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High Altitude Platform System (HAPS) Communication Support for Wildland Firefighting

Annual Estimates and Considerations

Aaron J. Burns
Carnegie Mellon University, Pittsburgh, PA
Ames Research Center, Moffett Field, CA

Marcus Johnson, Ph.D.
Ames Research Center, Moffett Field, CA

Jaewoo Jung, Ph.D.
Ames Research Center, Moffett Field, CA

Matthew Fladeland
Ames Research Center, Moffett Field, CA

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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA

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This report is available in electronic form at

https://ntrs.nasa.gov/

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Abstract

High Altitude Platform Systems (HAPS) are emerging aircraft and balloon-type technology that can host payloads and provide services from the stratosphere. One potential HAPS use case is to provide wireless communication services for mobile devices, such as LTE, to wildland firefighters who often operate in locations without terrestrial wireless communications coverage. In this research we analyze historical wildland fire data to provide estimates of the annual number of HAPS required to support a fire season. We apply agglomerative clustering to group historical daily satellite-based fire observations where each cluster is analogous to a required HAPS vehicle. Our lower and upper bound estimates span a range of years, communication payload footprints, the minimum days of clusters prior to launch, and categories of fires. Additionally, we consider a case where HAPS vehicles can be transferred between fires after the initial fire has dissipated. In our specific case study from 2022 "Significant" fires (greater than 40,000 acres), we approximate that either 8 balloon HAPS vehicles without considering overprovisioning for station-keeping limitations or 23 fixed-wing aircraft would be required. Overprovisioning can scale the estimate for balloon vehicles based on reader preference, and for reference, Google Loon overprovisioned by 5-10x. Furthermore, in the case where budgets are constrained and not all of the estimated HAPS vehicles can be acquired, we provide operational insight on where to deploy HAPS vehicles. Generally, in the Spring months we see that HAPS vehicles are needed in the south and southeast of the US which transitions to the north and west as the fire season progresses.

Introduction

The stratosphere is located at twice the height of commercial passenger aircraft but far below low earth orbiting satellites. Nevertheless, the stratosphere is at a sufficient altitude to provide a large ground footprint for payload services, e.g. communications, imagery and surveillance, scientific studies, radar calibration etc. [1], and does not require launching payloads into space. A broad category of aircraft, balloons and airships known as High Altitude Platform Systems (HAPS) are envisioned to reside in the stratosphere for extended periods to provide persistent coverage and access to services. As a result of the increasing demand for stratospheric services, the HAPS Alliance was formed which oversees and organizes companies that are interested in furthering stratosphere technologies. Members of the HAPS Alliance cover a broad range of community interests and can include HAPS vehicle companies, telecommunication service providers, members of academia and regional governments. The HAPS Alliance also provides a hub of information about HAPS vehicles, how to build, test and operate systems in the stratosphere and is a platform to discuss future regulations for stratospheric aircraft [2].

In this research we focus on using HAPS to provide communication services to wildland firefighters in remote areas where traditional cellular service is not available. To estimate the number of HAPS vehicles required to support the fire season on an annual basis we apply an agglomerative clustering machine learning algorithm to group daily satellite-based fire observations where each cluster of fire observations is equivalent to a HAPS vehicle. From this method we provide a series of estimated lower and upper bounds on the number of HAPS based on balloon and fixed-wing HAPS vehicle parameters, wildfire data from 2020, 2021, and 2022 and considering influential variables such as the radius of the communication footprint and the number of days with a certain number of fire clusters before a HAPS vehicle should be deployed. We also incorporate temporal considerations in our estimates where HAPS vehicle can transition between fires after the initial fire has dissipated. In our selected year of 2022, which most closely aligns with the 5-year rolling average of acres burned, we estimate that 8 balloons HAPS vehicles without overprovisioning for station-keeping limitations, or 23 fixed-wing HAPS vehicles would be required for the fire season. Additionally, in the case where only a limited number of HAPS vehicles can be acquired and deployed, we also provide operational insights on the best placement of the vehicles which consists of initially focusing on the south and southeast regions of the US and transitioning to the north and west as the fire season progresses.

Of note, our estimates and analysis are dependent on the accuracy of our datasets, scope of our fire observation clustering algorithm and modeling assumptions, the limitations and impacts of which are discussed throughout the paper.

HAPS Capability Overview and Wildland Fires

Types of HAPS Vehicles

HAPS can be divided into two broad categories: heavier-than-air, which includes fixed-wing aircraft, and lighter-than-air systems, which consists of balloons and airships [3]. Balloons can be further broken down into zero-pressure and super-pressure balloons, where super pressure balloons are sealed and stay aloft longer with a full description of both provided by NASA [4]. A non-exhaustive list of HAPS currently in development is shown in Table 1.

Table 1: HAPS Vehicle Summary

Company	HAPS	Type	Altitude (ft)	Max Observed Flight Duration (days)	Est. Payload (lbs)	Flown?
Aerostar	Thunderhead	Balloon	50-80k (1)	70 (2)	125 (1)	Yes (2)
Loon*	(many variants)	Balloon	52-65k (3)	336 (3)	575 (3)	Yes (3)
Airbus	Zephyr	Fixed Wing	70k (2)	64 (2)	17.6 (4)	Yes (2)
HAPSMobile	Sunglider	Fixed Wing	62k (5)	1 (5)	150 (6)	Yes (5)
Swift Engineering	SULE HALE-UAS	Fixed Wing	70k (2)	30 (2)	15-22 (2)	Yes (2)
UAVOS	ApusDuo	Fixed Wing	49k (7,8)	0.5 (7,8)	4.5 (7)	Yes (8)
BAE Systems	PHASA-35	Fixed Wing	65k (9)	Unable to locate	33 (9)	Yes (9)

*Loon no longer exists, but much of their technology has transferred to other HAPS companies

Sources

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(2) https://wildfiretoday.com/2022/08/18/mapping-wildfires-from-70000-feet/

(3) https://storage.googleapis.com/x-prod.appspot.com/files/The%20Loon%20Library.pdf

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Our research focuses on the general categories of station-seeking balloons and fixed-wing HAPS vehicles. Specifications on balloon vehicles are primarily derived from former company Loon's various balloon platforms and Aerostar's Thunderhead system. Data on fixed-wing aircraft are derived from HAPSMobile's Sunglider and Airbus's Zephyr aircraft.

The company Loon no longer exists but was an Alphabet subsidiary that provided internet and communications services in areas without coverage across the globe. This was accomplished through a network of HAPS "station-seeking" balloons equipped with a gondola capable of carrying an autopilot controller and LTE payload [5]. The company was established in 2011 and closed operations in 2021, not as a result of technical in-feasibility, but instead due to an unprofitable business case [5] [6]. Over the life of the company, Loon's balloons were able to successfully travel 70 million kilometers across 2100+ flights, stay airborne for over 300 days in some cases and record more than 1 million hours of flight time in the stratosphere. Documentation of Loon's venture along with key insights and lessons learned is available in the "Loon Library" [5]. More recently, SoftBank has purchased more than 200 patents generated by Loon.

Aerostar, formerly the company Raven Industries, worked closely with Loon and has continued developing HAPS balloon vehicles [7]. Aerostar has over 65 years of experience flying lighter-than-air balloon systems and one of their newest vehicles is the HAPS Thunderhead system [8]. The Thunderhead system is a zero-pressure balloon that can lift up to 125 lbs of payload into the stratosphere [9] and has a documented flight duration of 70 days in support of real-world Wildland firefighting efforts [10] [11]. This real-world firefighting support entailed providing imagery of four major fires in the 2021 season, including the large California Dixie fire [10]. The Thunderhead HAPS is also aided by an Aerostar control and flight prediction system [8], which enables the balloon to transit between locations and conduct "station-seeking" over an area of interest [10].

There are many fixed-wing HAPS in development as shown in Table 1. Two notable companies are HAPSMobile and their Sunglider aircraft, which enabled the first LTE video call from the stratosphere [12], and Airbus's Zephyr aircraft, which owns the HAPS fixed-wing flight record of 64 days [10]. Airbus intends to continue development and commercialization of their Zephyr aircraft with an anticipated deployment by the end of 2024 and a significant constellation of aircraft in the coming decade [13].

A major benefit to fixed-wing aircraft is the ability to station-keep, whereas balloons are more subject to wind patterns and are limited to "station-seeking". As a result, fixed-wing aircraft can provide predictable flight trajectories and corresponding service locations. One important unknown and constraint to fixed-wing aircraft, however, is their payload capacity and ability to host an LTE communication system. The Sunglider, for example, is able to carry an LTE payload, but the aircraft also has a relatively high payload capacity of over 100lbs (similar to the weight of current state-of-the-art HAPS LTE payload on balloon platforms). Other fixed-wing aircraft, such as the Zephyr, have a lower payload capacity, which is better suited to host lighter optical systems [13] [14] [15]. Nevertheless, several sources claim a communication relay could be an available service for Zephyr [13] [14] [15] [16]. Therefore, we assume that communication services may be viable through fixed-wing HAPS aircraft in the future, and we also provide an annual HAPS estimate for fixed-wing aircraft in this research.

Of note, one additional HAPS variant and important company that is not discussed in detail in this research is Sceye and their airship platform. Additional information on Sceye is available on their website [17].

Upper Class E Operations

HAPS are intended to operate in the stratosphere above 60,000ft which is classified as Upper Class E airspace. Currently, government aircraft are the predominate users of the airspace [18]. Industry and government expect to see an increase in Upper Class E commercial users to likely include balloon and fixed-wing HAPS, supersonic transports (SSTs) and high-speed unmanned aircraft systems (UAS) [19]. Regulations to support commercial stratospheric vehicles, however, are still in development, leaving companies such as AeroVironment to seek waivers to Part 107.31 to operate beyond visual line of site, in order to then apply for a Certificate of Authorization to leave restricted airspace. In the absence of definitive regulation, the community has developed its own set of best practices, some of which are informed by the Loon Library [5]. Some concepts to consider are an altitude reservation system such as the Federal Aviation Administration (FAA) Central Altitude Reservation Function (CARF) [20], deconflicting a HAPS vehicle's trajectory during ascent and descent from the stratosphere [21], and methods for managing high-altitude vehicle traffic [19].

To aid in regulation development, NASA and the FAA are forming an Upper Class E Traffic Management (ETM) Concept of Operations (CONOPS) for stratospheric operations. The ETM CONOPS defines the roles and responsibilities of airspace users and air traffic control during the transition to and from Class A and Upper Class E airspace. Additionally, the CONOPS discusses communication and separation concepts for users in Class E airspace and establishes a new concept of a flexible floor in Class E airspace that drops into Class A airspace to support typical HAPS flight patterns [5].

Cellular LTE from the Stratosphere

4G LTE is the common standard for cellular voice and data service across the U.S. There are many LTE bands including AT&T's Band 14, known as FirstNet, which resides near 700MHz and is intended to be a dedicated service for public safety and first responders [22] [23]. The FirstNet communication network is advertised to provide coverage across 2.81 million square miles and cover 99% of the U.S. population [22]. Nevertheless, while LTE service covers most of the U.S. population, the signal does not cover all locations, as shown in an LTE Coverage map in Figure 1 which is provided by the Federal Communications Commission [24]. The gaps in coverage can be caused by topography obstructions, e.g. valleys and mountainous regions, which also often align with the location of wildland fires.

Figure 1: AT&T LTE Voice Coverage Map (areas with coverage shown in blue) [24]

One of the possible use cases for HAPS vehicles is to provide LTE communications services. For wildland firefighters, providing terrestrial LTE coverage in remote areas directly protects life and property. Providing LTE service from the stratosphere requires a base station connected to terrestrial internet that transmits an LTE signal to the HAPS vehicle through feeder links [25]. The HAPS vehicle then provides an uplink and downlink service to traditional cellular users [25]. For this study the availability and location of a base station was not considered. For the HAPS communication broadcast payload, HAPSMobile used a "dual-Rickenbacker" system from Loon [26] [5], and they are developing a controllable phased array to reduce the impact of both platform and payload gondola movement during flight [27]. More recently Sceye has implemented a 3D beam-forming antenna [28], and Aerostar is using a payload developed by Abside Networks that benefited from development with Google Loon [29].

The first-ever LTE connection from a HAPS-mounted payload was successfully tested by HAPSMobile in September of 2020 [12]. Their Sunglider HAPS fixed-wing aircraft, flying at an altitude of 62,500ft, provided an LTE signal for 15 hours and was able to support video conferencing [12] [25]. Two additional HAPS companies, Sceye's airship in October of 2021 [28] and Aerostar's Thunderhead balloon system in April of 2022, have completed tests that provided LTE from the stratosphere. The Thunderhead system was cited as being capable of providing a viable internet service [30]. Airbus's Zephyr fixed-wing aircraft also intends to provide LTE service, however, even though they have had many successful flights to the stratosphere, the Zephyr has not yet tested LTE service technology [31]. The previously discussed payload constraints on fixed-wing aircraft will likely require further technology development prior to communication payload deployment.

The NASA/US Fire Service STRATO Project

The Strategic Tactical Radio and Tactical Overwatch (STRATO) project is a joint US Fire Service (USFS)-NASA flight project to demonstrate how station-seeking balloons might provide LTE coverage to remote wildland fire incident teams. With funding from the NASA Flight Opportunities Program and the National Interagency Fire Center, Principle Investigator Don Sullivan (NASA) is leading a team that includes USFS, NASA and Aerostar. The project is also in response to the Dingell Act of 2019 (Public Law 116-9), which requires Agencies to use the best available technologies to improve wildland fire management.

The purpose of STRATO is to provide LTE communications between incident commanders and the fire line that is often cut-off from any means of communication. For NASA the goals are to understand how these types of stratospheric platforms will operate in the airspace, what services they can provide such as observations, communications, and telemetry of field data into improved models of fire progression. Based on the results from this flight demonstration, the USFS and other incident response teams will be able to better understand the technical capabilities and limitations, the management and logistics footprint for providing the support, and the budget required to contract for flight services.

Wildland Fires of 2022

In our analysis we examine the 2020, 2021 and 2022 fire seasons. This section focuses on 2022 and is intended to provide an example characterization of fire events throughout the year.

The 2022 wildland fire season was defined by wind and droughts in some regions, higher-than-expected precipitation in others, along with warm temperatures and lightning conditions in Alaska and California as described by the National Interagency Coordination Center's (NICC) annual wildland fire report [32]. Just under 70,000 fires were recorded by the NICC, which was slightly higher than the 5- to 10-year averages, while the total number of acres burned was on pace with averages at 7.5 million [32]. A small subset of 1,289 fires were considered "large", where the fire consumed more than 100 acres of timber or 300 acres of brush as defined by the National Interagency Mobilization Guide [33]. The NICC annual report also highlights an even smaller set of 45 “significant fires” which exceeded 40,000 acres. Several of these fires received national attention including the Mosquito fire in California [34], the Hermits Peak fire in New Mexico [35], and a series of fires in Alaska [36].

Wildland fire location data is available primarily through two sources: the Fire Information for Resource Management System (FIRMS) and NIFC's open access database compiled by the Wildland Fire Interagency Geospatial Services Group. The FIRMS database provides satellite-based observations and is intended to provide closer to real-time awareness of wildland fire locations [37], whereas the NIFC data is primarily a record of fires, their initial location, status, response measures and final acreage, and containment dates [38].

Methods

Wildfire Daily Observation Clustering

Our methodology characterizes wildland fires by first clustering fire observations on a daily basis into geographically separated groups that can be covered by the HAPS vehicle communication footprint and then recording the total number of clusters. Our goal is to create clusters of observations where the maximum distance between all of the pairs of observations in the cluster does not exceed the diameter of the HAPS footprint. We chose Python’s SciKit Learn package because it is a well-documented machine learning package with a broad range of algorithms and is also open source, which enables analysis repeatability by other researchers. Python's SciKit Learn package, however, does not contain an algorithm that perfectly addresses our clustering objective. We explored SkiKit Learn's DBScan and OPTICS functions, along with a separate python package built to cluster based on maximum distance [39] but found that the algorithms were not able to limit clusters based on maximum distance between all of the pairs of observations. For example, DBScan allows for a threshold on the maximum distance between two observations, but this can result in a daisy-chain effect where a cluster of fire observations exceeds the HAPS footprint. Due to these limitations, we chose SciKit’s Agglomerative Clustering algorithm as a sufficient approximation. In our application, agglomerative clustering creates clusters based on the average distance between sets of observations and can only merge clusters up to a certain distance threshold [40]. We set the distance threshold as the diameter of the HAPS communication footprint. In our analysis we observed that agglomerative clustering can result in clusters that slightly exceed the desired footprint, however this behavior was infrequent and assessed to be minimally impactful.

Our daily fire observations are from the Fire Information and Resource Management System (FIRMS) [41] database which contains fire detections from several satellite-based sensors. We specifically use observations collected by the 375m resolution Visible Infrared Imaging Radiometer Suite sensor hosted on the NOAA-20 satellite that has the best resolution between two satellite sensor payloads that provide daily coverage of the globe [42] [43]. An example of the FIRMS observations for the second day of the Archie Creek Fire in 2020 is shown in Figure 2.

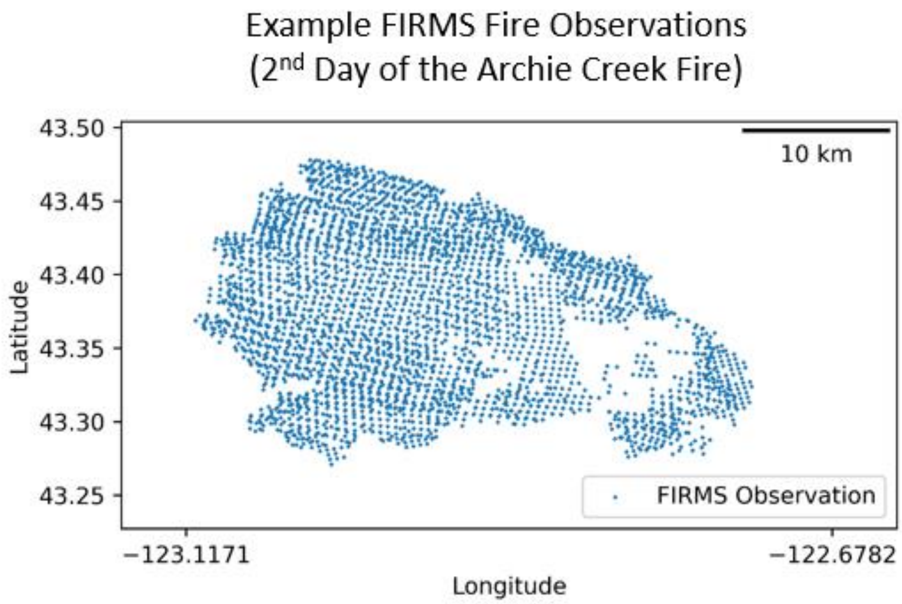

Figure 2: Fire Information and Resource Management System (FIRMS) observations from the 2nd day of the Archie Creek Fire in 2020

To iteratively explore individual wildland fires, we also used a historical fire perimeter database from the National Interagency Fire Center (NIFC) [38]. By comparing the recorded geographic perimeter polygon and start and stop dates of the wildland fire of interest with the FIRMS observations, we identified the relevant subset of fire observations. Of note, NIFC indicates that the historical perimeters database is not guaranteed to be accurate and may contain errors or missing information. The database also has minimal fire perimeter information prior to 2020. Nevertheless, the database does largely contain relevant and important information for our analysis and was the best source of data for analyzing the fire season on an annual basis.

An example image of FIRMS observation clustering is shown in Figure 3, from the 55th day of the Dixie Fire in 2021. In this image we see that there are three distinct fire clusters which in this case are determined by a HAPS vehicle communication coverage footprint radius of 30km (or a minimum of 60km of distance between the clusters). A smaller footprint radius will result in the same or more fire clusters and HAPS vehicles. In our clustering, we only allow clusters to form if there are more than 5 co-located FIRMS observations. Also shown in Figure 3, is that the agglomerative clustering algorithm does not perfectly meet our objective, as evident by the sections of the fire boundary (red polygon) that exceed the 30km-radius footprint. Finally of note, most wildland fires we examined only contain a single cluster of fire observations, and therefore the Dixie Fire example is atypical but was selected to illustrate the clustering method.

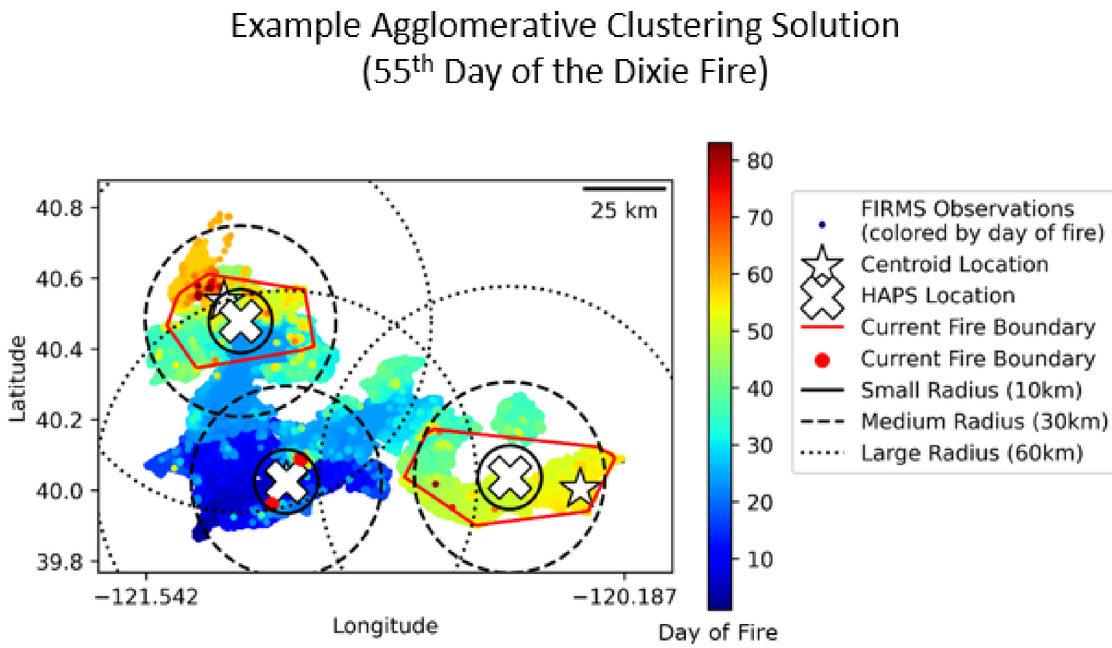

Figure 3: Fire Information and Resource Management System (FIRMS) Observation Clustering from the 55th Day of the 2021 Dixie Fire (minimum distance between clusters = 60km)

LTE Coverage Data

Another aspect we explored is the day-to-day percent coverage of the FIRMS observations by existing LTE communication services. This allowed us to study the trend of available communication resources without HAPS vehicles over the course of the fire. We leveraged LTE coverage maps, which are published by the Federal Communications Commission (FCC) for each major cell service carrier [24]. We specifically used the AT&T voice coverage map with the intent of representing AT&T's Band 14 FirstNet service for fire responders as previously discussed. This is a limitation to our analysis results as adding other service providers to our coverage map, e.g. Verizon and T-Mobile, may increase LTE coverage in wildland fire locations. We also selected the voice coverage map instead of the data coverage map to allow for an optimistic coverage estimate. This is due to our assumption that less bandwidth is required for voice services, which leads to a wider coverage area than from a data services coverage map.

Key Parameter and Assumptions

Our analysis has several key parameters with a range of possible values as described in Table 2.

Table 2: Key Model Parameters

Variable	Description	Value(s)
Fire year	Select which year is of interest	[2020, 2021, 2022]
Fire category	Type of fires to investigate, based on size or level of resources ("Significant" > 40,000	["Significant", Type 1 & Type 2]
dist_thres	Distance between two fire clusters where the clusters cannot be merged (proxy for HAPS footprint)	[10, 30, 60] km radius
min_frequency	Minimum number of days of a certain number of clusters to approve launching a HAPS	[3, 5, 7] days
HAPS_life_fx	Expected flight duration of fixed wing HAPS	60 days
HAPS_life_ba	Expected flight duration of balloon HAPS	240 days
min_obs_in_cluster	Minimum number of FIRMS observations in a cluster	5

To frame the analysis, we considered calendar years 2020 through 2022, as this data was available from both FIRMS and the NIFC perimeter database. We also limited the fires of interest to either Type 1 and Type 2 fires or “Significant” fires, which is any fire greater than 40,000 acres [32]. Type 1 and Type 2 fires are defined by an extended attack against the fire, which we assumed would include higher priority events with more resources and would therefore be a candidate situation for HAPS support [40].

To study variations in the performance of the HAPS vehicles, we varied the diameter of the communication coverage footprint and the “day threshold” variable or the number of days required at a certain number of clusters to approve the launch of a HAPS vehicle to support the fire. The size of the communication coverage footprint is derived from the Loon final report where the strongest, standard, and limit of service has a radius of 10km, 30km and 60km, respectively [5]. By using these settings, we imply that a Loon equivalent payload is likely to be used for future HAPS vehicles. For reference, a jointly developed Loon and HAPSMobile LTE payload was developed for the 2020 Sunglider HAPS communication demonstration [12] [5]. The time to launch and transit is more uncertain, but we selected 3, 5 and 7 days to explore the parameter. This is primarily based on the time it would take to transit from the launch location to the fire, as both the balloon and fixed-wing HAPS variant can be launched quickly. For example, Loon had an automated launch system, which can deploy a vehicle in 30 minutes [5] and the Sunglider fixed-wing HAPS variant does take time to reach the desired altitude, but this can still be accomplished within half of a day [25]. Loon is also likely more flexible on the launch location, as the automated launch rig could be assembled in different locations and an airport is not necessarily required. Fixed-wing HAPS, however, likely require an airport location, such as the Sunglider launch location at Spaceport America in New Mexico [25]. Weather is also important for fixed-wing aircraft, as calm winds are required during the climb to altitude and adverse conditions can cause delays. Of note, current balloon launch duration from time of tasking to launch can be several weeks due to administrative launch location determination, helium logistics, and pre-flight activities such as wind modeling. In our modeling we assume these pre-launch tasks are expedited, e.g. there are pre-determined launch location agreements where the winds are frequently monitored and helium providers are readily available.

We also fix two variables based on previous flight duration data from Loon and the fixed-wing Zephyr HAPS variant. Loon reports a range of flight duration values and indicates that they consistently exceeded 300-day flight durations and their end goal was greater than 1 year. For this analysis we use Loon's average of 240 days for their Quail balloon, which was determined based on flights that lasted longer than 20 days [5]. Of note, balloon HAPS providers may only guarantee support for shorter durations (e.g. several months), however, a 240-day duration creates a bounding case for our estimates. For the fixed-wing flight duration, we set the parameter at 60 days in reference to the longest flight of the Zephyr aircraft in 2022 [10] (64 days).

We make a series of additional assumptions in our modeling. First, we assume that the NIFC perimeters dataset has sufficiently accurate data, although as previously noted, there are some errors and missing values in the dataset. For example, there often is missing content to define the end of the fire in the context of when HAPS support would no longer be required. As a result, we use data in the following order of precedence based on availability. The end of the fire is ideally defined by the date of control; if not available, then the date of extinguish, followed by the date of containment, and if none of these data are available, we assume the fire continues until the end of the calendar year. We also only focus on CONUS-based fires and do not include events in Alaska or Hawaii. This is in part due to the shorter daytime battery charging hours at higher latitudes, which we assume limits photovoltaics fixed-wing flight patterns. We also limit our analysis to CONUS to simplify our temporal assessment, which allows for transferring HAPS fires and reflect potential HAPS operational considerations.

With respect to the HAPS vehicles, we assume that the communication coverage footprint has sufficient bandwidth to support all Wildland Fire resources in the cluster of the fire observations. We do not complete a bandwidth analysis or make assessments on how many users would require communication services in a specific cluster.

We also assume that both fixed-wing and balloon HAPS vehicles will be able to perfectly station-keep, and balloon vehicles will not require overprovisioning. We do this to provide an optimistic lower bound estimate of the number of HAPS vehicles in our results, which can be scaled based on a preferred overprovisioning factor required to provide adequate service, e.g. Loon anticipated 5-10x overprovisioning to provide consistent service [5]. Our no-overprovisioning assumption may not be realistic for real-world balloon HAPS vehicles, and the implications and limitations of this assumption are covered in more detail in the Discussion section. Additionally, we assume both types of HAPS vehicles will be able to transit between the center point of their assigned cluster each day. Also, we do not consider the location of a ground command center and assume that the HAPS vehicle will be able to receive an uplink from command at any cluster location.

Finally, in our percentage coverage of LTE service assessment of the FIRMS observations, we assume that the terrestrial cell coverage network has not been destroyed as a result of the fire activity.

Results

Annual HAPS Estimate

To estimate the annual number of HAPS vehicles required to provide coverage over the wildland fire season, we applied our previously described methodology across years, categories of fires, coverage footprint radius and the threshold of the number of days with a specific number of clusters required before HAPS launch. We present a range of results in Figure 4 under the assumption that the day threshold variable is fixed at the most stressing condition of 3 days across all presented scenarios. The resulting average trend is displayed for each year, where the lower bound is determined by the number of balloon HAPS vehicles required assuming no overprovisioning and a 240-day flight duration and the upper bound is estimated by the number of fixed-wing HAPS vehicles assuming no overprovisioning and a 60-day flight duration. For reference, the most pessimistic scenario we examined is in 2020, which had the most acres burned on record, with the lowest threshold of 3 days required to consider launching an additional HAPS vehicle, and the smallest footprint of 10km, which resulted in an estimated lower bound of 79 balloon HAPS without overprovisioning and an upper bound of 173 fixed-wing HAPS.

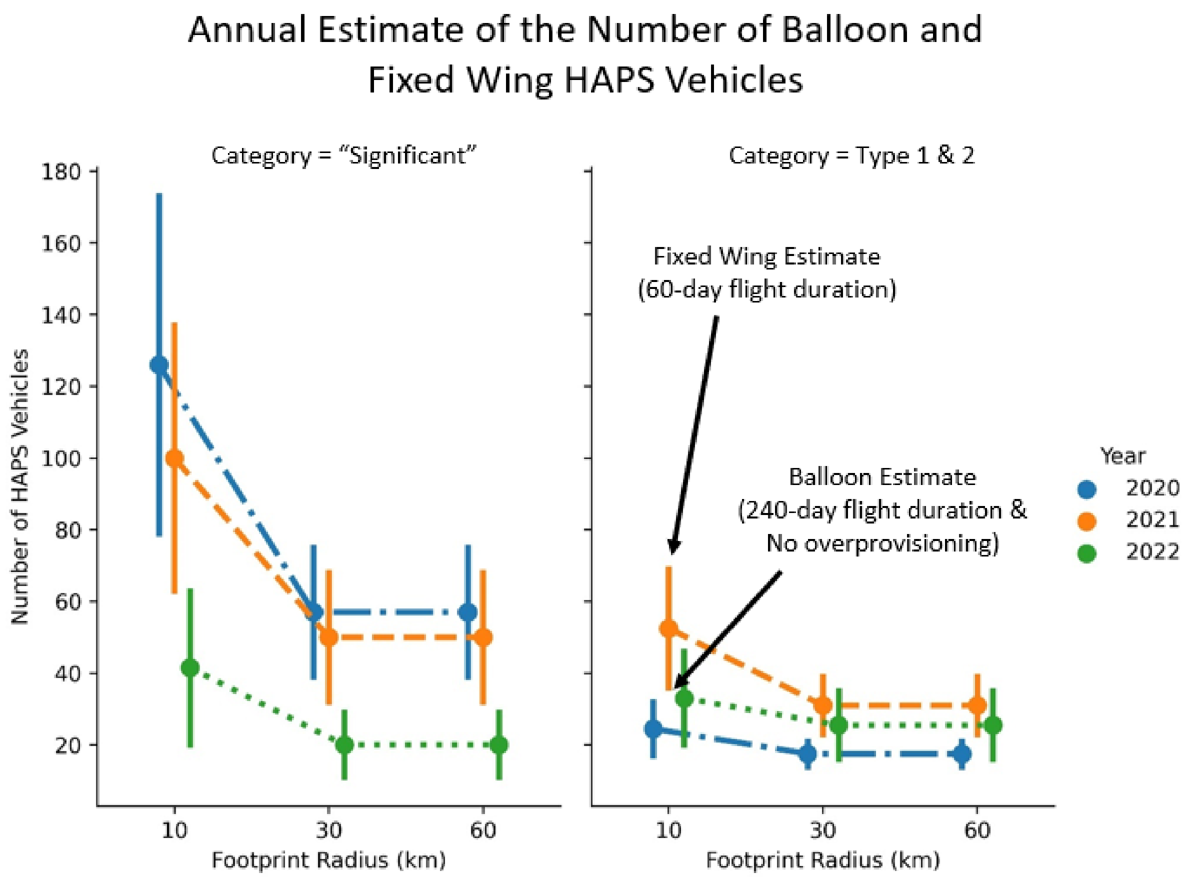

Figure 4: Annual HAPS Estimate for "Significant" and Type 1 & 2 fires. The average trend is displayed for each year given changes in communication coverage footprint radius. The upper bound is defined by the number of fixed-wing HAPS assuming a 60-day flight duration and the lower bound is defined by the number of balloon HAPS vehicles assuming a 240-day flight duration and no overprovisioning. This analysis also assumes that the day threshold variable is fixed at the most stressing setting of 3 days across presented scenarios.

Several trends and insights are apparent from Figure 4. First, the graphic in Figure 4 suggests that there can be a large difference in HAPS estimates for the "Significant" and Type 1 & 2 fires, especially for 2020. This indicates that not all of the "Significant" fires are considered Type 1 & 2 fires, e.g. there are large fires that do not require a high degree of firefighting support and / or there may also be inaccuracies in the fire perimeter database, e.g. a "Significant" fire may not have been properly recorded as a Type 1 or Type 2 fire. As discussed previously, errors may be present in the perimeter dataset but are expected to be minimal.

We also see a decreasing trend in the HAPS estimate with an increase in communication coverage footprint radius. This is an expected behavior, as a larger footprint will result in the equivalent or fewer clusters of co-located fire observations and therefore fewer HAPS vehicles. Also of note, there is no change in the lower and upper bound on the estimated number of HAPS vehicles for "Significant" fires and Type 1 & 2 fires between a 30km and 60km footprint radius. This is due to the typical size of the active portions of wildland fires, where most clusters of daily FIRMS observations are smaller than a 30km footprint radius and can be covered by the same number of HAPS vehicles.

Additionally, we examined estimates for the number of HAPS vehicles across the day threshold variable given a fixed 30km footprint radius. The resulting estimates are available in

Appendix Figure 7 and do not show as much variation or dependency on the day threshold variable.

LTE Coverage

The percentage of fire observations that have LTE coverage can vary between fires and throughout the duration of each fire. For example, the LTE coverage for the Bighorn Fire in 2020 is displayed in Figure 5, where we see significant variation in coverage throughout the fire.

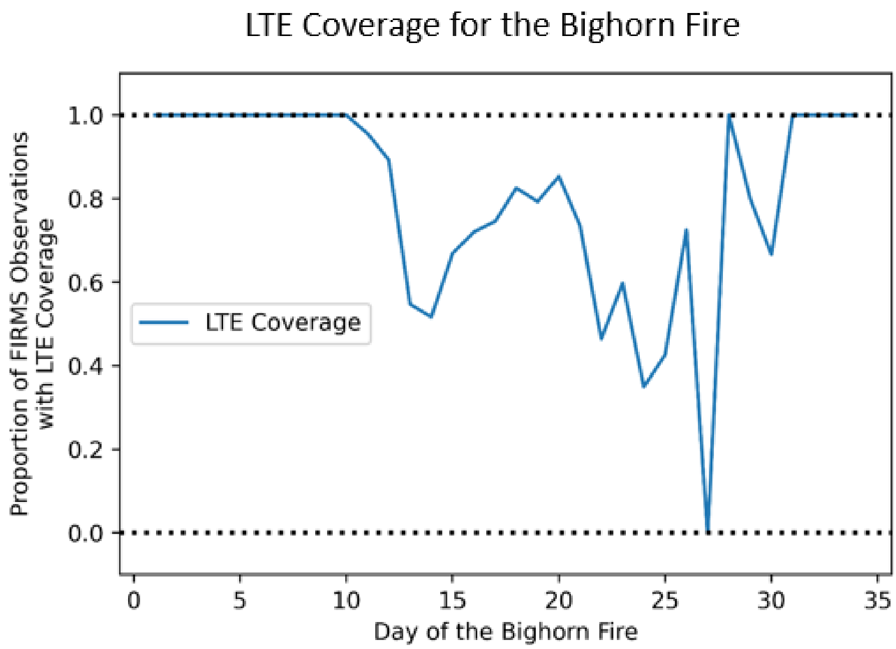

Figure 5: Proportion of FIRMS Observations with LTE Coverage (2020 Bighorn Fire)

Other fires are more consistent, such as the Telegraph Fire in 2021, which has a high percentage of coverage throughout the fire, while the Mosquito Fire in 2022 has a low percentage of LTE coverage. Both graphics are shown in Appendix Figure 8 and Figure 9, respectfully. In general, most fires do not have perfect LTE coverage and often have varying proportions of coverage, which may increase the need for additional communication resources such as those provided by HAPS.

Temporal Considerations

Our estimates for the annual number of HAPS vehicles thus far have assumed that a new set of vehicles will be deployed for each fire, however, it may be possible to transit HAPS vehicles to another fire after the initially tasked fire has dissipated. To explore this possibility, we temporally sequence HAPS vehicles as they address either "Significant" or Type 1 & 2 fires from the 2022 fire season. We examined the 2022 fire season as the number of acres burned was most similar to the 5-year average [44]. The schedule and estimate for the number of fixed-wing and balloon HAPS vehicles is shown in Table 3. In this analysis we do not include the time it would take to travel from one location to another but assume that if there is meaningful flight duration still available for the vehicle, then the HAPS vehicle can transfer to another fire.

Table 3: 2022 "Significant" Fires
(fixed-wing HAPS flight duration = 60 days, balloon HAPS flight duration = 240 days, day threshold = 3 days, footprint radius = 30km, no overprovisioning for HAPS vehicles)

Fire	Start	Stop	Duration	Max Clusters	Fixed Wing HAPS	Balloon HAPS
Kidd	17-Mar	8-Apr	22	0	-	-
Borrega	30-Mar	8-Apr	9	1	1	1
Hermits Peak	6-Apr	21-Aug	137	1	2,3,4	2
Calf Canyon	9-Apr	21-Aug	134	1	1,5,6	1
Cooks Peak	17-Apr	12-Sep	148	1	7,8,9	3
Cerro Pelado	22-Apr	26-Aug	126	1	10,11	4
Road 702	22-Apr	9-May	17	0	-	-
Black	14-May	18-Nov	188	1	12,13,14	5
Willow Creek	28-Jun	12-Jul	14	0	-	-
Moose	17-Jul	21-Nov	127	1	15,16	6
McKinney	29-Jul	11-Nov	105	1	17,18	7
Cedar Creek	1-Aug	31-Dec	152	1	19,20,21	8
Double Creek	30-Aug	14-Nov	76	1	4,22	1
Mosquito	7-Sep	11-Nov	65	1	6,9,23	2
				Total HAPS	23	8

We approximate that 8 balloon vehicles without overprovisioning for station-keeping limitations or 23 fixed-wing aircraft are required for the 2022 season. Additionally, given our assumptions, we observe that only 4 fixed-wing or 2 balloon HAPS vehicles have remaining flight duration after their initial tasking and can transfer to another fire. This is due to the seasonality and long duration of most fires where a cluster of fires start in the Spring months and will not conclude until early Fall. For example, those HAPS vehicles that can be transferred were assigned initially to a fire that started early in the Spring and concluded by early September, so they could be reassigned to the Fall fires. Fires that started in May or June however, may not conclude in time to transition HAPS to another fire. The trend is similar but more severe for the Type 1 & 2 fires shown in Appendix Table 4, where only one of each type of HAPS vehicle could be transferred to help fulfill the 24 fixed-wing or 15 balloon HAPS that were required for 2022.

Applying Limited Resources

We also explore how to effectively deploy a limited number of HAPS vehicles. This provides insight into the case where budgetary requirements do not allow for the acquisition of the estimated number of HAPS vehicles, which could be from 10s to 100s based on the types of fire supported and the level of overprovisioning required for balloon HAPS. Across the years and categories examined we see that fires tend to start in the south to southeast of the US and transition north and west as the fire season progresses. This trend is displayed in Figure 6 for 2022 “Significant Fires” and 2020 “Significant” fires in Appendix Figure 10. These fires also generally start in the Spring and taper off through the Fall, as previously noted in Table 3.

The strategy for the best use of a limited number of HAPS vehicles depends on the flight duration of the vehicles. For example, the fleet of balloon HAPS vehicles, which we assume can be aloft for 240 days, could be launched at the start of the fire season in the Spring and transition between fires throughout the season. Operational crews should be ready to launch these balloons from the south of the US and then be prepared to move the balloons to the areas of greatest need. This might include using the limited number of balloons to overprovision a single fire or split up the balloons to provide coverage at multiple fires. Throughout the season, the balloons should steadily transition north and to the west as shown in Figure 6.

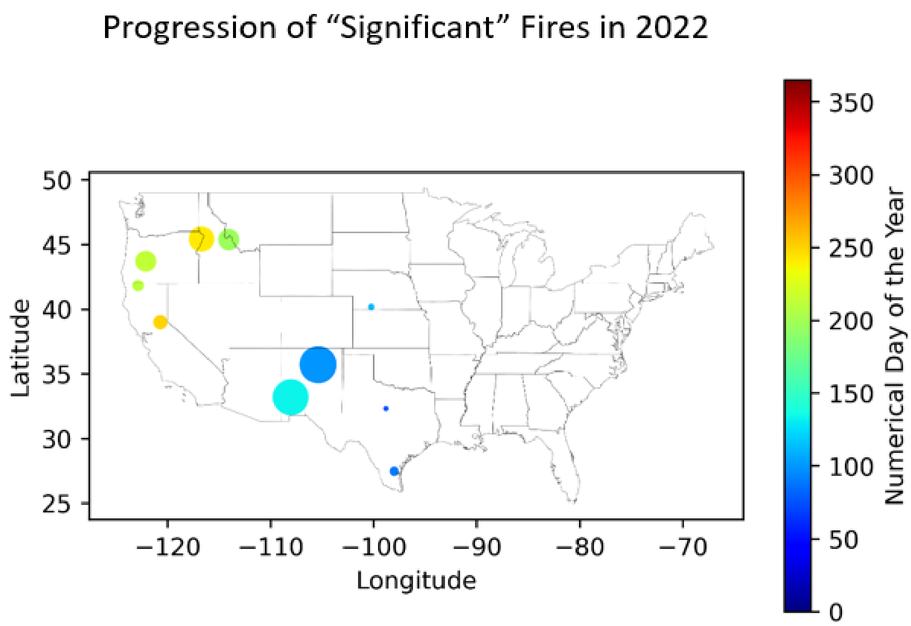

Figure 6: Progression of “Significant” Fires in 2022 (size of marker represents acreage of fire)

Fixed-wing HAPS vehicles, however, have a shorter flight duration of 60 days and should be conserved until launch is necessary. For example, fixed-wing HAPS could be saved and only launched in situations where the fire is predicted to quickly expand, threaten people and infrastructure and in areas where communication services are severely limited. The launch teams should also be similarly prepared for fires to transition north and to the west and should move fixed-wing HAPS vehicles to supporting takeoff locations.

Discussion

Key Takeaways and Operational Considerations

There are several key takeaways and considerations derived from our analysis results. Our analysis indicates that a non-trivial number of HAPS vehicles are needed to fully support the annual fire season as shown in Figure 4 and Table 3. Of note, the lower-bound balloon HAPS estimates from Figure 4 and balloons HAPS estimate from Table 3 do not include overprovisioning of HAPS vehicles, which may be necessary to compensate for an inability to “station-keep” and provide reliable communication coverage for firefighters. As a result, these estimates can increase by 5-10x, which was a strategy used by Google Loon [5]. This likely impacts the selection of balloon HAPS when compared with fixed-wing alternatives. Fixed-wing aircraft are an increasingly attractive option if future aircraft can carry a similar payload as balloons and stay airborne significantly longer than the 60 days used in this analysis.

Adding temporal considerations can reduce the number of HAPS needed for the fire season if we assume vehicles can be transferred between fires after the initial fire has dissipated. This can be employed operationally, but we estimate that only a few HAPS are able to be transferred each season due to the seasonality and longer duration of fires as previously discussed. Furthermore, if the estimated number of HAPS cannot be acquired, then the Fire Service can be prepared to deploy HAPS vehicles regionally based on the time of year, starting with the south to southeast and transitioning to the north and west as the fire season progresses.

From a technical perspective, a HAPS vehicle communication payload radius of 30km may be sufficient to provide coverage over most wildland fires. This is evident by the lack of change in our estimated number of HAPS vehicles in Figure 4 between a radius of 30km and 60km, which indicates that additional footprint radius does not reduce the number of fire observation clusters. This plateau in performance may also start prior to 30km. Further research is required to assess this hypothesis, but we presently observe evidence of an upper bound on the size of the communication footprint.

In terms of communication service, perfect LTE coverage over all fire observations is not guaranteed and there are many fires with poor coverage and varying coverage over the duration of the fire. This provides additional motivation for the use of HAPS vehicles, which can enable more consistent communication support which improves firefighter safety and wildland fire suppression efforts.

Additionally, the Fire Service can refine their estimate for the number of HAPS vehicles by deciding which types of fires are more likely to receive HAPS support between large “Significant” fires, Type 1 & 2 fires, or another preferred classification system. Our impression is that “Significant” fires are more likely to receive HAPS support, as many of the largest fires are also categorized as Type 1 and Type 2 fires, while many other Type 1 and Type 2 fires can be of shorter duration and smaller size and may not be an efficient use of HAPS vehicle resources.

Limitations

One of the key limitations to this study is the post-hoc method of analysis, e.g. we estimate the number of HAPS vehicles based on prior wildland fire events instead of from a real-time and uncertain fire planning and response perspective. This is likely to result in inaccuracies in our estimates, as the Fire Service during the fire season may choose to delay deploying HAPS resources until the fire is more severe or may incorrectly deploy HAPS to a fire that does not end up needing the support. An example operational paradigm to consider may be to wait to deploy a HAPS vehicle until the fire is predicted to expand rapidly and to be prepared to shift the HAPS between fires based on the evolving environment.

Additional realism on the deployment timeline for HAPS and the duration of support would also improve future modeling efforts. For example, air traffic control may not allow HAPS to be launched rapidly and may require a period of time between launch request and deployment. In this case, alternative smaller fixed-wing UAVs may be a better solution for initial response. Furthermore, LTE communication services may not be necessary for the full duration of the fire as described in our assumptions. Reducing the duration requirement may afford more flexibility to transfer the HAPS vehicles to another fire and has the potential to reduce the total number of HAPS vehicles.

There are also dataset, algorithm and assumption limitations as mentioned previously, several of which are worth reiterating. For our datasets, we have acknowledged that the NIFC wildfire perimeter dataset is missing data and has inaccuracies, but this is believed to be minimal. Nevertheless, this likely adds error to our HAPS estimates. Additionally, due to dataset limitations, we are not able to study HAPS estimates for years prior to 2020. This does not allow us to include 2015, which is the largest wildfire season on record by number of acres burned [44], or explore different trends that may be present in other wildfire seasons.

The agglomerative clustering algorithm used to group fire observations from the FIRMS database is also not perfect as evident by the fire boundary, which extends beyond the HAPS footprint radius of 30km in Figure 3. However, this inaccuracy is less likely to have an impact on our HAPS estimates. Also of note, as we previously discussed a balloon HAPS' inability to "station-keep", we also assume that a fixed-wing vehicle can provide perfect station-keeping. However, this may not always be guaranteed, especially if the HAPS vehicle needs to quickly transition between fire boundaries. This assumption may only have a small impact on our estimates but is important for understanding the operational limitations of fixed-wing HAPS vehicles.

Next Steps

This research provides a range of estimates and considerations for deploying HAPS vehicles that provide communication services for wildland firefighters. We see potential in a HAPS vehicle's ability to provide the intended services but also recognize the non-trivial magnitude of our estimates. As a result, there may be limited or reserved deployment options available that provide essential services for the worst fires but still maintain operational and financial feasibility.

Future analytical research efforts should improve upon our estimates by refining assumptions through updated HAPS vehicle performance parameters and current operations concepts. Additionally, real-world testing such as the US Fire Service/NASA STRATO Project is instrumental in proving capabilities and gaining community acceptance along with discovering unforeseen challenges. Subsequent test events should also be conducted as needed to further study the sustainability and effectiveness of the system, e.g. allowing a balloon HAPS to stay aloft for an extended duration and conducting transition activities between fires. Each of these efforts is intended to provide assessments for wildland firefighting stakeholders that better inform decisions on the operational acceptance of HAPS vehicles.

Appendix

HAPS Estimate (day threshold variation)

Figure 7 displays the range of the annual estimated number of HAPS vehicles across values for the day threshold variable and given a fixed footprint radius of 30km.

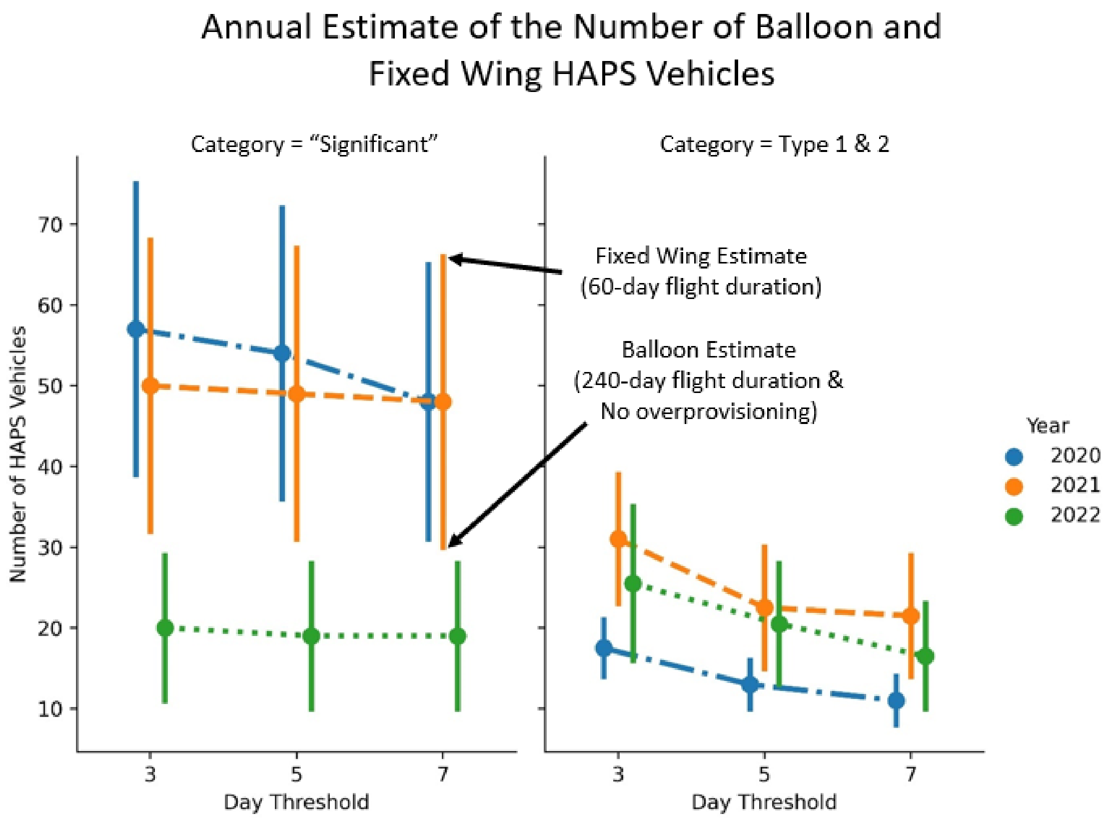

Figure 7: Annual HAPS Estimate for "Significant" and Type 1 & 2 fires. The average trend is displayed for each year given changes in the day threshold prior to launching a HAPS vehicle. The upper bound is defined by the number of fixed-wing HAPS assuming a 60-day flight duration, and the lower bound is defined by the number of balloon HAPS vehicles assuming a 240-day flight duration and no overprovisioning. This analysis also assumes that the communication coverage footprint is fixed at 30km across presented scenarios.

Additional LTE Coverage Graphics

Additional LTE coverage graphics from the 2021 Telegraph Fire and 2022 Mosquito Fire are shown in Figure 8 and Figure 9, respectfully. The Telegraph Fire had consistently high LTE coverage throughout the fire whereas the Mosquito Fire had a low proportion of LTE coverage.

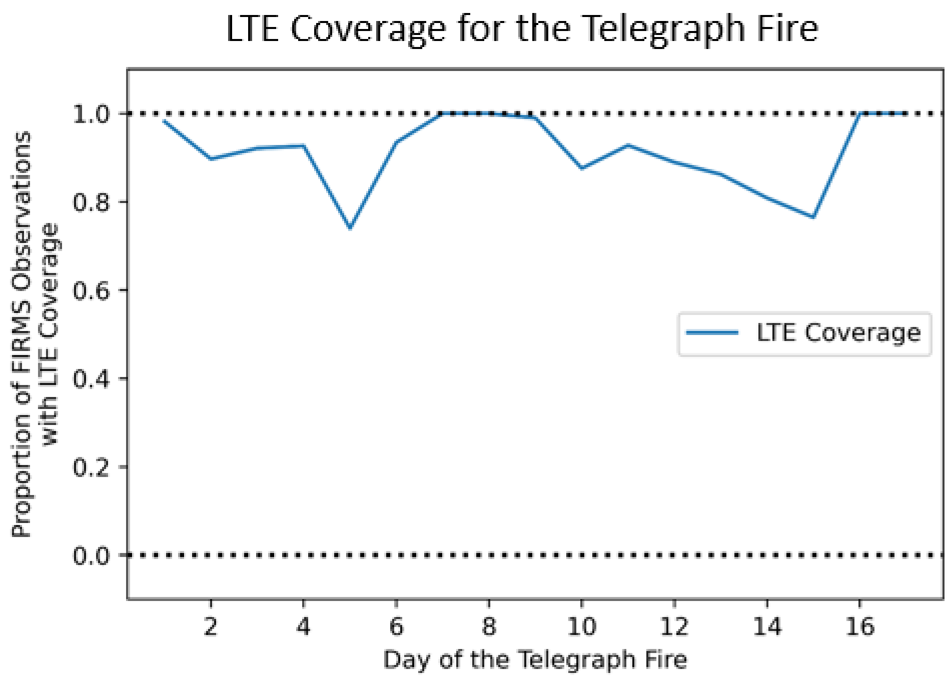

Figure 8: Proportion of FIRMS Observations with LTE Coverage (2021 Telegraph Fire)

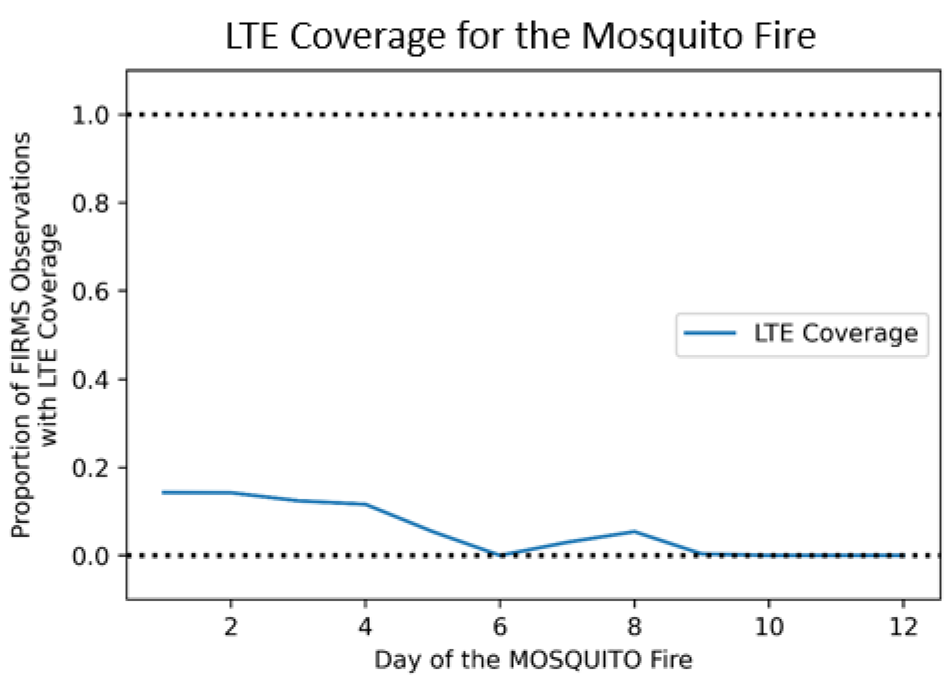

Figure 9: Proportion of FIRMS Observations with LTE Coverage (2022 Mosquito Fire)

Temporal HAPS Schedule (Type 1 and Type 2 Fires)

Table 4: 2022 Type 1 and Type 2 Fires
(fixed wing HAPS flight duration = 60 days, balloon HAPS flight duration = 240 days, day threshold = 3 days, footprint radius = 30km, no overprovisioning for HAPS vehicles)

Fire	Start	Stop	Duration	Max Clusters	Fixed Wing HAPS	Balloon HAPS
Thomas Divide	26-Mar	21-Apr	26	0	-	-
Calf Canyon	9-Apr	21-Aug	134	1	1,2,3	1
Bents Fort	12-Apr	19-Apr	7	0		-
Fort Lyons	12-Apr	25-Apr	13	-	-	-
Cooks Peak	17-Apr	12-Sep	148	1	4,5,6	2
Mesquite Heat	17-May	6-Jun	20	0	-	-
Chalk Mountain	18-Jul	10-Aug	23	0	-	-
1148	18-Jul	31-Jul	13	0	-	-
Alex	31-Jul	14-Sep	45	0	-	-
Vantage Highway	1-Aug	24-Oct	84	1	7,8	3
Miller Road	2-Aug	31-Aug	29	0	-	-
Camel Hump	17-Aug	15-Oct	59	-	-	-
Hog Creek 1	18-Aug	27-Aug	9	0	-	-
Parks	21-Aug	27-Dec	128	1	9,10	4
Shull Creek	23-Aug	27-Dec	126	1	11,12	5
Boundary	24-Aug	31-Aug	7	-	-	-
Copper Lake	24-Aug	31-Oct	68	1	13	6
Three Fools	25-Aug	27-Dec	124	1	14,15	7
Brush Creek 1	25-Aug	7-Sep	13	-	-	-
Skagit	25-Aug	27-Dec	124	1	16,17	8
Brush Creek 2	25-Aug	1-Nov	68	1	18	9
Twin Lakes	25-Aug	24-Oct	60	1	19	10
Copper Ridge	26-Aug	9-Sep	14	-	-	-
Silesia	26-Aug	31-Oct	66	1	20	11
Elbow	30-Aug	27-Dec	119	0	-	-
Kid	30-Aug	28-Sep	29	1	3	1
Little Chill	30-Aug	31-Oct	62	1	21	12
Mill	2-Sep	14-Sep	12	0	-	-
Mountain	2-Sep	30-Oct	58	1	22	13
Jones Creek	4-Sep	4-Nov	61	1	23	14
Aspen	4-Sep	30-Sep	26	0	-	-
Middle	7-Sep	5-Oct	28	0	-	-
Mosquito	7-Sep	11-Nov	65	1	24	15
				Total HAPS	24	15

Wildfire Progression

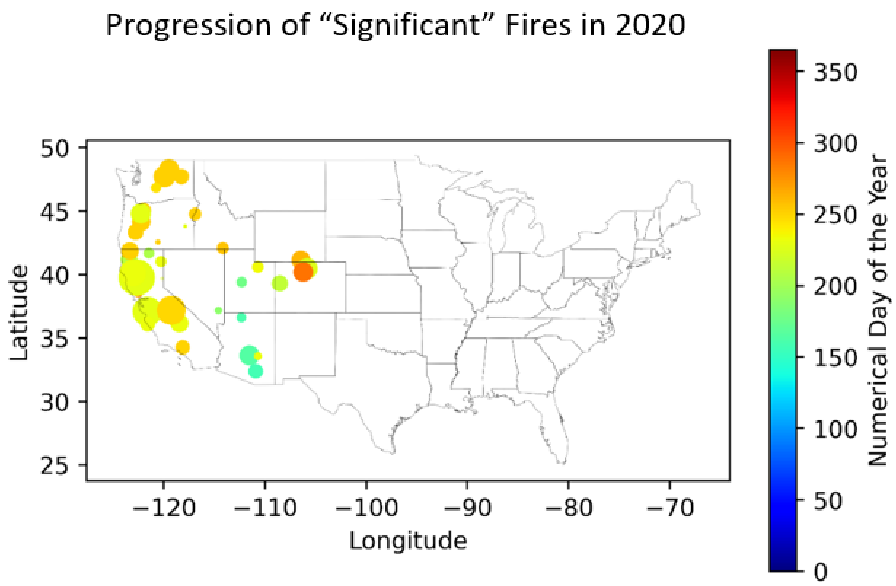

Figure 10: Progression of “Significant” Fires in 2020 (size of marker represents acreage of fire)

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