information requirements of wildfire response managers.

1.1. *The Remote Sensing Communication Model*

The RSCM is a conceptual model useful for relating remote-sensing methods and tools to the decision contexts in which they are employed and for the design of time-sensitive RSSs. It employs the metaphor of a communication system relaying information to conceptualize the collection of hardware, software, and people required to acquire, transmit, analyse, and employ remote-sensing data as fundamentally a system for the relay of information, where that information produces a varied effect depending on its and its employer's nature. It draws on Shannon's (1948) mathematical model of communication and the concept of information effectiveness proposed by Shannon and Weaver (1963) to relate RSS configuration to decision quality.

The RSCM considers remote sensing a communication system where the reality of scene conditions and states is the information source, the sensor is the transmitter, data transmission and distribution systems the channel, the analyst the interpreter, and the user the destination, as illustrated in Figure 1. The sensor samples and encodes reality, the channel transmits that encoded reality to an analyst, and the analyst interprets what the sensor has encoded and passes it to a user.

Based on the three levels of communication identified by Shannon and Weaver (1963) to determine the effectiveness of information, the RSCM dictates that to maximize the value of information produced by a RSS, the data delivered to an analyst must accurately characterize the phenomena of interest (A), the analyst must properly interpret those data into information that is relevant to the user (B), and the information must produce an effect when delivered to the user (C).

Through the concept of information travelling over a channel, where that channel has a given capacity in volume per unit time, RSCM highlights the effect of various RSS parameters on information timeliness. The RSCM considers transmitters (sensors), channels (i.e. transmission and distribution systems), and receivers (i.e. analysts) to all have a capacity that, in aggregate, determine the capacity of the system (Lippitt and Stow 2015b).

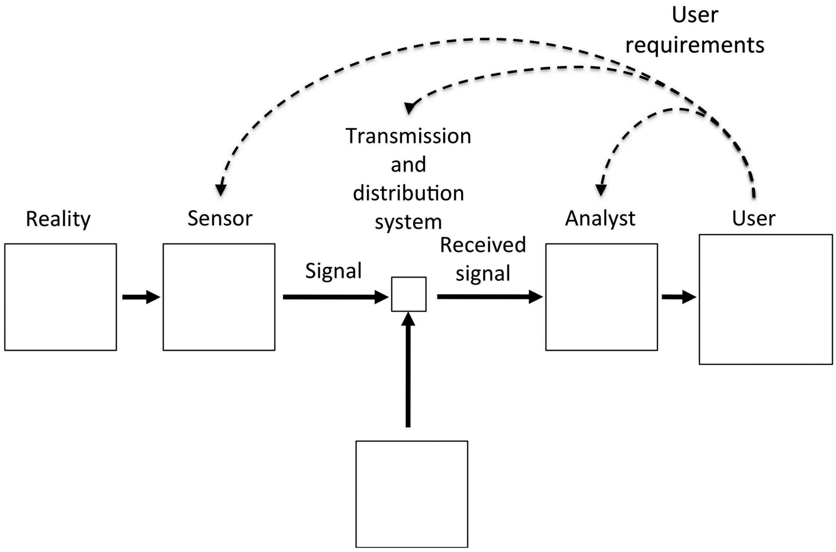

Figure 1. The Remote Sensing Communication Model. Information flows from reality to a user through the remote-sensing system, where the properties of that user and the decisions they intend to inform determine the optimal configuration of the remote-sensing system.

1.2. *Remote sensing of hazards*

Disaster management is typically conceptualized as a cycle with four phases: (1) reduction, (2) readiness, (3) response, and (4) recovery, in all of which GIS and remote sensing can play a significant role (Cutter 2003). While it is easy to see the potential benefits of access to remote-sensing-derived information in all phases of disaster management, the response phase presents a unique challenge to the remote-sensing community; information in the response phase is always time-sensitive. The adoption of remote-sensing techniques to address information requirements in the time-sensitive response phase has therefore been slow when compared to other phases (Joyce et al. 2009; CEOS 2005; Alexander 2002).

Programmes to provide information in support of the response phase are increasing in number (Joyce et al. 2009; CEOS 2005). The founding of several programmes seeking to better enable the use of remote sensing for hazard response, such as Sentinal Asia (Kaku et al. 2006) and the International Space Charter (Stryker and Jones 2009), make evident the growing importance of remote sensing as a hazard response tool. See Joyce et al. (2009) and Gillespie et al. (2007) for a thorough review of remote sensing of natural hazards. The most common hazard response remote-sensing application is wildfire detection (Ambrosia et al. 1998; Galindo, Lopez-Perez, and Evangelista-Salazar 2003; Visser and Dawood 2004; Laneve, Castronuovo, and Cadau 2006; Davies et al. 2009).

1.3. *Remote sensing of wildfire*

Satellite-based wildfire occurrence monitoring has matured to provide a sophisticated suite of information products to managers and continues to improve in terms of the size fires that can be detected and the frequency of observation (Schroeder et al. 2014), but remote sensing for tactical wildfire response remains a challenge. Tactical remote sensing of wildfire was demonstrated by the WILDFIRE programme (Ambrosia et al. 1998), which developed a RSS that transmitted data from the Airborne Infrared Disaster Assessment System (AIRDAS) thermal line scanner to a portable incident command centre nearby via cell phone modem. Maps of the controlled burn were produced at the portable command centre and made available within 20 min of acquisition. Building on WILDFIRE, the First Response Experiment (FiRE) again demonstrated tactical wildfire imaging with the AIRDAS thermal line scanner, but from the Altus II unmanned aerial system (UAS) platform (Ambrosia et al. 2003). Autonomous sensor control, on-board orthorectification, and an integrated ground-satellite communication system enabled delivery of orthorectified image products within 10 min. Building on the developments of FiRE, The Western States Fire Mission (Merlin 2009) deployed a modified MODIS simulator known as the autonomous modular scanner (AMS) on board a modified Predator A, known as Ikhana. The mission demonstrated operational tactical wildfire mapping over series of fires in the western United States and consistently delivered orthorectified thermal image data to incident commanders (IC) in less than 10 min. These programmes demonstrate the potential use of remote sensing to address tactical wildfire response information requirements, but they are all experimental in nature.

There are, however, operational tactical fire mapping programmes, the two most well tested of which are the United States Forest Service (USFS) National Infrared Operations Program (NIROPS, NIROPS 2015b) and the FIS (FM, Riggan and Hoffman 2003; Riggan, Tissell, and Hoffman 2003) operated by the USFS Pacific Southwest Research Station (PSW). NIROPS is a long-standing thermal imaging programme that began at Project Fire Scan in the 1960s (NIROPS 2015a) while FIS began operations in 2001 (Riggan, Tissell, and Hoffman 2003). NIROPS primarily images at night during periods of relatively low fire activity to provide updated fire perimeters to firefighters at their morning briefing. FIS operates at all times of day and is the focus of this study.

2. The United States forest service fire imaging system

The USFS-PSW operates the FIS to map active wildfire and wildfire-related properties such as vegetation density, burn severity, and structure damage. The configuration of the system when assessed in this study consisted of a King Air fixed-wing, twin propeller aircraft equipped with computing hardware, a Northrop-Grumman LN100GT inertial navigation system, and thermal infrared and multispectral imaging sensors. While the various imaging sensors on board (see Table 1 for a detailed description of the sensors) are useful for the variety of tasks conducted with the system, it is the thermal infrared imaging sensor, FireMapper 2.0®, that is primarily used to map intensity, spread, and extent of active wildfires. FIS is, among other activities, used to support the prioritization and allocation of firefighters and equipment by leveraging its ability to provide information on wildfire intensity and extent to wildfire ICs in time scales appropriate to support tactical wildfire suppression prioritization. While FIS is operated for a variety of wildfire remote-sensing tasks, the RSCM requires identification of a specific user or class of user in order to assess the effectiveness of a given RSS to inform that user's decision. Analysis of the FIS is therefore limited to its use for monitoring of active wildfire for tactical

Table 1. The Fire Imaging System (FIS) sensor specifications.

Waveband	Sensor	Wavelength (μm)	Image dimensions (pixels)	Focal length (mm)	Pixel size (μm)	Ground resolution at 5,000 m AGL (m)	Footprint at 5,000 m AGL (m)	Size on disk (kB)	Image encoding (bits)	Primary use
IR2	FireMapper™	8.1–9.0	327 × 205	26.4	46.25	8.75	2864 × 1796	134	16	
IR3	FireMapper™	11.4–12.4	327 × 205	26.4	46.25	8.75	2864 × 1796	134	16	Hot fires
IR4	FireMapper™	8.1 to 12.4	327 × 205	26.4	46.25	8.75	2864 × 1796	134	16	Cool Fires and smoulders
Va	Kodak Megaplus 1.6i	0.615–0.685	1528 × 1024	20.2	9	2.25	3404 × 2281	3030	12	Vegetation and Situational awareness
Vb	Kodak Megaplus 1.6i	0.815–0.885	1528 × 1024	20.2	9	2.25	3404 × 2281	3030	12	Vegetation and situational awareness
NIR	Sensors Unlimited 320 M	1.5–1.65	320 × 240	24.4	40	8.2	2623 × 1967	144	10	Moisture detection

Table 2. Standard operating procedure to provide Fire Imaging System (FIS) derived information to wildfire incident commanders.

Procedure number	Procedure	Estimated time (min)
1	Contacted by incident commanders – deploy assets	60–360
2	Image requested incidents and proceed to incident-local airfield	20–120
3	Conversion from raw files to image formats via custom software	<5
4	Conversion of quantized thermal radiance values to apparent kinetic temperature estimates	<1
5	Correlate image data to inertial navigation system (INS) measurements via Excel®	15–60
6	Upload to server via portable disk and file transfer protocol (FTP) and download by analyst	60–360
7	Direct projection via custom script in legacy image processing package	20–120
8	FTP upload coarsely registered image mosaic to server and email users to notify of availability	15–20
9	Production of GIS ready vector temperature map	15–120
10	FTP upload of GIS ready vector temperature map to server and email user to notify of availability	15–60
11	Orthocorrection, mosaic, and conversion to temperature map	1140–7200 (1–5 days)
12	FTP Upload of refined temperature map	15–60

decision support, which can include suppression activities, but also management of prescribed or naturally occurring wildfires in general, regardless of the need to suppress.

When deployed in tactical wildfire mapping mode, FIS is tasked by wildfire ICs. Typical deployments consist of the standard operating procedure (SOP) and estimated operation times depicted in Table 2, according to FIS operators (P. J. Riggan, personal communication, May 12, 2011; San Diego, CA). Note that only steps 1–8 are completed for tactical fire response while steps 9–12 are typically conducted for applications outside of suppression prioritization.

2.1. *The decision context*

Information from FIS has been used to make decisions about where to deploy firefighters and airborne fire retardant tankers, where to light backfires, and who should be evacuated. Decisions made using this information affect the safety of citizens and property (EG&G Technical Services 2008) and, as recent events have demonstrated (Karels and Dudley 2013), firefighters. Those critical decisions require a range of information; at a minimum, information on terrain, infrastructure, resources available, and wildfire location. Wildfire extent information derived from FIS is used by ICs in conjunction with these and other ancillary information sources to allocate resources.

Resources are reallocated as often as is required. When asked how quickly they need information on wildfire progression, ICs will always answer with some variant of 'yesterday', but major strategy decisions typically take place during briefings held every 6 or 12 h as personnel change shifts. During these briefings, maps play a critical role in both the strategic allocation of resources and in the relay of orders to subordinates (Alexander 2002). Absent the data from FIS, the primary source of wildfire location information available to ICs at these briefing sessions is typically a wildfire perimeter line. Wildfire perimeter lines are derived from a range of sources, typically including visual estimation of the wildfire boundary, global positioning system (GPS) equipped personnel walking portions of the perimeter, and when available, a GPS equipped helicopter flying the approximate wildfire boundary.

2.1.1. *The user*

The primary decision-maker that FIS serves is the IC of the wildfire being mapped. Typically from CalFire or the USFS in the case of California, ICs are experienced firefighters who are specially trained to manage the range of firefighting assets at their disposal to protect life and property. This often but not always means extinguishing the wildfire to which they are assigned. ICs are deployed to and responsible for a single wildfire. For the duration of that wildfire ICs are in the field, which typically means a remote area with limited connectivity and computing resources.

In some instances, mobile command centres with satellite broadband connectivity and computing resources are available. Geographic information system (GIS) and image processing capacity is beginning to be available to ICs, but expertise and availability are variable; the paper map remains the preferred medium of display for many ICs (R. Serabia, personal communication, June 29, 2009; Ramona, CA).

2.2. *FIS as a communication system*

The FIS can be analysed in terms of how well it addresses problems associated with the three levels of communication identified by the RSCM (i.e. effectiveness analysis): (1) the technical problem of communicating appropriate data, (2) the semantic problem of interpreting those data into appropriate information, and (3) the effectiveness problem of employing that information to produce an effect of value. An evaluation of how well FIS addresses these three problems is intended to identify portions of the FIS configuration that are not optimized to address the information requirements of ICs and suggest alternative configurations that better meet those requirements. The timeliness of FIS is estimated using RSCM capacity analysis under both current and proposed configurations to determine the effect of proposed configuration changes on information timeliness (Lippitt and Stow 2015a).

2.2.1. *The technical problem*

The RSCM describes the technical problem (level A) as the problem of acquiring, transmitting, storing, and distributing remote-sensing data of appropriate spectral, spatial, radiometric, and temporal resolution and of sufficient fidelity to address a given information requirement (Lippitt, Stow, and Clarke 2014a). To optimize level A, sensors at appropriate wavelengths must sample the land surface at suitable spatial and radiometric detail and at an appropriate point in time over a sufficient extent, and data must be delivered to the analyst with a minimal level of compression related noise or errors.

The technical capacity of the FIS programme to acquire, transmit, and distribute remote-sensing data has been demonstrated through extensive field campaigns. The Firemapper II® sensor (FM) records wavebands appropriate for the detection and intensity measurement of both active wildfire fronts (i.e. IR3) and cooler smouldering fires (i.e. IR4). A focal length of 26.4 mm results in a nominal ground sampling resolution of 8.75 m from the FIS standard operating flight altitude above ground (AGL) of 5000 m, which can be refined to 2.6 m nominal ground sampling distance by reducing AGL to 1500 m. Image data are recorded at 16-bit radiometric resolution, which is sufficient to differentiate wildfire occurrence and intensity (Riggan, Hoffman, and Brass 2009).

As an airborne asset, FIS has the ability to image areas on time scales limited only by the flight speed of the aircraft (cruise airspeed = about 472 km h^{-1}, or 255 kn) relative to wind speed and swath width of the sensor. Processing and transmitting those data, however, limits the rate at which image data or other information products can be provided to ICs. In the case of deploying FIS to provide wildfire location information for tactical suppression decision support on a six-hour (360 min) briefing cycle, the timeliness of information delivery is the primary constraint on the utility of FIS produced information to ICs. This suggests that RSS configuration changes that reduce the time required to transmit FIS acquired information to analysts, currently estimated to require 75–420 min, will better address the technical problem.

2.2.2. *The semantic problem*

The RSCM describes the semantic problem (level B) as the problem of interpreting the received data into information of an appropriate type, reliability, and timeliness to meet the information requirements of a given user. To optimize level B, data must be interpreted or processed in such a manner that information that is relevant to the user is produced. For FIS, addressing the semantic problem requires that the data collected be interpreted by the receiver into information appropriate for the prioritization of suppression activities by ICs.

In the FIS RSS, the receiver is a system of people, computers, and algorithms that complete steps 3–5, 7, and optionally steps 9 and 11 of the SOP described in Table 2. The information produced by steps 3–5 and 7 of the SOP are all of sufficient spatial and thematic reliability to allow ICs to allocate resources, though steps 9 and 11 improve the thematic and spatial reliability, respectively. The type of information produced (i.e. apparent kinetic temperature estimates) provides ICs with detailed information on wildfire extent, intensity, and progression. The timeliness with which the data are interpreted into information and the multiple transmissions (i.e. extended channel) that are required mean that from the time data capture is complete, 130–720 min are required to present information to ICs. Given a 6 h (360 min) briefing cycle and preference for information as quickly as possible, there is potential that the information will not reach ICs within the required time period; suggesting that the timeliness of analyst portions of the RSS should be targeted for improvement to better address the semantic problem.

The single most time consuming analysis step of the FIS SOP is not analysis at all but rather the transfer of data between various portions of the analysis sequence. The transfer of data from a local airport nearby an incident to an off-site analyst (i.e. SOP step 5) requires 60–360 min. To deliver the first viable information product to ICs, the analyst uses a custom script within a legacy image processing package to project apparent kinetic temperature estimates to ground coordinates and mosaics the resultant projected frames (SOP step 7). That mosaic is then uploaded to a publically available web site for viewing or download by ICs. To eliminate step 6, step 7 can be conducted on board the aircraft. Using a software utility that permits projective orthocorrection of image frames on low-resource computers like a laptop (e.g. Fraley 2011) will eliminate the need for redundant data transfer. Software can also readily automate the correlation of image frames and inertial navigation system (INS) records (step 5). Elimination of step 6 and optimization of steps 5 and 7 hold potential to improve the timeliness of information to ICs without changing the type or reliability of that information and, therefore, better address the semantic problem.

2.2.3. *The effectiveness problem*

The RSCM describes the effectiveness problem (level C) as the problem of providing information to a user that enables a decision-maker, whether human or machine, to make a decision that produces an effect of value. To produce an effect of value, the decision-maker (i.e. user) must be able to readily ingest and understand the information presented, which requires consideration of the decision-maker's properties. For the FIS to produce information that maximizes the effectiveness of decisions prioritizing resources for the suppression of wildfire, the information presented to ICs must be readily ingestible, understood, and related to other key information sources. The properties of a given information product that might influence the ability of a decision-maker to ingest information are numerous, but in the case of wildfire ICs in California, there are some well-understood needs owing to an established SOP.

Currently, FIS supplies information to ICs by making available web viewable map products and downloadable GIS ready temperature products. These offer several advantages: ease of use, flexibility, and straightforward production. Assuming that there are appropriate analyst, computing, and connectivity resources available, the current delivery mechanism provides the required information in a highly flexible format that can be adapted to the needs of ICs. The availability of analyst, computing, and connectivity resources to ICs in the field is highly variable, however. In particular, connectivity can be a challenge in the remote locations in which wildfires often occur. Given this, the variable proficiency of ICs with digital mapping technologies, and general reliance on paper and other static map media, the optimal format to provide information on wildfire presence is in the form of a static map, either paper or file (Ambrosia et al. 1998).

Since a static map does not easily integrate with other critical information (e.g. elevation, slope, critical infrastructure, roads), wildfire presence information must be integrated with appropriate ancillary information prior to delivery. The standard operating procedure of ICs points to a ready solution in this case also; ICs in California regularly use maps produced under the Thomas Series by Rand McNally (San Diego County 2010) (R. Serabia, personal communication, June 29, 2009; Ramona, CA). These maps, known more commonly as 'Thomas Brothers maps', provide detailed elevation contours, roadways, and location information. Integration of wildfire temperature information with Thomas Brother's maps, or similarly formatted maps with similar information, allows ready ingestion of wildfire presence information by ICs and should, subsequently, improve the effectiveness of resource allocation decisions made by ICs. Figure 2 shows an example of one such map.

2.3. *System capacity*

The timeliness of the FIS can be estimated based on the capacity of the sensor, transmission system, and receiver. We can estimate the sensor, channel, and receiver

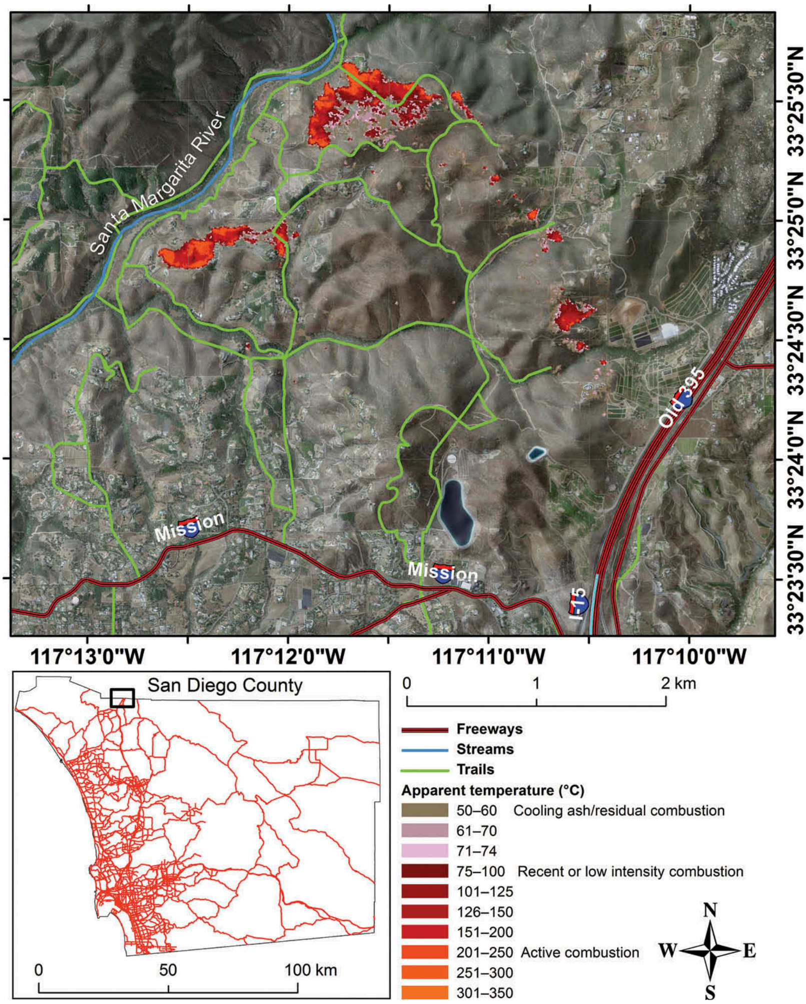

Figure 2. An example static map product produced using the FireMapper thermal-imaging radiometer. Analysis of the FIS using the Remote Sensing Communication Model revealed that a static map with thermal data contextualized by other relevant information can improve the effectiveness of FIS produced information by better integrating with CalFire standard operating procedures.

capacities based on the sensor and platform, transmission, and image processing characteristics of the FIS. To explore the net effect of various possible FIS configurations, system capacity is estimated for SOP steps 2–8 under current FIS configuration and alternate configurations suggested by the effectiveness analysis above.

To explore the bounds of possible missions, the capacity of the FIS is estimated for two contrived wildfires: a 809 ha (2000 acre) fire and a 121,406 ha (300,000 acre) fire. The first is intended to simulate smaller more typical wildfires in southern California while the second is intended to simulate larger more catastrophic wildfires like the Cedar Fire of 2003 (EG&G Technical Services 2008). The time required to deploy to a wildfire from Lancaster, CA (T_D) will have a linear effect on the time requires to image a scene (T_{Acq}), but given that the aircraft can also operate from other airports closer to the fire, we hold

T_D constant at 12.71 min, or the time required to travel 100 km, as an estimate of the distance from a given wildfire to a nearby staging airport.

2.3.1. *Sensor capacity*

The FIS employs a King Air A100 aircraft; a dual engine, pressurized cabin, fixed wing aircraft with a maximum operating altitude of 10,700 m and max cruise speed of about 472 km h^{-1}. While there are a series of sensors operated on FIS, thermal infrared data from the FM sensor are prioritized when deployed in the context of tactical suppression decision support. The cruise speed and altitude of the aircraft interact with the camera model of the FM sensor to determine the sensor capacity (C_{Acq}) in bits per unit time:

$$C_{\mathrm{Acq}} = \beta B_{\mathrm{A}}, \tag{1}$$

where β is the rate of acquisition in area per unit time assuming no end lap or side lap and B_A is the number of bits per unit ground area. Acquisition time (T_{Acq}) can then be estimated by

$$T_{\mathrm{Acq}} = \frac{B_{\mathrm{S}}}{C_{\mathrm{Acq}}} + T_{\mathrm{D}} + T_{\mathrm{M}}(N-1), \tag{2}$$

where B_S is the number of bits required to image a scene, T_D is the time required to deploy the sensor to the scene, and T_M is the time required to manoeuvre the platform between flight lines or paths, and N is the number of flight lines or paths required to image the scene.

Under current configuration FIS is operated at an acquisition altitude of 5000 m and therefore acquires data at a ground sampling distance of 8.75 m using the FM sensor. With typical total redundancy of 68% and all three channels (IR2–4) captured (i.e. configurations 1–4), sensor capacity (C_{Acq}) can be calculated as 203,265 bits s^{-1} with an acquisition rate (β) of 324,218 m^2 s^{-1}. To image an 809 ha scene (i.e. configuration 1), total acquisition time (T_{Acq}) is estimated to be about 42 s. To image a 121,406 ha scene (i.e. configuration 2), T_{Acq} = about 105 min.

Adjusting the sensor configuration to acquire only IR4 results in unreliable kinetic temperature estimates for hot fires because of saturation, but still allows accurate retrieval of active fire location for both cool and hot fires. Limiting acquisition to only the IR4 channel (i.e. configurations 1 s–4s), sensor capacity is reduced (C_{Acq} = 67,755), while the time required to image (T_{Acq}) the example 809 and 121,406 ha scenes remains the same. Because the sensor capacity is reduced, the data quantity collected is reduced substantially, as shown in Table 3.

2.3.2. *Channel capacity*

FIS is not currently configured for wireless data transmission. The channel is therefore typically composed of writing data to an external hard drive, walking that hard drive to an internet enabled computer at or nearby the staging airport, uploading the data to a file transfer protocol enabled server, download of the data from that server to an analyst (i.e. collectively SOP step 6), and upload of the derived information product to a publicly accessible webpage (i.e. SOP step 8). The channel, in this case, is described by five sub-channels each with a capacity: disk write capacity (C_{C1}), disk read capacity (C_{C2}), internet upload capacity from the airport (C_{C3}), internet download capacity (C_{C4}), and internet

Table 3. Alternative Fire Imaging System (FIS) configurations assuming a 68% redundant acquisition (E_S). System configuration numbers 1–4 are Remote Sensing Communication Model (RSCM) capacity calculations for current FIS configurations for example 809 ha and 121,406 ha scenes. Subsequent configurations are proposed modifications to current configurations where letters in the configuration number represent the updated component: s, sensor; c, channel; r, receiver.

	System configu-ration number	Number of spectral wavebands (R_λ)	Ground sampling distance (R_G) (m)	(B_A) (Bits m^{-2})	Rate of acquisition (β) (m^2 s^{-1})	Area of scene to be imaged (A_S) (ha)	Total acquisition time (T_{Acq}) (min)	Sensor capacity (C_{Acq}) (bits s^{-1})	Transmi-ssion time (T_{Chan}) (min)	Receiver capacity (C_{Reca}) (records s^{-1})	Receiver time (T_{Rec}) (min)	Total time required to produce information (T_{RSS}) (min)	Time difference from current configuration (ΔT_{RSS}) (min)
Current configuration	1	3	8.75	0.63	324218	809	0.70	203265	26.25	2814.5	8.16	35.11	-
	2	3	8.75	0.63	324218	121406	104.85	203265	55.42	18.7	70989.00	71149.27	-
	3	3	2.62	6.99	97265	809	2.33	680138	28.24	252.3	397.42	427.99	-
	4	3	2.62	6.99	97265	121406	349.50	680138	353.60	1.6	8829454.85	8830157.95	-
Sensor changes	1s	1	8.75	0.21	97265	809	0.70	67755	26.12	8338.8	5.35	32.17	−2.94
	2s	1	8.75	0.21	97265	121406	104.85	67755	35.85	56.2	7892.03	8032.73	−63116.54
	3s	1	2.62	2.33	97265	809	2.33	680138	26.79	757.0	48.63	77.75	−350.24
	4s	1	2.62	2.33	97265	121406	349.50	680138	135.24	5.1	981212.76	981697.50	−7848460.45
Channel changes	1c	3	8.75	0.63	324218	809	0.70	203265	19.20	2814.5	8.16	28.06	−7.05
	1sc	1	8.75	0.21	324218	809	0.70	67755	19.10	8438.9	5.35	25.15	−9.96
	2c	3	8.75	0.63	324218	121406	104.85	203265	40.43	18.8	70989.00	71134.28	−14.99
	2sc	1	8.75	0.21	324218	121406	104.85	67755	26.18	56.3	7892.03	8023.06	−63126.21
	3c	3	2.62	6.99	97265	809	2.33	680138	20.65	252.4	397.42	420.40	−7.59
	3sc	1	2.62	2.33	97265	809	2.33	226713	19.59	757.0	48.63	70.55	−357.44
	4c	3	2.62	6.99	97265	121406	349.50	680138	257.47	1.7	8829454.85	8830061.82	−96.13
	4sc	1	2.62	2.33	97265	121406	349.50	226713	98.53	5.1	981212.76	981660.79	−7848497.16
Analyst changes	1cr	3	8.75	0.63	324218	809	0.70	203265	19.20	2814.5	28.16	48.06	12.95
	1scr	1	8.75	0.21	324218	809	0.70	67755	19.10	8438.9	25.35	45.15	10.04
	2cr	3	8.75	0.63	324218	121406	104.85	203265	40.43	18.8	71009.00	71154.28	5.01
	2scr	1	8.75	0.21	324218	121406	104.85	67755	26.18	56.3	7912.03	8043.06	−63106.21
	3cr	3	2.62	6.99	97265	809	2.33	680138	20.65	252.4	417.42	440.40	12.41
	3scr	1	2.62	2.33	97265	809	2.33	226713	19.59	757.0	68.63	90.55	−337.44
	4cr	3	2.62	6.99	97265	121406	349.50	680138	257.47	1.7	8829474.85	8830081.82	−76.13
	4scr	1	2.62	2.33	97265	121406	349.50	226713	98.53	5.0	981232.76	981680.79	−7848477.16

upload capacity from the analyst location (C_{C5}). The FIS channel timeliness (Lippitt and Stow 2015b), $T_{Chan,}$ can be estimated by

$$T_{Chan} = \frac{B_S}{C_{C1}} + L_1 + \frac{B_S}{C_{C2}} + L_2 + \frac{B_S}{C_{C3}} + L_3 + \frac{B_S}{C_{C4}} + L_4 + \frac{B_S}{C_{C5}} + L_5 + \frac{D}{V} - T_{CT}, \quad (3)$$

where D is the distance of the scene from an airport with an internet enabled computer, V is the cruise speed of the aircraft, L is latency, and T_{CT} is the total time of concurrent transmission by channels. Assuming an airport distance (D) of 100 km, disk write capacity (C_{C1}) of 320 Mbit s^{-1}, disk read capacity (C_{C2}) of 320 Mbit s^{-1}, internet upload capacity (C_{C3}) of 1.0 Mbit s^{-1}, internet download capacity (C_{C4}) of 8 Mbit s^{-1}, internet upload capacity (C_{C5}) of 4 Mbit s^{-1}, and latency ($L_{1,2,3,4,5}$) of 120, 120, 20, 300, and 120 s, respectively, and that the disk is written in transit (T_{CT} = C_{C1}), transmission time (T_{Chan}) can be estimated at approximately 26.25 min for an 809 ha scene and 55.42 min for a 121,406 ha scene, for the standard operating procedure of 5000 m acquisition altitude and acquisition of IR2-4 (i.e. configurations and 1–2). Limiting acquisition to only the IR4 channel (i.e. configurations 1s–4s) reduces the total quantity of data to travel over the channel and therefore reduces total transmission time (T_{Chan}), as shown in Table 3.

Under the revised configuration suggested by the effectiveness analysis above, the channel is revised to eliminate SOP step 6 (i.e. C_{C3} and C_{C4}). The time required to transmit information, in this case, is estimated by

$$T_C = \frac{B_S}{C_{C1}} + L_1 + \frac{B_S}{C_{C2}} + L_2 + \frac{B_S}{C_{C5}} + L_3 + \frac{D}{V} - T_{CT}. \quad (4)$$

Assuming the same sub-channel capacities outlined above, (T_{Chan}) can be estimated at approximately 19.2 min for an 809 ha scene (i.e. configuration 1c) and 40.43 min for a 121,406 ha scene (i.e. configuration 2c), for the SOP of 5000 m acquisition altitude and acquisition of IR2–4.

With the updated channel, limiting acquisition to only the IR4 channel reduces total transmission time (T_{Chan}) to 19.1 min for a 809 ha scene (i.e. configuration 1sc) and 26.18 min for a 121,406 ha scene (i.e. configuration 2sc). See Table 3 for details.

2.3.3. *Receiver capacity*

Interpretation of FIS generated data into information digestible by ICs requires steps 3–5, 7, and optionally 9 and 11 from the FIS SOP outlined in Table 2. Under the current SOP, these steps are completed by a combination of human and automated procedures. Conversion of raw data to image formats (i.e. SOP step 3) and conversion from thermal infrared radiance to apparent kinetic temperature estimates (i.e. SOP step 4) are automated procedures triggered by the FIS sensor operator. The correlation of image data to INS data (SOP step 5) is currently completed in Microsoft Excel® by the FIS sensor operator. Initial data organization and editing is followed by automated correlation of INS fields to image frames based on GPS and central processing unit clock times. Direct projection of image data to ground coordinates based on the sensor model and orientation (i.e. SOP step 7) similarly requires an initial data organization followed by an automated processing procedure.

The RSCM provides methods for estimating the capacity of automated and human receivers (Lippitt, Stow, and Clarke 2014a). For automated receivers, receiver capacity

(C_{Reca}) is estimated based on the complexity of the algorithms employed. 'Big O' notation can be used to describe the complexity of algorithms in terms of the upper bound of the computation 'work' required, and subsequently estimate the maximum number of computational cycles per record (ϕ) required to process a given data set using those algorithms (Burger and Burge 2008). Adding two bands, for example, can be described as having a linear complexity, or $O(n)$, meaning the number of computations required is linearly related to data volume. The single operation of addition must be performed rc times, where r is the number of rows and c is the number of columns, such that ϕ increases linearly with the number of records input. In remote sensing, the number of records is a function of the number samples collected, P_S, so adding two bands can also be said to have complexity of $O(P_S)$, or more simply stated, P_S.

Conversion of raw data to image formats and conversion from thermal radiance to apparent kinetic temperature estimates are both automated procedures. Conversion of raw data to image formats is a simple conversion that requires query of each pixel once. Estimation of apparent temperature requires relating each pixel to its associated black body calibration value by regression, which requires query of all pixels in the image once and all pixels in the black body calibration image once. The algorithm complexity for steps 3 and 4 can therefore be estimated as P_S and collectively $3P_S$.

The correlation of image data to INS data is conducted by brute force matching after initial data organization. Initial data organization is not dependent on the quantity of data or size of area captured but rather the proficiency of the analyst; FIS sensor operators estimate this process to consistently require five minutes to complete, regardless of dataset size (P. J. Riggan, personal communication, May 12, 2011; San Diego, CA). The correlation of image data to the appropriate INS record requires a query of all GPS time field entries once for each image frame time stamp. The complexity of matching INS fields to image time stamps can therefore be estimated as $n \log_2 n$. The total number of INS records (R_{INS}) can be estimated by

$$R_{INS} = h_{INS} T_A, \tag{5}$$

where h_{INS} is the sampling rate of the INS in hertz. The total number of frames and therefore the total image time stamps acquired (F_S) can be estimated by

$$F_S = \frac{P_S}{ij(1 + E_S)}, \tag{6}$$

where i is the number of detectors samples in the x direction, j is the number of detectors in the y direction, and E_S is the redundancy of acquisition. The total number of INS records (R_{INS}) and total number of image time stamps (F_S) can therefore be estimated to be 491 and 30 for an 809 ha fire and 73,706 and 4,433 for a 121,406 ha fire, respectively.

Under the current SOP, direct projection of image data to ground coordinates based on the sensor model and orientation (i.e. SOP step 7) requires several steps from an algorithmic perspective: (1) initial data reformatting for import into a legacy image processing software, (2) projection of image coordinates to a surface described by a digital elevation model, (3) resampling of kinetic temperature values to the new projected grid, and (4) mosaicking of the resultant images into a single product. Reformatting data requires a single query of each sample and can therefore be considered to have a complexity of P_S. Projection of image coordinates is completed by projecting the location of each pixel to a digital elevation model and requires query of each pixel, P, and its corresponding value in the digital elevation model once. The complexity of projection can be estimated to be $P_S \log_2 P_S$. Nearest neighbour resampling of projected images requires query of each pixel and its nearest neighbour in the unprojected image as defined by the projective camera model and can be estimated to have a complexity of P_S. Mosaicking with a 'most nadir' rule requires calculation of angle for each sample, followed by a sorting to determine the sample of lowest angle, followed by population of a new grid encompassing the scene, and can be considered to have a complexity of ${P_S}^2$.

To define the upper bound of complexity for the FIS receiver configuration outlined here, complexities are aggregated to the most complex weighting, ${P_S}^2$. If we consider the problem as the upper bound of all complexities, the computational cycles per record (ϕ) can be estimated as

$$\phi = \frac{(P_S + R_{INS} + F_S)^2}{P_S + R_{INS} + F_S}. \tag{7}$$

For the estimated 532,797 records (P_S) required to image an 809 ha scene at 8.75 m ground sampling distance with IR2–4 (i.e. system configuration 1), ϕ is estimated as 532,953 cycles per record. On the 1.5 GHz processor deployed on FIS, C_{Reca} is estimated as 2815 records s^{-1}. Receiver time (T_{Rec}) is then estimated to be ≤ 3.16 min, excluding the 5 min required for the sensor operator to organize INS and image time stamps. Total receiver time (i.e. SOP steps 3–5 and 7) is estimated to be ≤ 8.16 min. For the approximately 79.9 million records (P_S) required to image a 121,406 ha scene with IR2–4 (i.e. system configuration 2), ϕ = 79,942,938 cycles per record and total receiver time can be estimated to be ≤70,989 min, or 1183.23 h.

Imaging a 809 ha scene at 2.62 m ground sampling distance with IR2–4 (i.e. system configuration 3) requires 5.94 million records (P_S) and receiver time (T_{Rec}) is estimated to be ≤6.62 h including the 5 min required for the sensor operator to organize INS and image time stamps. For the approximately 297.13 million pixels (P_S) required to image a 121,406 ha scene with IR2–4 (i.e. system configuration 4), total receiver time is estimated to be ≤981,212.76 h, or 16,353.55 days. When only IR4 is utilized (i.e. configurations 1scr–4scr), the number of records (P_S) is reduced significantly, resulting in increased receiver capacities (C_{Reca}) and therefore reduced receiver time (T_{Rec}). See Table 2 for details.

Assuming that ancillary data for the scene are compiled in advance of the imaging mission, integration of the kinetic temperature mosaic into a map product that approximates Thomas Brother's maps requires that the analyst open the required data sets in an appropriate GIS or mapping software and output the resultant product into a printable document format, such as the portable document format ®Adobe. The process is independent of data quantity and requires a static amount of time for the analyst to complete. The estimated maximum time to complete the process is 20 min. Configurations 1cr–4cr and 1scr–4scr (in Table 3) show the range of different sensor and channel configurations with the receiver modified to include integration into a static map product.

2.4. *Proposed time-sensitive FIS*

The analysis above of how well FIS addresses the three problems of effective communication reveals that the information provided to ICs is of sufficient reliability and appropriate type to address their information requirement for suppression prioritization, but that under some conditions, FIS could fail to provide information to ICs in the required time period. It also reveals that information is provided in a format that is not readily ingested by some ICs. To modify the FIS to better meet the timeliness requirements imposed by a six-hour briefing cycle and provide information that is readily ingested by all ICs, changes to the FIS sensor, channel, and receiver are proposed and the impact of the proposed changes on FIS timeliness is estimated in Table 4.

Limiting acquisition to IR4 (i.e. configurations 1s–4s) does not change the amount of time required to acquire data (T_{Acq}), but does reduce the time required to transmit and process it, as seen in Table 4. Reduction of the total number of sub-channels required to transmit the acquired data and derived information further reduces the estimated amount of time required to transmit data (T_{Chan}). By conducting image processing steps on board the aircraft instead of at an off-site location, SOP step 6 is eliminated and transmission time is reduced by up to 62%.

Modification of the receiver (i.e. analyst) to permit image processing on board does not result in a change to the estimated time required to produce information (T_{RSS}); the image processing steps conducted in SOP steps 3–5 and 7 remain the same. Integration of kinetic

Table 4. Change in Fire Imaging System (FIS) timeliness under the proposed changes to sensor, channel, and receiver configuration. Change in (Δ) acquisition time (T_{Acq}), transmission time (T_{Chan}), receiver time (T_{Reca}), and total system timeliness (T_{RSS}) are listed in minutes, where negative is a reduction in time and positive is an increase in time when compared to the current system configuration.

	System configuration	Δ Acquisition time (T_{Acq}) (min)	Δ Transmission time (T_{Chan}) (min)	Δ Receiver time (T_{Reca}) (min)	Δ Total (T_{RSS}) (min)
Sensor changes					
	1	-	−0.13	−2.81	−2.94
	2	-	−19.57	−63,096.97	−63,116.54
	3	-	−1.45	−348.79	−350.24
	4	-	−218.36	−7,848,242.09	−7,848,242.09
Channel changes					
	1	-	−7.05	-	−7.05
	2	-	−14.99	-	−14.99
	3	-	−7.59	-	−7.59
	4	-	−96.13	-	−96.13
Receiver changes					
	1	-	-	+20.00	+20.00
	2	-	-	+20.00	+20.00
	3	-	-	+20.00	+20.00
	4	-	-	+20.00	+20.00
Total					
	1	-	−7.15	+17.19	+10.04
	2	-	−29.24	−63,076.97	−63,106.21
	3	-	−8.65	−328.79	−337.44
	4	-	−255.07	−7,848,222.09	−7,848,477160

temperature estimates to a map, however, requires an estimated 20 min to complete, and therefore increases receiver time (T_{Rec}) proportionally. See Tables 3 and 4 for details.

Given that the time savings introduced by updating the FIS sensor configuration to only acquire IR4 and that doing so still allows FIS to produce sufficiently reliable information on the location of active wildfire, acquiring only IR4 is recommended when imaging in support of suppression prioritization. As ICs identify ways to take advantage of the more detailed temperature information permitted by acquiring IR3 and IR4 and transmission rates increase with technological innovation, however, this recommendation is likely to change. Similarly, given the reduction in transmission time (T_{Chan}) and no change in information reliability offered by the proposed changes to FIS channel configuration, it is recommended that SOP step 6 be eliminated by conducting image processing steps on board the aircraft. Given the widespread reliance on paper map products by ICs, it also recommended that the current receiver configuration be amended to allow the integration of the FIS produced information into a static medium map with appropriate ancillary information (e.g. roads, terrain, structures). Production of a map product does necessitate additional receiver time, but also ensures that the information produced can be effectively employed by all ICs, even in limited connectivity or computing resource environments.

3. Discussion and conclusions

The RSCM provides a useful framework for identifying portions of the FIS that should be targeted for optimization or reconfiguration. Analysis of a RSS such as the FIS, in terms of how well it addresses the three problems of effective communication (i.e. effectiveness analysis) clarifies the dependencies between technical configuration, analysis procedures, and the needs of the user for which the information is intended. Coupled with the ability to test assumptions about the impact of proposed changes on the timeliness of information delivery, the RSCM provides an effective framework in which to consider the design of RSS for time-sensitive applications. While the FIS for active wildfire monitoring is the case study presented here, there is no reason to suggest that the RSCM will not adapt readily to the evaluation or design of any TSRSS with a clearly definable user and decision context. The ability to readily model a matrix of RSS configuration options on information timeless is useful for the design of TSRSSs *a priori*, but also holds potential to enable on-the-fly re-configuration of TSRSSs to satisfy unanticipated information requirements or, perhaps more importantly, to enable design of flexible TSRSSs using networks of sensors, channels, and receivers.

A key limitation of the RSCM is that it does not make explicit the effect of various RSS configurations on the reliability or type information produced. It does make clear that information type, reliability, and timeliness must be considered when configuring an RSS to meet the information requirements of a given user (Lippitt, Stow, and Clarke 2014b), but limits the quantitative estimation of RSS configuration impacts to timeliness. In the case of FIS, the reliability of information produced from the FM sensor is well understood, which enabled ready estimation of the impact of proposed changes (i.e. change from IR1–3 to IR4 only) on reliability. In many hazard response cases where extraction of certain information from remote-sensing data of various characteristics is well understood (Hodgson, Davis, and Kotelenska 2005), the effect of RSS configuration changes on reliability can be readily estimated. For applications where the reliability of information extraction from remote-sensing data are less well understood, the inability of the RSCM to directly estimate the impact of configuration changes on information reliability represents a substantial limitation.

The sizes of the example fires used in these analyses were selected to encompass the upper and lower bound of fire extents for which FIS might be called into service. Timeliness estimates for imaging an 809 ha fire fall well below those provided by FIS operators and time estimates for imaging a 121,406 ha fire are orders of magnitude higher than those provided by FIS operators, suggesting that modelled timeliness estimates, particularly for large scenes, exhibit substantial error. The time estimates provided by FIS operators are based on their aggregate experience imaging fires of variable size, but the degree of deviation of modelled timeliness from FIS operator estimates, particularly for receiver time (T_{Rec}), suggest that: (1) empirical validation of RSCM-capacity-based timeliness is warranted, (2) receiver complexity estimates for FIS and other automated receivers require validation, or (3) that factors beyond algorithm complexity (e.g. write speed, disk latency, bus speed, existing computational load, etc.) employed by 'Big O' notation need to be accounted for to accurately estimate receiver capacity (C_{Reca}).

Analysis of the FIS in the context of the RSCM revealed several configuration changes that can be readily made to improve the effectiveness of the information produced when employed by ICs for wildfire suppression prioritization. Limiting spectral sampling collection to a single waveband (i.e. IR4) reduces the total quantity of data to be transmitted and processed. Completion of image-processing steps on-board reduces the length of the channel and therefore transmission time. Providing the information to ICs in the form a static map requires more receiver time, but guarantees that all ICs are able to readily employ the produced information. Collectively, the identified changes will provide refinements that enable delivery of information on wildfire locations in a timelier manner than the current SOP and will better ensure that FIS produced information is used to its potential. At the time of this submission, the FIS is currently being upgraded by: using small jet propulsion aircraft as platforms, enabling on-board analysis, automated on-the-fly projection of image frames and quick mosaicking (SOP steps 5, 7, and 8).

The RSCM holds potential to improve the timeliness, and subsequently effectiveness, of remote sensing for many time-sensitive applications, particularly hazard response. The development of RSSs for specific time-sensitive applications (e.g. wildfire, earthquake, and, oil spill response) and emergency response areas, such that those predetermined RSSs can be activated during an appropriate event, is likely the only way to ensure timely and effective use of remote sensing in a hazard response context (Leifer et al. 2012; Stow et al. 2015). This does not require that the configuration of a TSRSSs be static. In fact, enabling the design of flexible RSSs based on a network of platforms, sensors, channels, and receiver's, such that the RSS can adapt (i.e. be re-configured) to difficult-to-anticipate user requirements, likely represents one of the most important contributions of the RSCM. The RSCM provides a framework for configuring such systems to meet the specific information requirements of users, weather those user requirements are static and well understood or dynamic and difficult to anticipate.

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