MONTANA UNIVERSITY SYSTEM RESEARCH INITIATIVE

Autonomous Aerial Systems for Wildfire Management in Montana

Final Report – July 14, 2017

Prescribed fire ignited by UM students. Imagery from DroneFire UAS used to measure fireline intensity.

Submitted by:
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Overview

The MREDI Dronefire project kicked off in January 2016 as a partnership between The University of Montana's Office of Autonomous Aerial Systems (AASO), UM's National Center for Landscape Fire Analysis, Montana businesses, land management agencies, and non-governmental organizations. The project sought to grow a public-private research sector focused on application of UAS to natural resource problems. Its goals were to: (i) stimulate UAS innovation, entrepreneurship and workforce development in the state of Montana focused on fire management; (ii) establish the infrastructure and resources necessary for sustainable autonomous aerial research; (iii) coordinate and guide faculty, staff, students, and business owners in implementation of UAS in an evolving research and regulatory environment; and (iv) increase Montana's competitiveness to take advantage of future opportunities in UAS research and application. Nine specific objectives stemmed from these goals (listed in the project proposal and summarized below in Accomplishments).

As this final report will show, Dronefire achieved its goals and objectives. Significantly, all of Dronefire's partnerships, capacity, technology, and research were developed *after* the start of the project and as a direct result of MREDI. In short, MREDI facilitated emergence of a Montana drone R&D sector focused on natural resources in 17 months of effort with $900K. Half of the initial investment has already been directly returned to Montana in additional grants and contracts ($454K) with another $3.5 million in grants submitted and in review. Beyond direct return on investment, Dronefire enabled formation of three new companies, created 12 jobs, supported 7 students, and produced 25 durable partnerships. The project has positioned Montana to capitalize on future opportunities to grow UAS research and application.

To understand MREDI's unique contribution to economic development in Montana, it is necessary to consider how this Initiative differed from traditional public research efforts. Foremost were MREDI's requirements to partner with the private sector in Montana to solve Montana problems and grow emerging research sectors. These requirements are distinctive and we can say with conviction that none of Dronefire's partnerships would have developed without MREDI. While the benefits that accrue to Montana from more traditional research efforts are substantial, they are usually incidental, untargeted, and directed by the whims of funding organizations that rarely consider economic development or Montana directly. Consequently, there is often little motivation for Montana researchers to work with Montana businesses to solve Montana problems. In the case of Dronefire, MREDI did more to connect University R&D with private enterprise in Montana than a decade of alternatively funded research.

Following, we list major accomplishments of the project, describe long-term impacts, and summarize metrics in terms of leveraged grants and contracts, partnerships, and jobs. Specific details on individual project tasks can be found in the five quarterly reports published for this project. Looking forward, it is worth highlighting some opportunities and challenges for drone R&D. First, there is enormous interest in Montana in the use of drones in natural resource management to gain efficiencies in monitoring, intelligence gathering, and data collection, and to reduce human exposure to risk. There is also a strong sense of opportunity in the Montana business sector. Second, UAS technology is more complex and less mature than most people think. Failure rates are still relatively high and drones are still largely technology in search of problems to solve. Third, the cost of drone technology ranges from economical (~$500) to expensive (>$1 million) but the cost of training and supporting drone operators and data analysts is consistently expensive and it is not yet evident that drones are cost-effective for many applications. Fourth, the regulatory environment is complex, rapidly evolving and represents a barrier to widespread use of drones for commercial purposes. Further, the natural resource agencies that would use drones commercially are struggling to adapt their policies to accommodate them. Fifth, civil-sector drones have not been designed to operate efficiently in mountainous terrain and this shortcoming represents an opportunity for the Montana business sector.

List of accomplishments (by objective)

Objective 1. Establish a field laboratory for UAS research and development where UAS can be deployed consistently to measure and monitor forests and fuels.

- A permanent UAS R&D field laboratory (Droneport) was established at UM's Lubrecht Experimental Forest to test new platforms, sensors, and technology. The Droneport is located behind a locked gate, is fenced to exclude livestock, has large take-off/landing zones and long lines of site, and contains a weather station and windsock. It has hosted fly-ins for three private companies and supported 53 missions. Additionally, six highly-measured field sites were established nearby to facilitate testing of drone-based measurements of forest, fire, and fuel properties. A fixed-wing test area was also established at UM's Bandy Ranch, capitalizing on the area's expanse of flat hay fields. Flexible FAA Certificates of Authorization (described below) have been granted to the Droneport. Collectively, these resources provide a unique locus for drone R&D in Montana.

Objective 2. Contract with Montana's UAS companies to collect and test data from at least ten different platforms and instruments.

- The project contracted with five Montana companies and one Idaho company to collect data from six platforms and nine sensors. Total contracting costs accounted for ten percent of the budget. We tested an additional sixteen platforms and thirteen sensors off contract. Contracts advanced research in thermal infrared mapping of fires, fire weather modeling, wildlife habitat characterization, multispectral remote sensing, and water quality assessment.

- Dronefire developed contract specifications for aircraft, sensors, and software. Seven companies completed the bid process and were awarded contracts pending proof of insurance. We completed at least one mission with five of those seven companies. Coupled with changing FAA regulations, the current contracting process through the State of Montana is not flexible or responsive enough for this rapidly developing industry. Our experience is leading directly to new specifications and requirements for a statewide, multi-vendor Drone Services Contract.

- Dronefire produced durable partnerships with ten companies, including a collaboration between SUAT (Kalispell) and Resonon Inc. (Bozeman) to integrate Montana-made UAS and hyperspectral sensors and to conduct market assessment for UAS hyperspectral services.

Objective 3. Develop two research UAS complementary to private sector systems.

- The Dronefire team designed, built, and tested two low-cost fixed wing systems for mountain flying in forested terrain. The UM Quadranger is a vertical takeoff system (quadcopter) which transitions to horizontal flight. The UM Talon is a conventional fixed wing suitable for mapping large areas. Both systems address shortcomings in existing drone technology for natural resource applications discovered by the Dronefire team. These efforts have resulted in development of high-level, end-to-end capacity to integrate flight systems, electronics, software, and sensors. In addition, the project custom-built a hexcopter in partnership with SUATS (Kalispell) to carry a Resonon (Bozeman) hyperspectral camera along with other heavier payloads.

- We acquired and tested sixteen drone platforms (12 rotor-wing; 4 fixed-wing) and thirteen electro-optical sensors, accounting for 20 percent of the project budget. Eleven platforms and nine sensors are currently available to faculty, grad students, and partner companies and agencies for research through UM's AASO. Two platforms and one sensor are made in Montana. The testing of so many platforms and sensors reflects a divergence from what was initially considered for the project. Reasons for this are threefold. First, it quickly became apparent that for most applications, it did not make sense to invest tens of thousands of dollars in a single UAS given the potential for damage to equipment. Instead, it was more beneficial to spend less on more systems. Second, the lifespans of companies in the UAS industry are currently short, requiring a broader scope for identifying useful platforms and sensors. Third, the demand for UAS in Montana for research, training, and demonstration overwhelmed our ability to deliver with only a couple of platforms.

Objective 4. Train at least 12 pilots, students, and researchers in the deployment and application of UAS.

- The project produced 11 remote pilots. Four pilots with FAA private pilot licenses were trained to fly drones and seven additional pilots were certified under FAA Part 107. Part 107 pilots spent an average of 10 hours each in self-study to pass the FAA exam and trained on UM flight simulators and UAS. Our certificates of authorization (COA) require additional flight and crew resource management training for UM pilots. We used UM's flight and Crew Resource Management (CRM) training protocols which includes simulator time, flight training with a current pilot, and online resources developed though DroneFire.

- DroneFire worked with three companies to develop a UAS training curriculum. Sands Unmanned Aircraft Training (Kalispell) delivered a weeklong, 2-credit course through UM's Department of Physics and Astronomy. The class had eight students enrolled and included a module in GIS mapping applications from drones. Additionally, a UAS module was added to Forestry's remote sensing class (32 students) and twelve students completed an introduction to UAS piloting and data collection class in Geography.

- Twenty-nine UM and MT Tech undergraduates were trained in UAS operations and data processing. Seven graduate students were funded to use UAS in research. Eight technicians were hired and trained to acquire and process UAS data.

- One MS student completed a semester internship with Skyefish (Missoula) to develop automated fire detection algorithms that can be integrated onto machine-learning capable UAS.

- Twelve UM researchers are using drones in research, as a direct outcome of Dronefire.

Objective 5. Develop capacity to operate in the regulated environment.

- Dronefire acquired two Certificates of Authorization (COAs) from the Federal Aviation Administration (FAA) to test drones. The first allows line-of-sight flight in class G airspace nationally below 400 ft AGL during day or night. The second allows flight up to 2000 ft AGL at Lubrecht Forest (day or night) using remote observers to maintain line-of-site. Procedures and protocols for interacting with local FAA flight standards offices and flight control centers have been established, tested, and refined over the course of more than 100 missions. COAs of this sort are uncommon, are difficult to acquire, and provide valuable R&D opportunities for project partners.

- The Dronefire team flew 150+ missions for 10 natural resource partners under FAA Part 107, UM COAs, and Special Use Permits, establishing a documented, reproducible track-record of performance. In doing so, Dronefire has built world-class drone capacity extending beyond the life of the project.

- We developed four novel special use agreements to operate drones on active wildfires and deployed UAS on three wildfires. Although the use of drones in operational fire has so far been limited nationally due to safety concerns associated with UAS in airspace shared with piloted aircraft, we accomplished eight missions. These are some of the first operational missions on wildfires in the United States and represent a huge accomplishment of the project. Rotor-wing platforms were deployed on the Roaring Lion Fire (Bitterroot NF), the Alice Fire (Lolo, NF), and the Barrette Fire (Lolo NF) to test instruments and techniques for gathering fireline intelligence. We achieved four primary objectives: 1) Developed and tested agreements and protocols for operating UAS in the fire environment on federally administered active wildfires; 2) Demonstrated UAS capabilities and flight procedures to fire personnel; 3) Tested performance of small rotor-wing platforms for gathering real-world fireline intelligence in the form of video inspection and mapping of fireline; and 4) Acquired thermal infrared imagery to identify presence/absence of heat. These missions represent an important precedent in fire management and are leading to additional R&D in the fire environment.

- We are currently working with Forest Aviation Officers (2 forests), Regional Aviation Safety Manager, Regional Helicopter Inspector Pilot, and Regional Aviation Officer to develop contract and agreement strategies to facilitate long-term UM UAS engagement with USFS Region One.

Objective 6. Work with vendors to understand how to develop client bases in natural resources and wildfire.

- Dronefire resulted in establishment of three new companies in Montana- Commander Navigation (Hamilton), DoubleC LLC (Miles City), Aerial Solutions LLC (Missoula). These companies connected to natural resource clients through our partnerships with The Nature Conservancy, USFS, Trout Unlimited, Bandy Ranch, Burnt Fork Ranch, and Lubrecht Forest, among others.

- Two Dronefire graduate students were finalists in the Barrett Business Challenge for developing a business plan to use drones to map defensible space for the insurance industry. Dronefire provided the bridge between fire management and research to make the business plan feasible. Negotiations with the insurance industry are ongoing.

- Our research and demonstration with natural resource management agencies is producing operating procedures, workflows, techniques, and technology that ultimately will be used by the private sector and the agencies themselves. Dronefire has provided the stimulus to begin the process of tech-transfer. UM’s FireCenter and AASO are the bridge connecting Montana UAS business with natural resource management applications.

- Dronefire partnered with Skyefish, a Missoula drone manufacturing and software development company to identify opportunities in fire management. We acquired a Skyefish platform and gimbal and used UM FireCenter field observers and technical specialists to provide feedback to the company on flight planning software for use in fire (terrain following; mission interruption and resumption; import of sample points, incorporation of sensor parameters).

- Commander Navigation and Dronefire tested technology and methods for capturing multispectral data on wildfires. The business opportunity is to replace low-elevation. manned helicopter mapping flights with lower risk UAS or manned fixed wing flights. Development of a platform-agnostic thermal imager that can detect and provide coordinates of heat in real-time is necessary. Testing occurred through FireCenter partners on the Bitterroot and Lolo National Forests.

Objective 7. Develop workflows and algorithms to characterize fire and fuels and relate to existing field and remote sensing measurements.

- UAS were deployed on 32 fire missions as part of five experiments (described in the 4th Quarter Report). In partnership with The Nature Conservancy, drones were integrated into prescribed fire operations to: (1) measure total fire energy using a drone-mounted thermal imager; (2) characterize spatially explicit fire effects by mapping vegetation and fuels pre- and post-fire; (3) create high resolution 3-D fuel beds from high density imagery to correlate with fire behavior measurements; (4) document wave properties and vorticity of flaming front using high speed video to validate theoretical fire behavior models; (5) evaluate utility of drones for conducting fire line inspections. Additionally, we conducted eight infrared missions with the Prescribed Fire Science Consortium at Tall Timbers Research Station in Tallahassee, Florida.

- Fire weather data were collected from drone and balloon radiosondes and ingested into the Weather Research and Forecasting Model (WRF) to produce fine resolution forecasts for site-specific fire weather applications. Novel accomplishments include development of UAS mission protocols for radiosonde measurements, integration of measurements and models, and automation of data ingestion directly from aircraft to WRF. Research is ongoing.

- We developed and tested terrain following methods to allow drones to negotiate complex terrain without pilot intervention.

- Current infrared cameras include both long and short wave imagers that are integrated on rotor wing UAS; with integration onto VTOL fixed wing in progress. We developed both laboratory and field-based procedures to calibrate IR imagery into energy and temperature values and designed, tested and are using camera filters to optimize performance at high temperatures encountered on wildfires (which are typically hotter than OTS IR cameras can handle (they saturate).

- We quantified the limits of rotor wing under current FAA regulations for collecting coupled overhead and oblique imagery on wildfires (up to 3km from launch point, 30 minute duration) along with maintenance and operating costs. We have limited these missions to “site-specific” applications covering relatively small areas, but where timing and flight plan flexibility are key these mission are highly reproducible for monitoring/repeat coverage instances. Fixed-wing aircraft provide longer dwell times (up to 1 hour), lower per hour flight costs, but higher development and maintenance costs and less flexibility in flight planning. Our VTOL fixed-wing is uniquely suited to mountain flying with limited take-off locations, and is able to generate 5 acres per minute on a mapping mission with 75% overlap. Both kinds of platforms can be flown manually or autonomously; mapping is most efficient in autonomous flight with fixed wing platforms.

- As part of platform and sensor evaluation at the Bandy Ranch (Ovando), we acquired high-resolution multispectral imagery of (center pivot) irrigation practices. In consultation with the Ranch manager, we have modeled water use efficiencies and shortcomings; directly resulting in modifications to amount and timing of water application.

- We have an on-going project monitoring aspen restoration activities on Burnt Fork Ranch (Stevensville) and are acquiring monthly imagery across the growing season to measure aspen regeneration rates and growth-and-yield in thinned stands. Outcomes will include a protocol for long-term monitoring (annual to semi-annual) using UAS imagery while keeping costs at or below field-based alternatives.

- Dronefire developed methods to model fuel beds in 3-D from close range drone imagery. Fuel beds were subsequently burned in prescribed fires and fire characteristics measured with drone-based thermal imagers. Spatial gradient analysis is being used to quantify fire-fuels gradients to understand fuel controls on fire behavior. This ongoing research is foundational to study of fuel treatment effectiveness.

- Photogrammetric workflows were developed and tested to derive 3-D pointclouds and orthometric maps from drone imagery. We built a 28-core processing workstation to handle photogrammetric workflow. New hardware reduced processing time by a factor of six (from 48 hours to 8 hours for each Lubrecht Droneport test dataset).

Objective 8. Formulate policies and procedures for UAS operations.

- Dronefire developed and published institutional practices for acquiring and operating UAS within the Montana University System in consultation with UM Offices of Risk Management and Legal Services. The Dronefire project was structured to transition seamlessly to UM's Office of Autonomous Aerial Systems (AASO) at project end. All of its institutional policies and procedures currently appear under the aegis of AASO (http://www.umt.edu/aaso/). We have: registered aircraft and acquired tail numbers; completed operations manuals for all aircraft; developed FAA compliant flight and maintenance reporting standards; published procedures for radio lost links, lost communication, and flight emergencies, and tested protocols for daisy-chaining observers to maintain line of site; formalized procedures for contracting with the private sector; produced a sales and service structure and pricing for MUS-wide use of UAS platforms and sensors in a post-Dronefire environment.

- We have developed special use agreements for wildfires on both private and public lands. Private lands agreements have tiered from extant research agreements (including cost share agreements). Public lands access is highly restricted and dependent on controlling agency policy. Given that much of our work is on National Forest System lands, we have had to pioneer "Special Use Agreements" whereby UM requests access to NFS property. These agreements are the first ever in the Region, and incorporate performance metrics, liability and safety mitigation, and checklists to ensure that all necessary stakeholders and line officers are aware of UAS operations. Operational controls are tightly regulated, and include NOTAMS, flight following with interagency dispatch, and appropriate notifications to relevant aviation and safety personnel. We are working with the USFS to extend these use agreements to applications outside of fire; ranging from forestry, soils, water, and wildlife to NEPA planning processes and vegetation inventory and mapping.

Objective 9. Solicit research from at least five other research groups within MUS to stimulate diversification of application of UAS to natural resource problems.

- Twelve faculty are engaged in UAS research on fire behavior, fuel measurements, weather forecasting, forest growth and yield, watershed assessment, and forest health. In partnership with researchers from many agencies, organizations, and universities, Dronefire flew operational infrared missions with the Prescribed Fire Science Consortium, tested radiosondes, characterized snow melt, monitored trumpeter swans, prairie dogs, and sage grouse, mapped lichens, developed 3-D models of fuel beds, and measured fire energy. The breadth of effort reflects expansion of Dronefire technical capacity as well as growth in interest from the research and land management communities.

- Examples include:
    - Wildlife Biology – assessing caribou habitat in Alaska using UAS.
    - Ecology – measuring spatial patterns and timing of snowmelt in mixed conifer forest.
    - Tourism – UAS impacts on recreational users of public lands.
    - Restoration – Ninemile Placer Project restoration monitoring.
    - Hydrology – water flow and flooding in the Bitterroot River.
    - Wildlife Biology – osprey nest inspection and trumpeter swan monitoring
    - Wildlife Biology – mapping and census of prairie dogs and sage grouse.
    - Forestry – conducting regeneration surveys using UAS.
    - Wildlife Biology – thermal characterization of micro-climates within trees for insect dynamics.
    - Hydrology – sediment connectivity and morphologic/vegetative controls in stream channels.
    - Forestry – classification of forest structure.

Long-term impacts and future activities

Dronefire has created a critical mass of UAS R&D in Montana focused on the natural resource sector. Nearly all of the research initiated during the project is ongoing and will continue for the next 2-5 years. Approximately 40 percent of the awarded external grants and contracts ($180K) related to this project are for new research. Additional grants for $3.5 million are under review. We will continue to work with the three companies started under Dronefire and maintain ongoing collaborations with 12 private and public sector partners.

Future research is focused in two primary areas- fire and fuel characterization and fire weather forecasting. Examples include: (1) Collaborative research (includes one UM PhD student) with USFS Rocky Mountain Research Station on firefighter safety zones. We are using rotor-wing aircraft fixed with multiple infrared cameras to quantify radiant heat emitted by wildfires. These measurements are being used to determine separation distance guidelines so that fire crews can objectively establish more effective safety zones; (2) We are flying ultra-high resolution video cameras on small format UAS to image active fire fronts. This video imagery is being used to measure changes in flame geometry associated with convective transport of heat and propagation of the flaming front; (3) We are collaborating with SUAT (Kalispell); Quantum Weather, Saint Louis University, DOE, and the USAF to develop instruments and methods for collecting atmospheric weather data from drones. These data are being used to develop near-real time, site-specific forecasts for wildfires.

Dronefire principal investigators, UM AASO and the National Center for Landscape Fire Analysis, have built capacity to sustain drone R&D for several years. AASO is responding to requests to consult on statewide public agency and private sector best practices for UAS operations policies and procedures. We are currently pursuing a funding model for expanding AASO to represent public agencies statewide. Additionally, AASO is fielding dozens of requests for demonstration flights to assess sensor and software capabilities for partners such as US Forest Service, US Fish and Wildlife, and The Nature Conservancy. While new sensors are coming online at a fast pace, private companies often cannot afford to purchase, calibrate, and train on an entire line of sensing capabilities including Infrared, Multispectral, and Hyperspectral cameras without knowing demand for such capabilities. AASO continues to demonstrate platforms and sensors to partners and has been documenting market interest to share with the private sector.

MREDI funding had a significant and timely impact on UM's National Center for Landscape Fire Analysis (FireCenter). Funded as we were entering our 16th year as an MUS Center, the project came into our portfolio at a good time; three things lined up: 1) it occurred at a time when intervening research obligations were such that we could commit time and resources to support the project, 2) fire season 2016 was relatively benign and our external commitments were manageable, and 3) in FY 17 we were engaged in the process of writing a new 5-Year Center Scope of Work. Thus for a comparatively low cost to DroneFire, the FireCenter staff were able to envision, plan, and execute the work needed to meet the needs of DroneFire/MREDI without compromising our core research portfolio.

Strategically, our Center is oriented around programs in *Fire and Fuels Sciences*, *Remote Sensing and Geospatial Technology*, and *Science Delivery*. At the outset we strived to make the objectives of DroneFire correspond with our program investments. In practice, MREDI extended our thinking, our capacity, and our relationships with external stakeholders in significant ways.

Fire and Fuels Sciences

FireCenter has been continuously engaged in mapping and quantifying wildland fuels. Whether to support resource assessment (inventory), hazardous fuels reduction, or decision-support associated with wild land fire incidents, fuels are a primary driver of hazard, risk, and opportunity within the field of wildland fire management and community response planning and mitigation. The science of fuels characterization has most needed repeatable, quantification of fuel amount, arrangement and condition to support intervention *at a fine scale*. We have developed custom fuel models using field and remote sensing based methods though innovative use of drones and UAS. We have acquired data sets on on-going hazard fuel projects, have mapped wildfire incidents, and have completed two major fire field campaigns in the southeastern US.

We have received over $400,000 in extra-mural funding to support these fuels projects and the DroneFire capacity added significantly to that effort.

- We are recognized as a national leader in the use of UAS for fire and fuels characterization.
- We have completed two proposals to apply UAS to fire/fuels research.
- We have three graduate students working with UAS data.
- We have partnered with two national Forests, two NGO's, a private research forest in the southeastern US, and the USDA Fire, Fuels and Smoke Program.
- We have developed custom technology to complement OTS hardware for thermal infrared remote sensing, flight planning and image acquisition.
- We have extended OTS software to support geometric and radiometric calibration of UAS imagery.
- We have developed customized but extendable calibration techniques that allow users to convert "pictures" to "research grade data."

Remote Sensing and Geospatial Technology

- The FireCenter has traditionally performed three primary forms of remote sensing:

1. Thermal infrared sensing of radiant energy emitted by active fires.
2. LiDAR (both terrestrial and airborne) for fuels and vegetation characterization and mapping.
3. Optical imaging targeted to the causes and consequences of fire severity.

- Many of our approaches also involve data fusion; whereby we integrate multiple types or forms of remote sensing to assess the biophysical fire environment. Flexibility extant in DroneFires's suite of vehicles and sensors ensures that data fusion techniques can be more fully explored.
- While UAS-based approaches will not overtake other platform/sensor combinations, the capacity added through DroneFire is significant:
    - We can now control and optimize the timing, areal extent, sensor payload, and spectral resolution of remote sensors to maximize benefit/efficacy.
    - Much work has been put into platform alternatives. We have identified operational envelopes for "small format" work using mostly rotor-wing UAS and large area collections based on vertical take off and landing (VTOL) UAS.
    - New software has been developed for data collection as well as post-collection processing that is compatible with standard GIS or desktop mapping applications; making the ingest of UAS data more seamless.
- Future work with more capable sensors will continue to be a focus of the FireCenter's UAS program of work.
- In particular we are excited to assess longer wavelength sensors in the near, mid, and long wave portions of the infrared spectrum. Historically these wavelengths have proven valuable; but have not seen significant R&D by UAS manufacturers.
- As mentioned, radiometric calibration of sensors is mandatory if scientifically sound results are to be expected. With both optical and infrared cameras we now have standard operating procedures in-place to calibrate in house sensors.
- Geometrically, UAS based data have been a challenge to process. The resolution elements (pixels) in close-range UAS imagery are orders of magnitude more resolved than with more traditional forms of remote sensing. We now have protocols in place that use a combination of a priori ground control points, on-board GPS and INS/IMU data streams, and post-processing software that enables us to place images into real-world 3-dimensional (mapped) feature space.
- Given our new-found mapping capability we can now perform multi-date collections and while finely resolving location, and can also derive 3-dimensional point clouds from overlapping imagery.
- Several flight planning and mission scoping softwares are in hand to support the variety of missions that we perform. Historically many of these programs were not optimized for terrains unlike the mountainous, forested landscapes that constitute our operations areas. We now have terrain-aware protocols and flight optimization routines that have dramatically reduced data acquisition errors and inefficiencies. We also have decreased the number of re-flights needed to collect high quality imagery (perhaps by as much as an order of magnitude).

Science Delivery

- FireCenter has worked closely with both new and existing stakeholders on the application of UAS to quantitative remote sensing.
- We have a network of over 20 peers at UM who are at work with us on use of UAS.
- We have worked closely with two national forests to fly UAS, collect imagery and demonstrate the efficacy as well as documenting costs associated with these new techniques.

- On both the Bitterroot and Lolo national forests, we developed and signed 3 Special Use Agreements that enabled us to conduct both fire and project flying. In the case of the roaring Lion, Alice, and Barrette fires we were the first to fly UAS on wildfire for these forests.
- We are continuously engaged with forest aviation officers to ensure appropriate use and documentation for UAS that are flown over National Forest System lands.
- We increasingly recognize that overcoming regulatory constraints as well as the overhead costs of developing and deploying UAS capacity are the primary challenges to further use of these tools. By investing in demonstration of UAS with partners like the TNC and the Lolo National Forest, we are path finding in ways unanticipated at the outset of DroneFire.
- We have greatly expanded the application arenas within which UAS can be applied. For example, our work on stream channel mapping, snow cover monitoring, and large area forest inventory and assessment are new areas for future collaboration and fund raising.
- Further work with AASO is warranted so that UM in general and the DroneFire team specifically can be a conduit for lessons learned that will make it easier for new adopters to realize the potential for UAS.

Informal and Pedagogical Impacts

- We are working efficiently within the regulatory environment.
- Are well partnered with AASO who is the UM proprietor for UAS evolution.
- Have carded pilots and remote pilot certifications.
- Standard operations and maintenance record keeping and reporting.
- Cost and fee schedules that allow us to fully scope cost/benefit of proposed collections.
- As FireCenter develops a new 5-Year program of work, supported by the National Fire Plan, we intend to add a new program element focused on the evolution of UAS in our research and application portfolio.
- We will maintain and operate a suite of capable platforms and sensors, and are actively engaging with external sponsors to seek opportunities for furthering this work.

Summary Project Metrics

Total additional grants received (4 grants for $453K)
Total additional grants in progress (5 grants for $3.5 million)
Number of partnerships formed (16 private sector and 9 public sector)
Number of new Montana businesses created (3)
Patents awarded or in progress (0)
Commercial products developed (0)
Jobs created (12)

Detailed Project Metrics

Total additional grants received (4 grants for $453K)

- UAS for Fire Behavior Characterization, Rocky Mountain Research Station $50K
- Fine-grained Wildland Fire and Fuels Characterization for Fire Modeling, Western Threat Assessment Center, $40K
- Aerial Manned/Unmanned Flight Services, Adelos – USAF, $20K
- Fire and Smoke Model Evaluation Experiment, Joint Fire Sciences Program, $199K

- Active Fire Remote Sensing, National Fire Plan, $145K

Total additional grants in progress (5 grants for $3.5 million)

- Sediment Connectivity and Morphologic and Vegetative Controls, National Science Foundation, $511K
- Biophysics of Plant-Insect Interactions, National Science Foundation, $887K
- UAV-Radiosonde Weather System Commercialization, Murdock Trust, $171K
- UAV-Radiosonde Weather Systems, Montana Board of Research and Commercialization Technology, $130K
- Demonstrating How UAV Systems Enhance Fire Management, ESTCP Environment, $1.8 million

Number of partnerships formed (16 private sector and 9 public sector)
Private Sector (16)

- Sands Unmanned Aircraft Training (SUAT) LLC, Kalispell
- Commander Navigation, Hamilton
- Skyefish, Missoula
- Birds Eye of the Big Sky, Missoula
- RDO Equipment Company, Missoula
- Chilton Skis, Missoula
- DoubleC LLC, Miles City
- Aerial Solutions LLC, Missoula
- ADVASO, Idaho
- Trout Unlimited, Montana
- The Nature Conservancy Montana and Georgia
- Tall Timbers Research Station and Land Conservancy, Florida
- TESLA Foundation
- Quantum Weather, Missouri
- Resonon Inc., Bozeman

Public Sector (9)

- Bitterroot and Lolo National Forests, Montana
- Missoula Fire Sciences Laboratory
- Bandy Ranch, Ovando
- Burnt Fork Ranch, Stevensville
- Lubrecht Experimental Forest, Potomac
- Saint Louis University
- USFS National Technology Development Program – Aerial Firefighting Use and Effectiveness
- US Fish and Wildlife Service

Number of new Montana businesses created (3)

- DoubleC LLC (aerial service provider)
- Aerial Solutions LLC (aerial service provider)
- Commander Navigation (UAS integration)

Patents awarded or in progress (0)

- In partnership with Sands Unmanned Aircraft Training (Kalispell), UM's AASO has submitted a proposal to the Murdock Foundation's Commercialization program for an UAS radiosonde system. Result of funding is potential spin off company and 1-2 patents.

Commercial products developed (0)

Jobs created (12)

<u>Private Sector</u>

- Red Castle Resources
- Burnt Fork Ranch
- Aerial Solutions LLC
- DoubleC LLC

<u>Technician</u>

- Glacier National Park
- Montana Space Grant

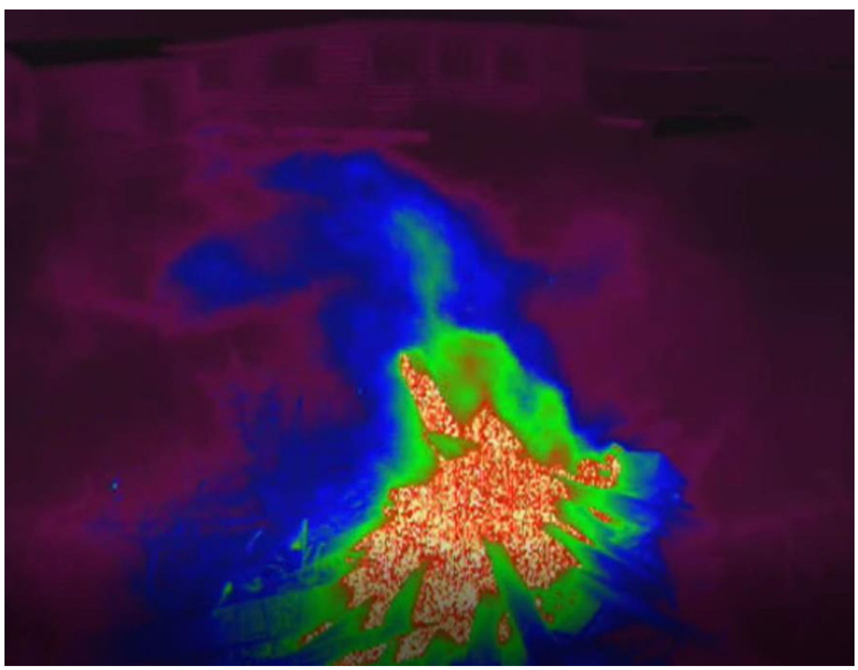
<u>Student</u>

- UM College of Forestry and Conservation
- UM Department of Geography

<u>Research Scientist/Engineer</u>

- UM National Center for Landscape Fire Analysis
- UM AASO

Pictures



Characterizing thermal energy produced in pile combustion at the Lubrecht Forest flight area using ground-based sensors (top) and from drone (bottom). The bottom image is from a drone-mounted thermal infrared camera sensing at 8-14 micron wavelengths.

Overview of launch site on Roaring Lion Fire, Bitterroot National Forest.

DroneFire technician preparing vertol FF6 platform for launch on prescribed fire in Georgia.

Researchers collecting coincident *in situ* and drone-based thermal data. Sensors in the fire are being used to calibrate thermal imagery from the drones.

Researchers light ignition strip to carry fire into highly instrumented field plots. Drones are being used to characterize thermal energy from multiple look-angles and elevations.

Drone with thermal camera hovering over field plot.

Calibrating thermal camera on burning slash piles at Lubrecht Experimental Forest.

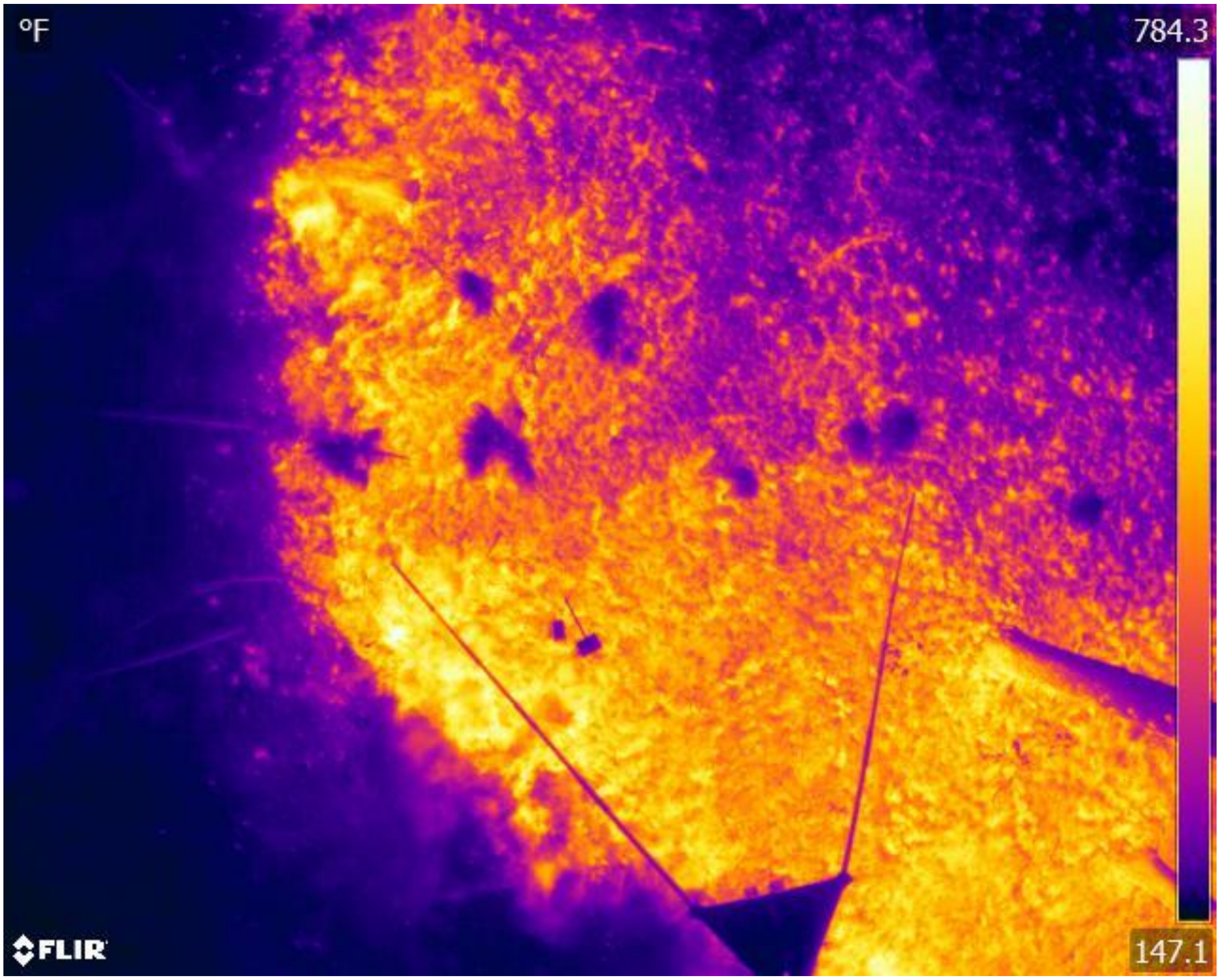
Drone and firefighter.

A UM drone flying with a University of Florida drone on a prescribed fire in Florida.

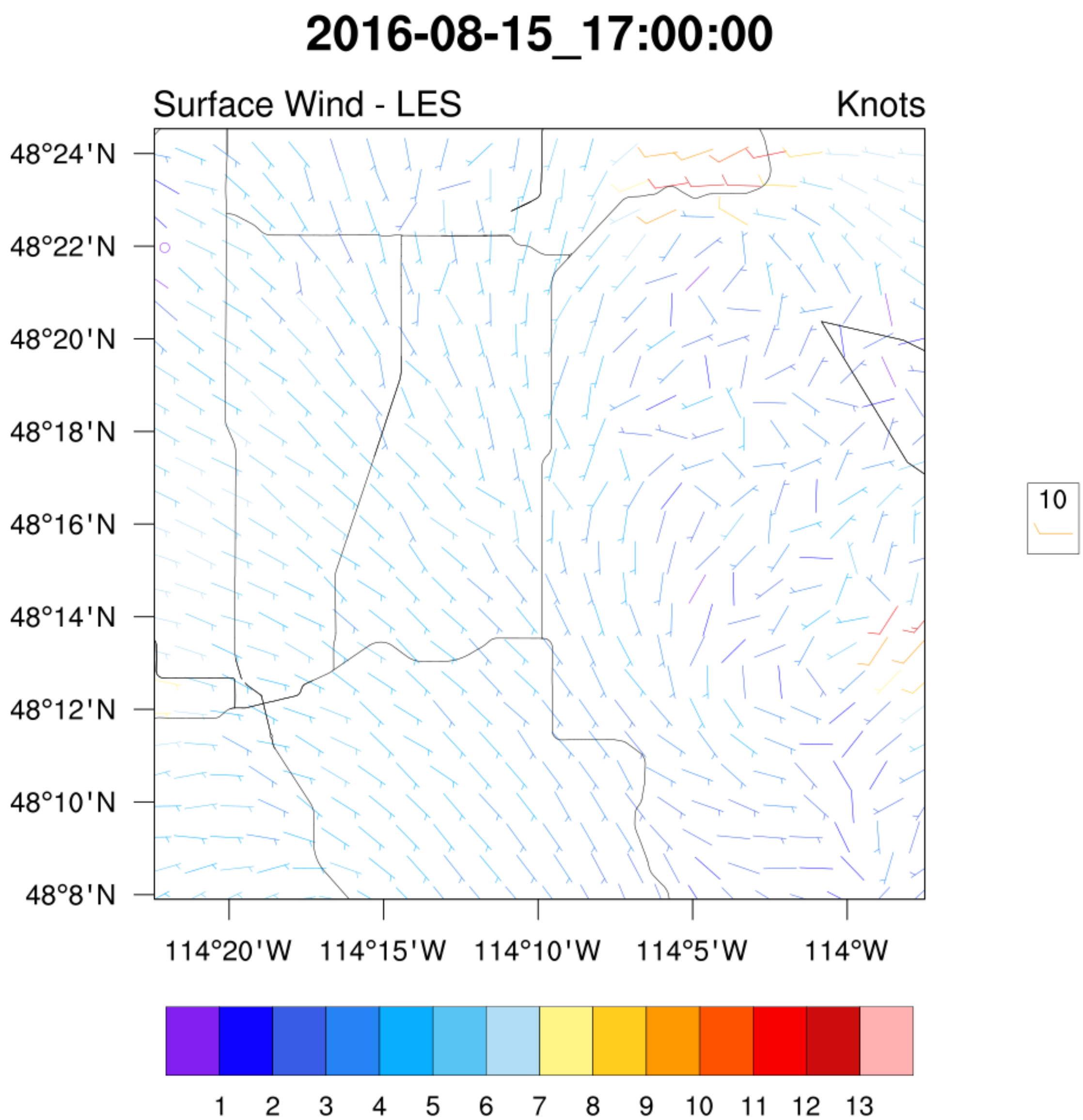
Dronefire and Nature Conservancy staff preparing to image prairie dog towns with thermal IR camera near Malta, MT.

Testing the vertol Quadranger transition from hover to forward flight at UM's Bandy Ranch near Ovando, MT

Dronefire pilot discussing mission with fire manager in Florida.



Thermal IR image of fire burning through a research plot. The rectangular and triangular features are *in situ* sensors measuring fire energy.

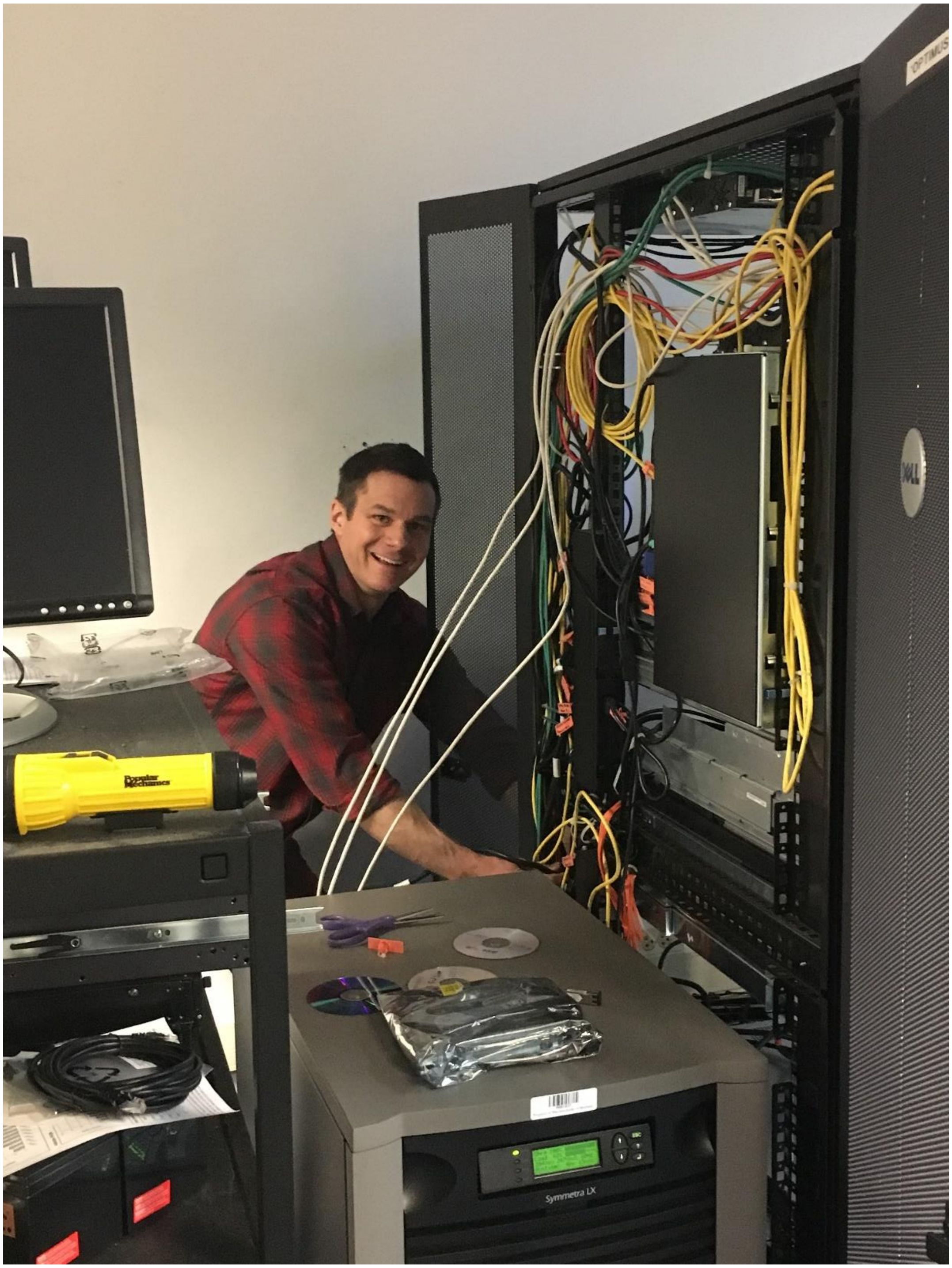


Modeled wind field from drone measurements.

Recreational pilot flying DJI Phantom on UM oval at ‘fly-in’.

Students work with DJI Phantom suspended below balloon at UM 'fly-in' highlighting some of the current regulatory absurdities in UAS flight operations- photo by Todd Goodrich (UM photographer).

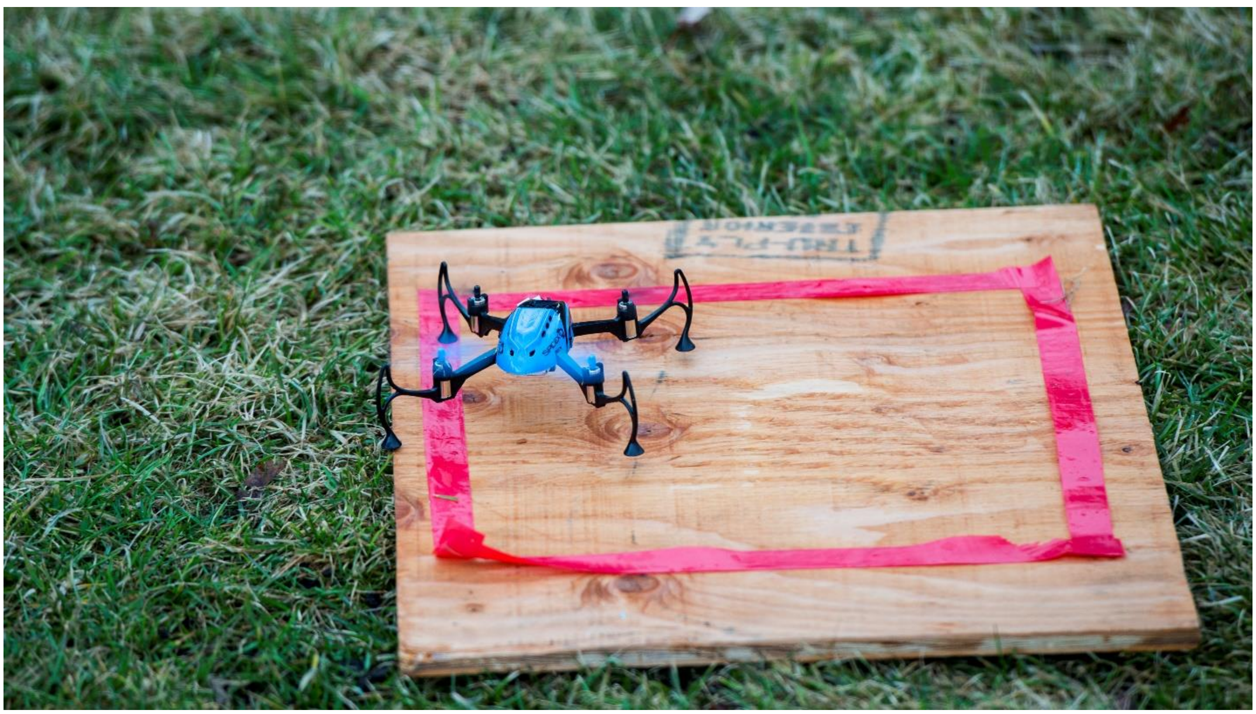
Skyyfish engineer assembling drone at Missoula facility. Skyyfish is a project partner in hardware/software manufacturer and integration.



Configuring the cloud computing cluster at UM for DroneFire, March 2016.

Testing and flying in UM's Schreiber Gym.

Student test-flying drone in net on UM oval- photo by Todd Goodrich (UM photographer)



Student landing drone on target at UM ‘fly-in’- photo by Todd Goodrich (UM photographer)

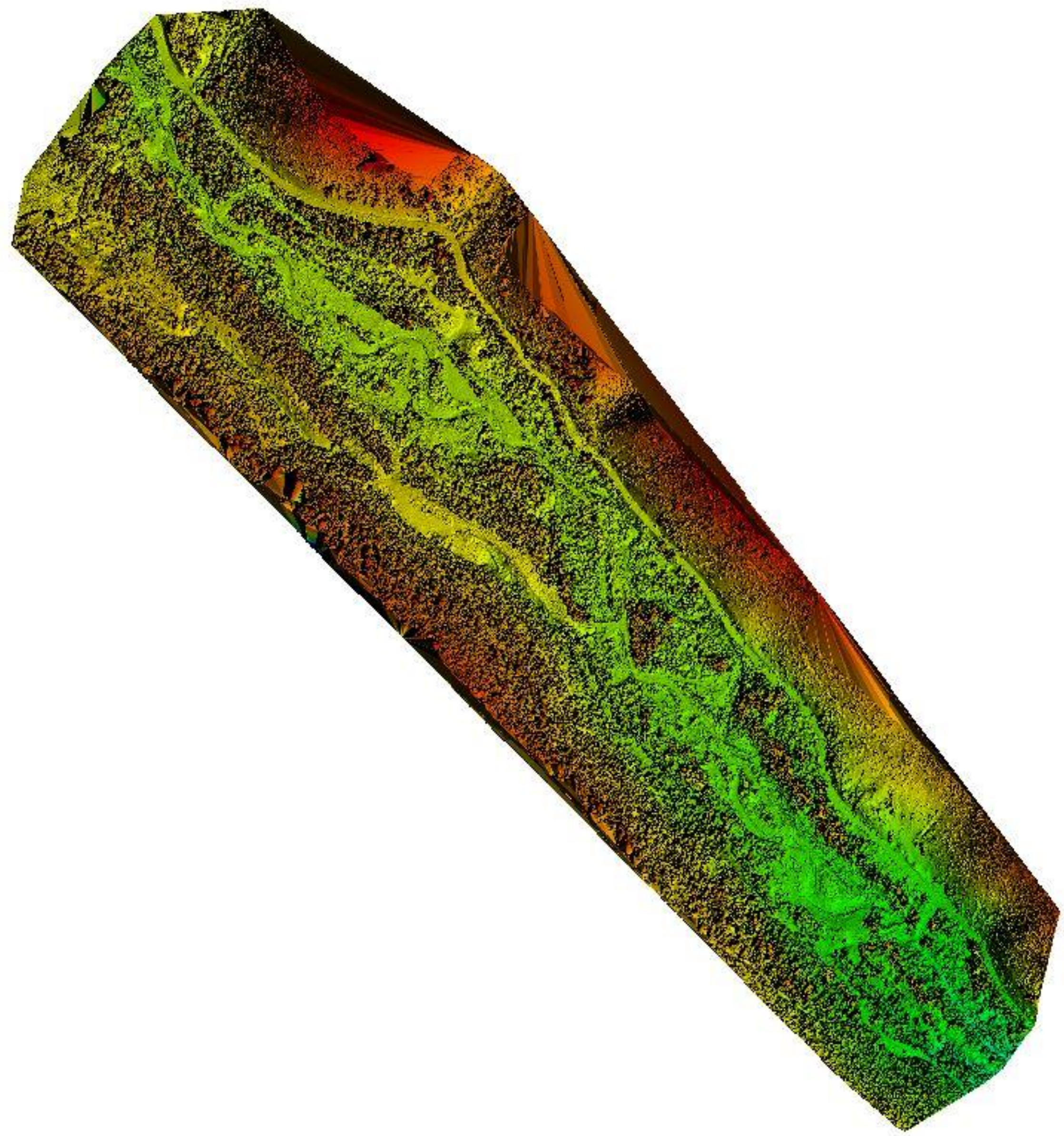
Student teaching citizen how to fly at UM ‘fly-in’

The practice flying net set up on the UM Oval.

Steep learning curve - broken rotors after test-flight.

Students prepare for flight within forest canopy to image fuel plots in the Fire-Fire Surrogate Study at Lubrecht Experimental Forest.

UM researchers testing meteorological sensors on drones with SUATS enginners at the SUATS flight facility in Kalispell.



Digital surface model of the Ninemile Placer Restoration area. Data values are within ±15 cm relative to GPS ground control. Colors show object heights resolved to 0.5 m. Measurements are being used to examine vegetation and topographic controls on water flow in restored stream channels.