Project TetraNet : Augmenting Wildfire Mitigation With Rapid-Scale Deployment of Low-Cost Nanosatellite Networks Driven By Computer Vision Analysis

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Scienteer Project # 148238

Introduction

Each year, millions of acres of land are lost to the devastating effects of wildfires, contributing to damages of population health, the ecosystem, and global desertification. And as nearly 85% of regional wildfires are caused by human related activities[1], forest fire mitigation is a social responsibility for all people. However, local firefighters struggle to receive constant updates on wildfire progression and often lose opportunities to control small fires that transform into devastating blazes

In response, this project proposes a fully integrated system of low cost, suborbital terrain monitoring devices to augment wildfire mitigation. **Project TetraNet** offers advantages to existing solutions in the major areas:

(1) Replacement of networks in regions that lack proper infrastructure
(2) Low cost and easily scalable
(3) Low latency connection for rapid updates
(4) Rapid deployment via specialized weather balloons
(5) Highly intelligent with an onboard computer vision system to guide local officials

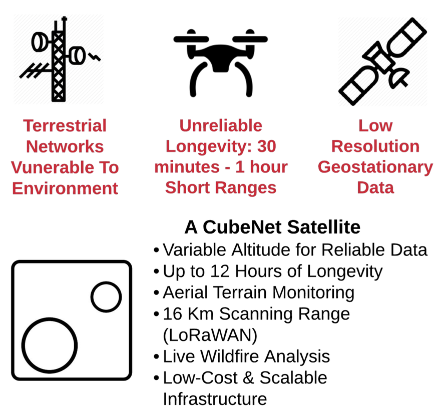


Fig. 1: Advantages of Proposed Suborbital Nanosatellite Network

Climate Change and Wildfires

Amidst the progression of global warming and rising temperatures, wildfires have become increasingly rampant and widespread: a global record 10 million acres of land burned in 2020 (Figure 2), contributing to the displacement of millions of people and inflicting irreversible damage to population health and the environment. Wildfire mitigation is crucial to keep these numbers under check.

Figure 2. Top Five Years with Largest Wildfire Acreage Burned Since 1960

Year	Acres burned (millions)	Number of Fires
2020	10.27	58.3
2015	10.13	68.2
2017	10.03	71.5
2006	9.87	96.4
2007	9.33	67.8

Source: NIFC.
Note: Number of fires in thousands.

Wildfire mitigation calls for detecting premature fires and suppressing them before they develop into large scale wildfires. However, local officials struggle to keep up with the rapid progression of wildfires due to unreliable communications that depend on slow reporting, counteracting any mitigation technique. Therefore, the proposed project's goal is to empower firefighters and local officials with TetraNet devices for surveillance and monitoring.

Engineering Goal

The aim of Project TetraNet is to offer a low cost, highly reliable system that can provide real time information on wildfires and terrain to local officials. The project can therefore be separated into three critical categories: reliability, performance, and full-stack integration.

Reliability

Forest fire mitigation requires constant updates which arrive at a predictable manner. The TetraNet devices must therefore deliver data without compromising latency and network lapses. In addition, rapid deployment is allowed through the weather balloon platform.

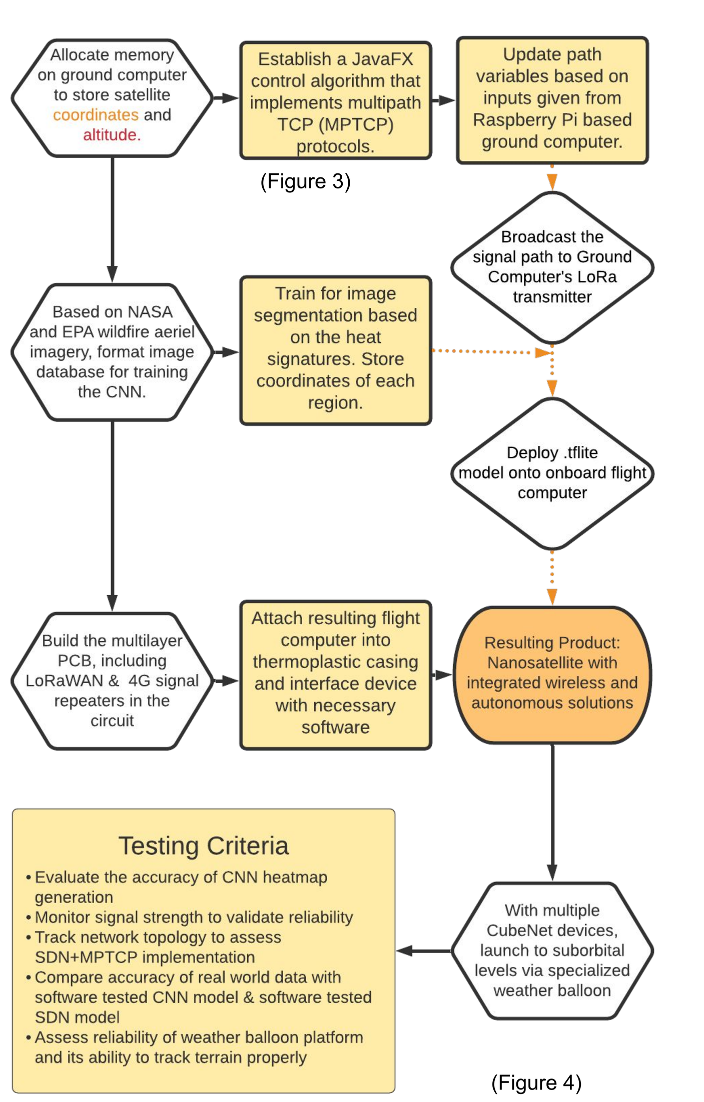
Performance

Data analysis is critical in the case of wildfires. To assist anyone who may use these devices, a TetraNet satellite is equipped with an onboard computer vision model. With predictive analysis, the computer can detect new wildfire spurts that may have gone unnoticed.

Integration

Capturing data and presenting information to the end user is crucial for transparent communication. The integration with the JavaFX program will allow users to understand and analyze unfolding conditions while also taking the advantage of a live aerial view.

Materials & Methodology



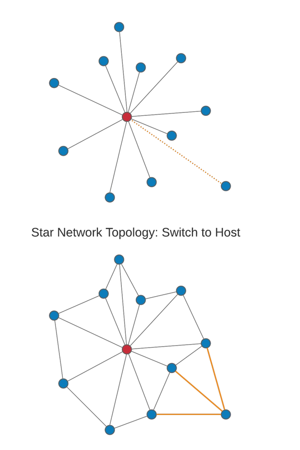
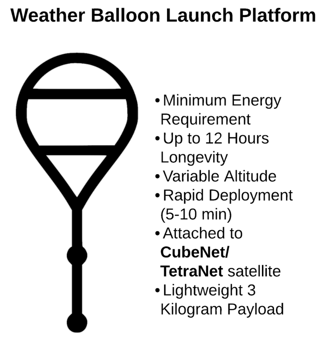


Fig. 3: Mesh Networks
A multipath protocol is necessary to enable all satellites to be interconnected, maximizing connected devices.

Weather Balloon Launch Platform



Maximum Altitude: up to 35,000 meters
Fig. 4: **Aerial Demonstration**
Weather balloons offer quality data with highly efficient equipment.

CV Terrain Analysis

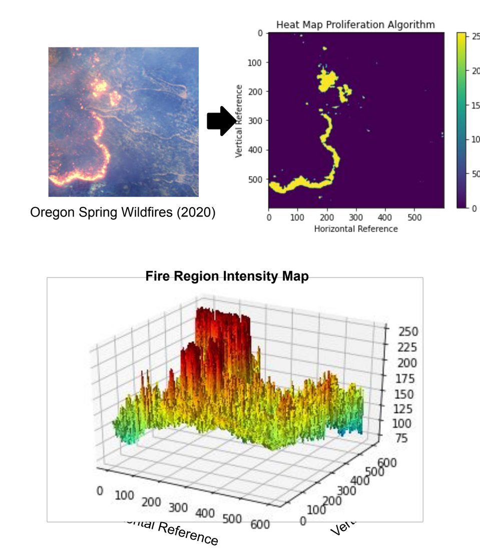
Section I: Convolutional Neural Network Validation

For accurate wildfire detection, TetraNet devices operate on an overhead view of the terrain. As a result, the Computer Vision model is trained on similar conditions based on the National Aeronautics and Space Administration (NASA) and the United States Environment Protection (EPA) wildfire satellite imagery databases. Data is selected from wildfires that have occurred in temperate zone regions of California, Washington, and Oregon since 2015 and are all stored in the form of raster/ vector data. A total of 1,000 images have been selected and trained to identify key features that influence wildfire spreading factors:

1) Terrain topology and features
2) Current weather-related patterns i.e., temperature and wind bearing
3) Vegetation land mass and area
4) Altitude and air pressure
5) The time of the day

The CNN network functions under an image segmentation algorithm, allowing the trained model to detect wildfires down to a 15-meter area. As a result, the model is accurate and retains key features of wildfire behavior patterns. Extracted features include coordinates of the wildfire, intensity of the spread, and the likelihood of the wildfire's future direction (Figure 4 & 5). All predictions are based on the segmentation algorithm.

Fig. 4: **Convolutional Neural Network Heat Map Algorithm: Image Segmentation**



The extracted convolutional neural network visually represents key features dealing with relative heat maps.

Section III: Real World Terrain Analysis

In real world testing, a TetraNet device evaluated terrain over the Texas- Oklahoma border, an area that is commonly susceptible to wildfire breakouts during summer seasons. In its first test flight, a single TetraNet device was able to evaluate terrain for as far as 35 kilometers, as shown in Figure 5. In this specific test, the density of vegetation is analyzed to calculate wildfire risk in local areas.

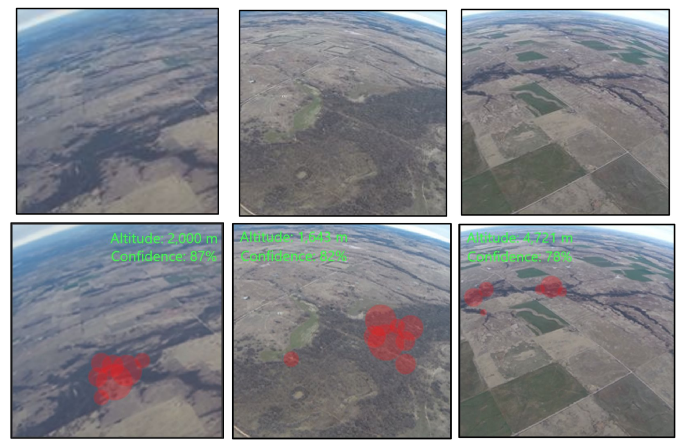


Fig. 5: **Real World Application: Live Terrain Monitoring**
Model Trained to identify dense, high risk areas prone to future wildfires.

Being able to predict future wildfires is crucial to mitigation. Local authorities require a better understanding of an ever changing landscape in order to counteract wildfires.

Fig. 6: **Monitoring terrain over the Texas- Oklahoma border.** Each nanosatellite can travel up to an altitude of 35 kilometers. Camera is facing downwards.

Section III: Model Performance

The resultant CV model is trained on over 80 epochs and resulted in an average accuracy of 84.6%, taking into account the predicted vs. ground truth of wildfire distribution.

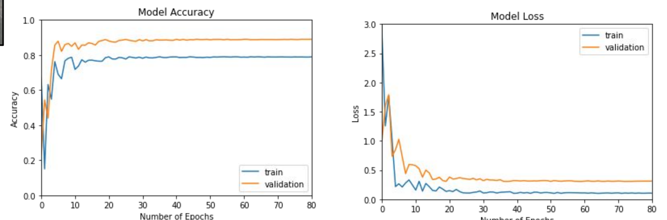


Fig. 7: **CNN Model Accuracies.**
Validation accuracy is up over 84%, while its loss function stabilized at 0.48- both values over 80 trained epochs.

Designs

The Nano-Satellite Encasing was prepared using high-performance thermoplastics and thermoplastic composites rather than conventional polymers in order to produce accurate models that are strong and display malleable qualities without being brittle. These parts comprised of the following instruments: In order to account for the inertial forces acting on the balloon in the vertical axis, the aerodynamic drag and lifting force was calculated using the following equation.

$$F_{lift} - G - \frac{1}{2}\rho v^2 S C_s = 0$$

ADCS (Attitude Determination and Control Subsystem): TetraNet satellites employ various sensor modules in order to actuate positioning.
1) BMP180 module to determine barometric related readings based on spatial region from earth.
2) GPS Spot Tracer was installed which relayed signals from TetraNet to contemporary satellites.

The ground layer PCB which is connected to 8 external solar panels acting as the power generator for the circuit. Each solar panels comprised of ~10 photo voltaic cells arranged in a configuration that produced a maximum 40 volts of electricity (estimated by the solar cell efficiency equation) which was stored in 3 lithium ion rechargeable batteries, so the solar panels could generate an infinite power source that could fuel a TetraNet mission during the day and last for the entirety of the night in the sky.

Fig 8: **TetraNet Satellite propelled by Helium filled Latex Balloon**

Fig 9: **Illustration of the TetraNet bus, its subsystems and sensor complement**

$$\eta = \frac{J_s V_{oc} F}{P_t}$$

$\eta = Solar\ efficiency$
$P_t = Light\ power\ density$
$J_s = Current\ density$
$F = Fill\ factor$

Software-Defined Networking

Wildfire mitigation demands fast and reliable communication in order to enable efficient responses. Therefore, the TetraNet network must operate with minimum latencies over large distances. A software defined algorithm is proposed in response to the requirements. Multipath TCP takes advantage of a communication device's multiple IP addresses, simultaneously performing tasks with the operation of multiple networking interfaces- TetraNet devices utilizing the 4G band and LoRaWAN modules. MPTCP allows the devices to minimize time processing data and output terrain analysis at faster rates (Figure 10).

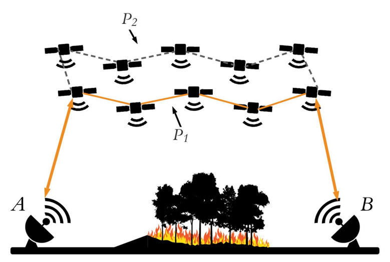


Fig. 10: **SDN & MPTCP Protocol**
Lowest Cost Operation enables MPTCP to direct signal over P_1 as opposed to P_2.

Overall network performance proves to be reliable over existing control protocols, including the standard TCP and ECMP protocols. As a result, TetraNet's network architecture is significantly faster than existing protocols that default in current telecommunication systems.

In order to analyze the effectiveness of the nanosatellite communication, key features are analyzed including throughput in Kbps, packet loss rates, and the spreading factor vs code rate relationships (Figure 11). All indicators are related to the distance between ground and flight computers for effective analysis over the performance of the networks.

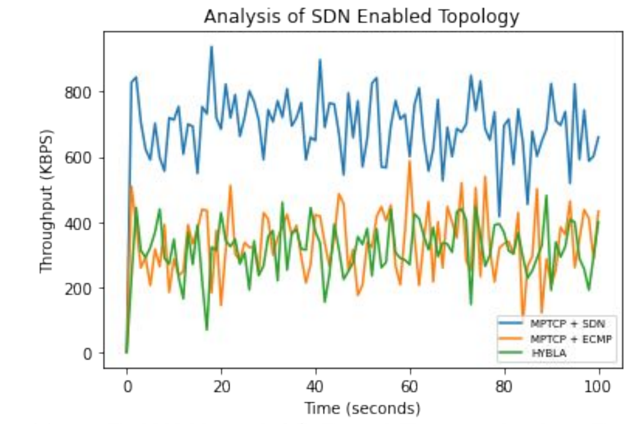


Fig. 11: **LoRaWAN and 4G Band Transmission Rates**
Average throughput for the SDN transmission is at 721.632 Kbps*. TetraNet's SDN implementation performs well.

TetraNet Performance

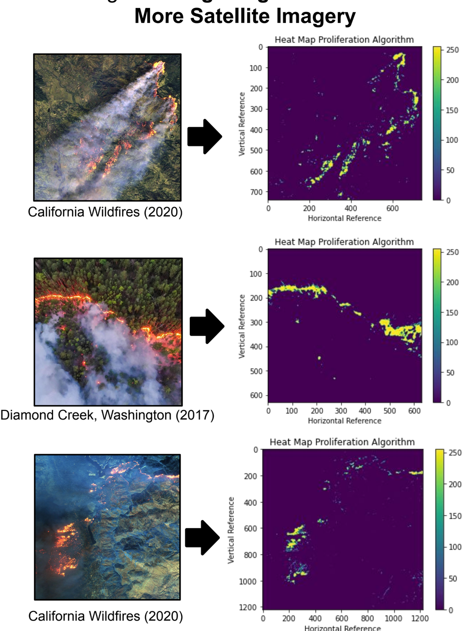


Fig. 12: **Image Segmentation on More Satellite Imagery**

Neural Network Analysis

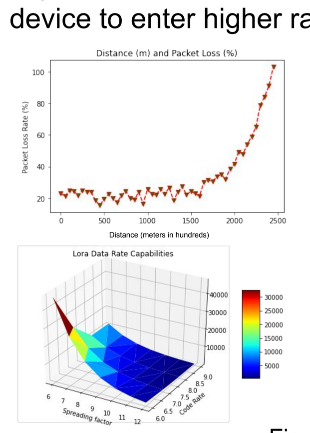
Reflecting on the model's performance, the CNN performs with statistically reliable accuracy in both detecting ongoing wildfires as well as predicting sites with high risk. The model is well acclimated to temperate region analysis, being able to detect the zones of wildfires across the NASA and EPA databases (Figure 12).

$$u^{k+1} = \frac{1}{m}\sum_{l=1}^{m}\left(I - mrA_l(u^k)\right)^{-1} u^k$$

Fig. 13: **AOS Image Segmentation Algorithm.**
The CNN is trained on a semi-implicit AOS segmentation algorithm. AOS offers lower cost coupled with a higher efficiency when compared to explicit image segmentation methods. Stability τ < ∞ denotes a high accuracy throughout epoch turnovers.

Connectivity and Data Rates

For reliability, performance is measured on indicators of throughput and network capacity. As the device reaches a range of 25 kilometers altitude, the packet loss is at 100%. Further improvements to the LoRa module will benefit the device to enter higher ranges of altitude.



With the increase of the network's spreading factor, the amount of time the message will broadcast, the code rate will decrease significantly. The resulting effect allows the devices to optimize communication with more battery saving options.

Fig. 14 **Networking Capabilities**

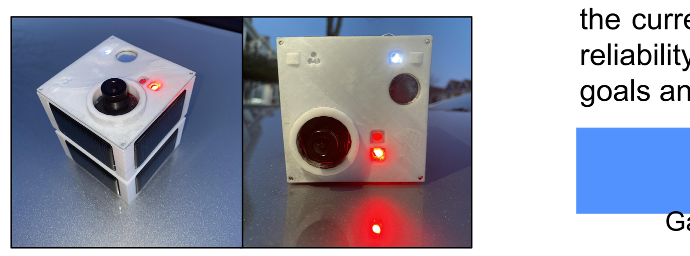


Fig. 15: **A TetraNet Nanosatellite**

Reliability Analysis

The device can deliver a dynamic view of terrain along with accurate analysis. With the advantage of launching on a weather balloon platform, counterweights will allow the nanosatellite to travel to any desired altitude, allowing researchers and officials to gather reliable data for the spread of wildfires. The device may last up to 12 hours if anchored to the ground. Otherwise, a TetraNet satellite may last up to 5 hours of flight time depending on the counterweights set on the launch platform.

Data Analysis

In summary, the performance of the TetraNet devices indicate a better-than-expected performance. The key indicators test network connectivity and terrain analysis features, both relevant to the functionality of TetraNet. The following represents the key results attained from the data:

Networking Results:

1) Throughput stabilizes at a value of ~720.217 Kbps within 10km range (Figure 11)
2) Beyond 25 kilometers, packet loss maximizes at 100%
3) LoRaWAN module connects 72% of the entire flight path (~ 25 km)
4) 4G band connects 23.21% of flight path (~10 km & Figure 16)
5) For majority of flight observation, connection is retained.

CV Performance:

1) The image segmentation algorithm resulted in an 84% accuracy on validation test set
2) Real world image analysis averaged around an 82% confidence on detecting wildfire prone areas
3) The models accurately computed the coordinates and intensities of progressing wildfires
4) Overall, CV proved capable of both tracking and monitoring instances of wildfires

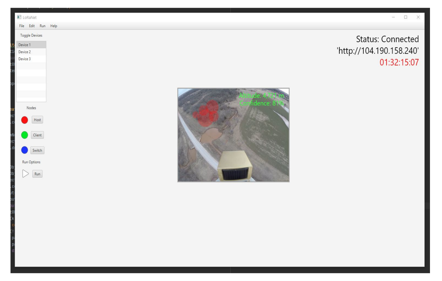


Fig. 16: **Streaming Data To Java Application**
Video is compiled onboard the flight computers and sent via 4G bands to the ground. Data streams for altitudes up to 10 kilometers.

Discussion

Project TetraNet can accurately capture and record data on a local and regional scale. The device provides high resolution data for local officials and improves peoples' current understanding of their geography. However, the data also suggests several areas of improvement as well. Networking still requires connectivity along all attainable altitudes and more data is needed for improving on the current CV model, especially data that is attained from the nanosatellite itself.

Reliability

TetraNet devices can monitor terrain with predictable viewing angles, yet certain environmental variables are out of the experiment's control (Figure 17). Overall, however, the delivery and clean data for CV analysis satisfy the engineering goal's requirements.

Performance

More data is required to validate TetraNet's capabilities on tracking wildfires. The trained CV models performed well on a theoretical basis, yet it has not been applied to real wildfire events. Improvements on performance therefore relies on further testing and experimentation utilizing self generated data.

Software Integration

Connectivity and network performance is measured through the JavaFX platform. The nanosatellite can stream data up to 10 km and send atmospheric readings via LoRa for 25 km. To improve connectivity, higher energy radio modules are required.

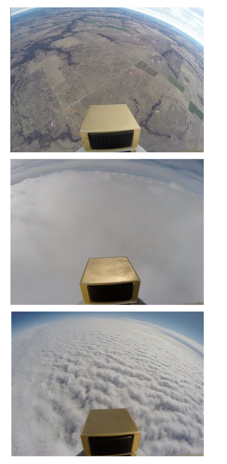


Fig. 17: **Environmental Variables Limitations on Observable Altitude.**

Future Research & Applicability

Recently, there has been a movement against forest fires, spearheaded by California's deployment of drones to suppress fire propagation. Several involved companies are turning to geostationary satellite data despite most susceptible regions lacking access to such analytics; additionally, traditional methods of terrain analysis are severely time-consuming. In response, Project TetraNet presents an alternative through cheap, quick, sustainable equipment that gathers vital data in times of emergency. By integrating natural phenomena, like helium's properties, with a compact multi-sensor, TetraNet foregoes traditional costly answers to maximize efficiency.

One avenue for progression is furthering the connection stability and upgrading sensors, both of which had room left for improvement. Given TetraNet's large relevance in this increasingly fire-prone world, it could also be tested on an active wildfire, potentially opening connections to other fire-fighting services.

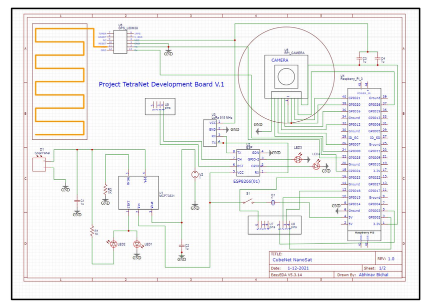


Fig. 18: **TetraNet V1.0 PCB Design**
The future satellite will host its own development board with programmable I/O pins

Conclusion

While TetraNet nanosatellites provide usable data for terrain analysis, there still remains further research over different environmental circumstances. The lack of real-world wildfire data (other than the images based on NASA and EPA databases) and uncontrollable environmental settings means that the device cannot track terrain over different atmospheric conditions well. However, the current testing results prove that the concept model can deliver data with statistically proven reliability measures and performs predictably. Ultimately, the project has proven its engineering goals and is ready for the next phase of improvements on data capture and signaling capabilities.

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CV: A Heruistic Approach for Terrain Analysis

Analyzing image databases from NASA MODIS satellite imagery as well as EPA aeriel databases is a good indicator of the performance of TetraNet data. To begin the data analysis process, an image segmentation algorithm is utilized to extract important features from wildfire data. The following images demonstrate the results of the convolutional network's data.

$$T_{j+1} = 0.5(\mu_{j,ob} + \mu_{j,bg})$$

Fig. 1: Adaptive Thresholding:
Detects pixel energy values via pixel energy values derived from background normalization. The resulting value will derive key features above each threshold value.

Fig. 2: Washington State (2019)

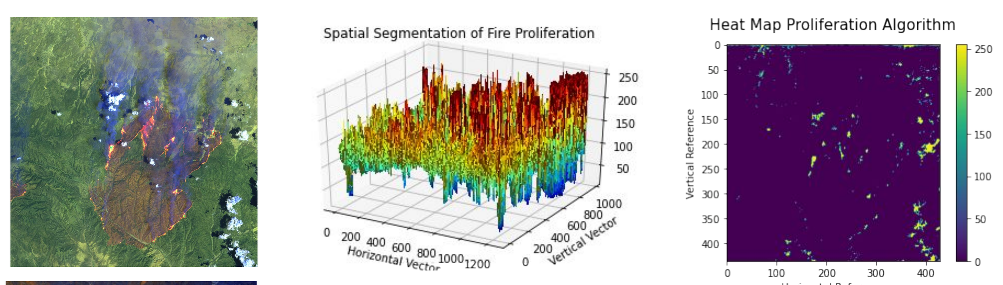


Fig. 3: Southern California (2020)

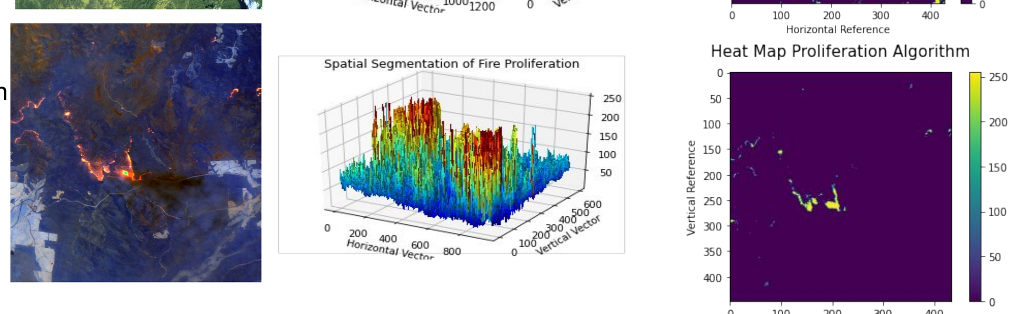


Fig. 4: Washington (2020)

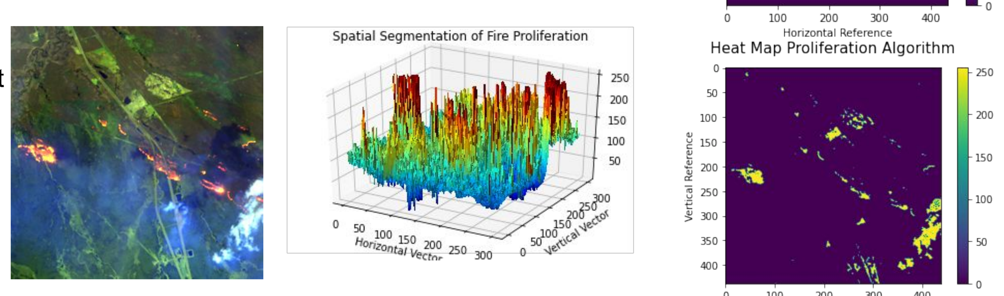
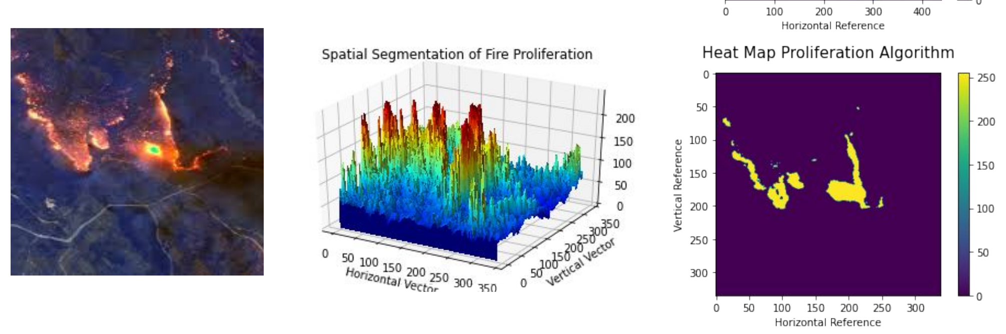


Fig. 5: Southern California (2020)



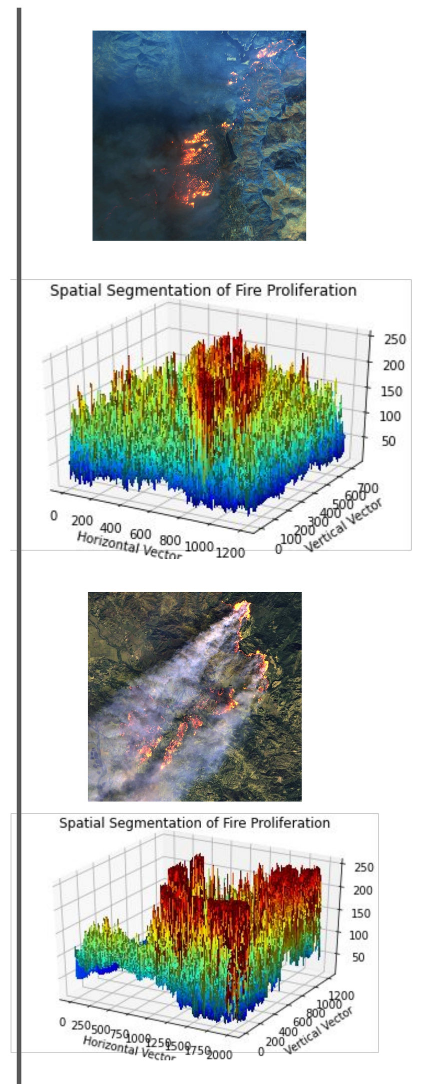


Fig. 6 More Generated Heatmaps

Observed Trends Based on the Past Decade's Accumulated Wildfire Data

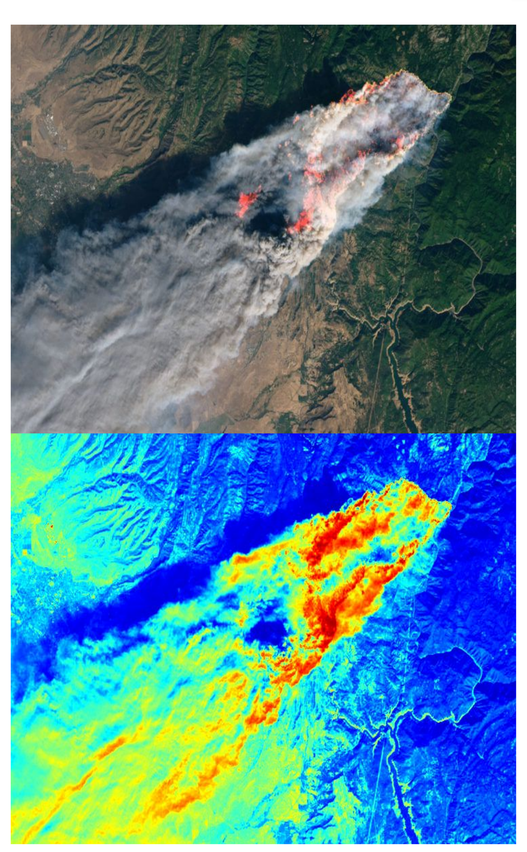


Fig. 7: Heat Map View of Satellite-Position Wildfire Image. Used to Predict Direction and Intensity of FIre.

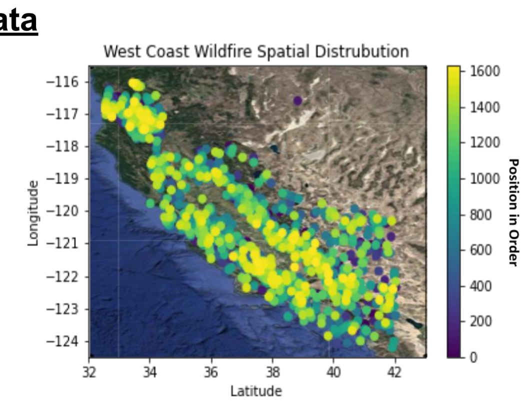


Fig. 8: California Fires Over the Past Decade Organized by Geographic Location and Order of Appearance.

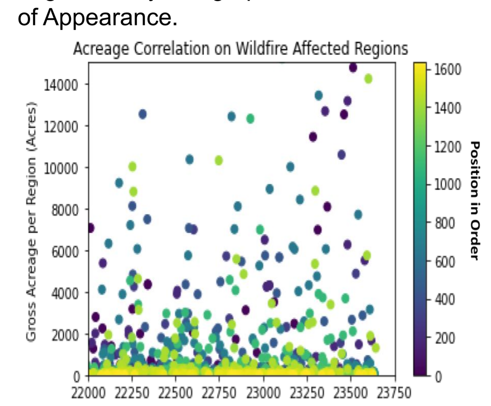


Fig. 9: Acres Affected by California Wildfires Based on Geographic area, labeled by Order of Occurrence.

Fig. 10: Applied CNN for wildfire prone area tracking- confidence increases with altitude.

Launching Sub Orbital Satellite

Fig. 11: Graphical Representation of the Engineering Goal, Relating and Describing the Three components: Reliability, Performance and Full-Stack Integration.

$$V_b = \sqrt{\frac{\pi D^3(\rho - \rho_B)g/6 - (m_{B+mP})g}{C_D \rho \pi D^2/8}}$$

Fig. 12: Equation is Used to Calculate the Ascent Rate of the TetraSat Balloon When it is in Its Steady State (Generally Windless, Unobstructed). CD = Coefficient of Drag, mB = Mass of Balloon, mP = Mass of Parachute, g = Acceleration of Gravity, D = Diameter of Balloon, ρ = Mass Density of Air, pb = Mass Density of Balloon

Nanosatellite Tracking and Flight Path

Fig. 13: At an Altitude around 35 km, the Latex Balloon Ruptures Due to the Helium Gas Inside of it Expanding. At this point, the parachute deploys and brings the device down safely.

Tracking the nanosatellite is essential to coordinate attained data with geographical points of reference. The nanosatellite's altitude, atmospheric conditions, and GPS coordinates are all logged throughout the flight for a better understanding of the flight path and necessary improvements for future desings. The following reveals the test flight path's data:

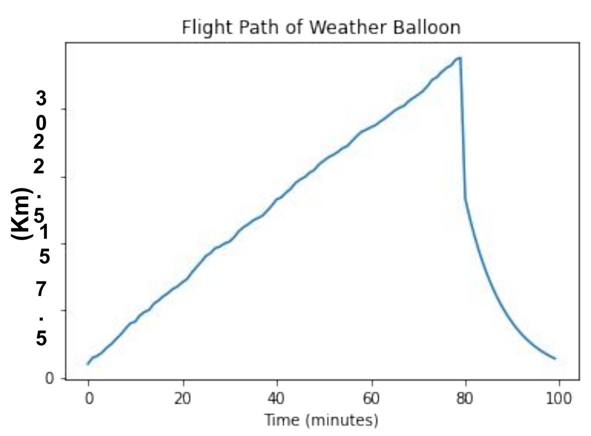
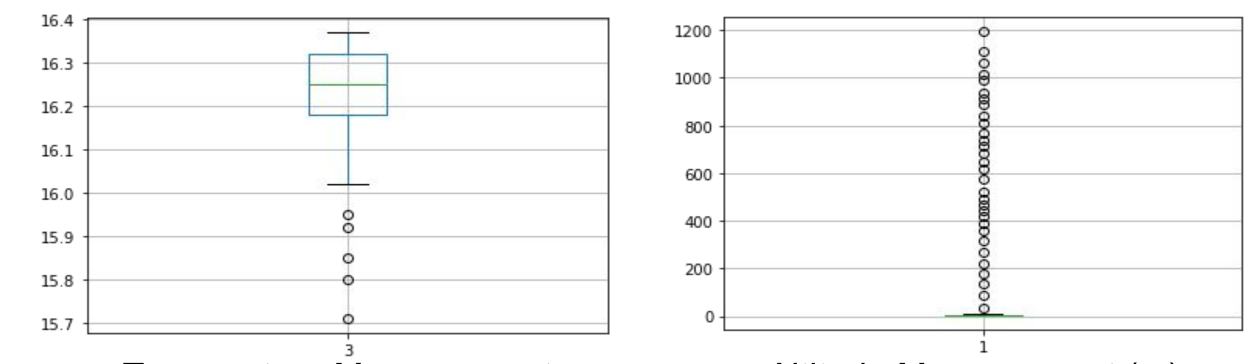
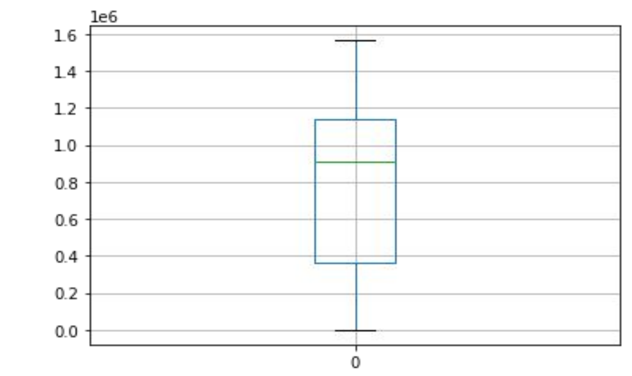


Fig. 14: Altitude vs. Time:



Temperature Measurement

Altitude Measurement (m)



Atmosphere Measurement (Pa)

Fig. 16: Temperature, Pressure and Altitude data Gathered Live from Launched TetraNet Weather Balloon. The Connection was Maintained Well Following Launch, Allowing the TetraNet Prototype to Travel an Extremely Long DIstance While Sending Data.

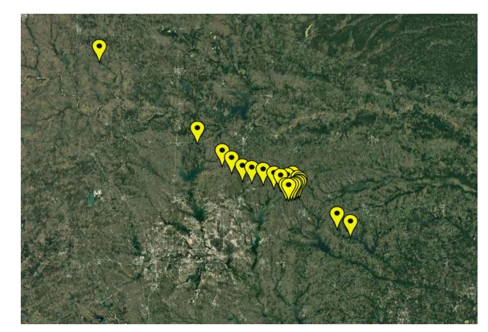


Fig. 15: 3 Hour Flight Path of TetraNet Balloon From Tracker (Top to Bottom). Areas Without Markers have Either Vertically Out-ranged the Ground Devices or had Velocity High Enough to Travel Far distances..

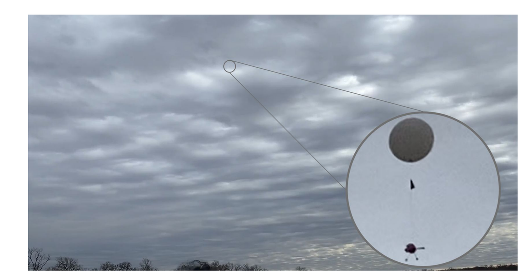


Fig. 17: TetraNet Weather Balloon Distance a Few Minutes Immediately After Launch, Still Connected to Ground Computers and Supplying Information.

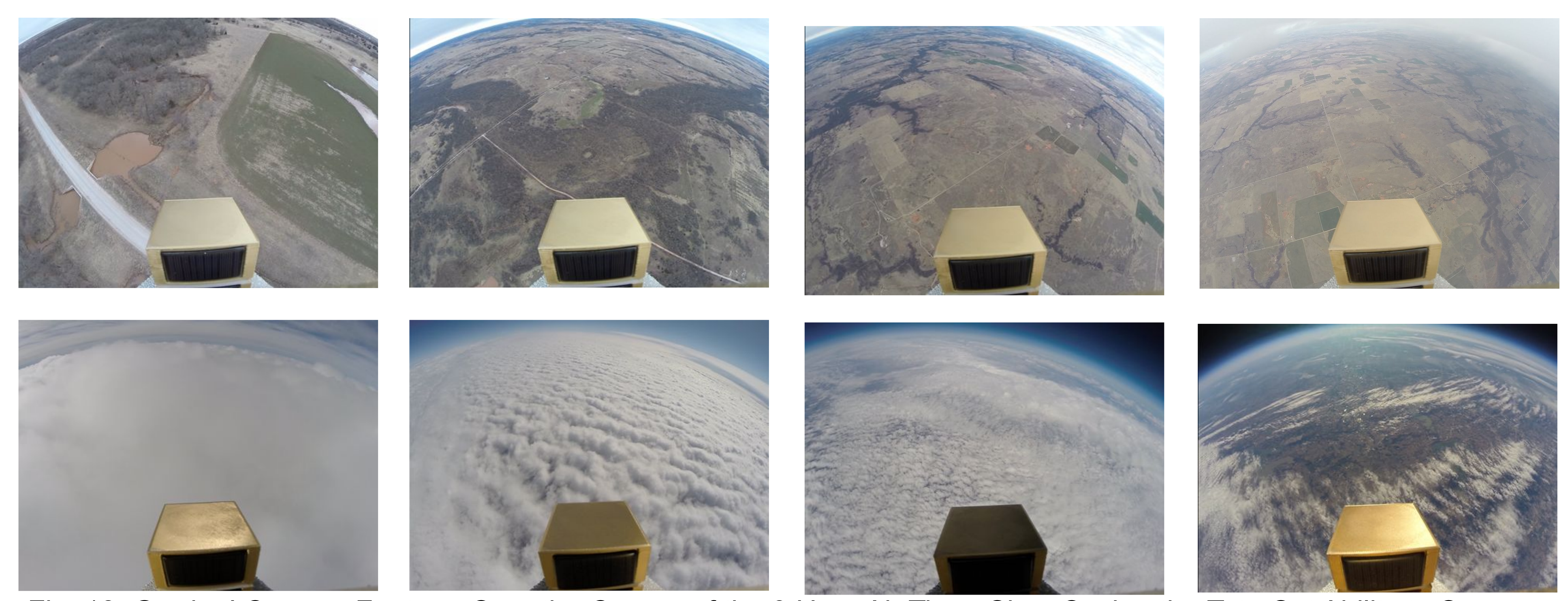


Fig. 18: Gradual Camera Footage Over the Course of the 3 Hour Air Time, ShowCasing the TetraSat Ability to Survey Large, Spaced Areas at All Needed Altitudes. This Means the TetraSat is Capable of Both Detailed Reconnaissance of Small Areas and Broad Surveying of Large Areas.

Launch Platform Engineering

The payload shell was constructed using 2 semi-globes of lightweight polystyrene, with a platform clamped in-between (weighing in about 394 grams in total). While the bottom section had 4 plastic mini-tunnels drilled into 4equally-spaced positions along the lip to securely attach the payload (any higher section would strain the adhesive).In order to provide landing stability, base supports were installed through the bottom to the center of the payload to decrease wind-drag of the ascent.

Fig. 19: Materials for the launch of the TetraSat (Model 1) Weather Balloon making use of Helium (He), a 600 gram Latex Balloon and the designed Payload Container, housing additional parts.

Fig. 20 : Coating TetraNet Prototype I Chassis in Paint, After Printing its Designed 3D Model.

Fig. 21: TetraNet Prototype II under development using PPCB architecture.

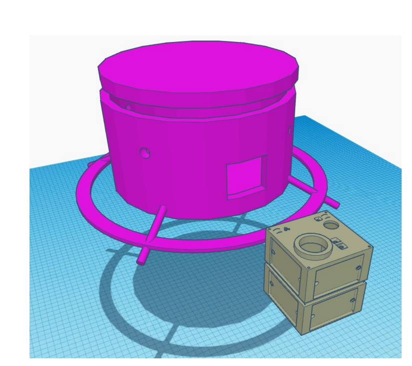


Fig. 22: Early Prototype of the TetraSat Payload Structure, Created Using 3D Modeling Software. The 3D Model of the TetraSat was Printed and Used for trials.

Fig. 23: Finalized Construction of the Payload Carrier, Protecting Batteries from the Cold and Supporting Camera, GPS and TetraSat

Multipath Enabled Networking

The networking aspect takes into consideration each individual device and its performance. The simulations is trained on NS3 networking engine based on the Linux- based Ubuntu 20.10. The resulting data is a reflection of the behavioral patterns for TetraNet device networking as well:

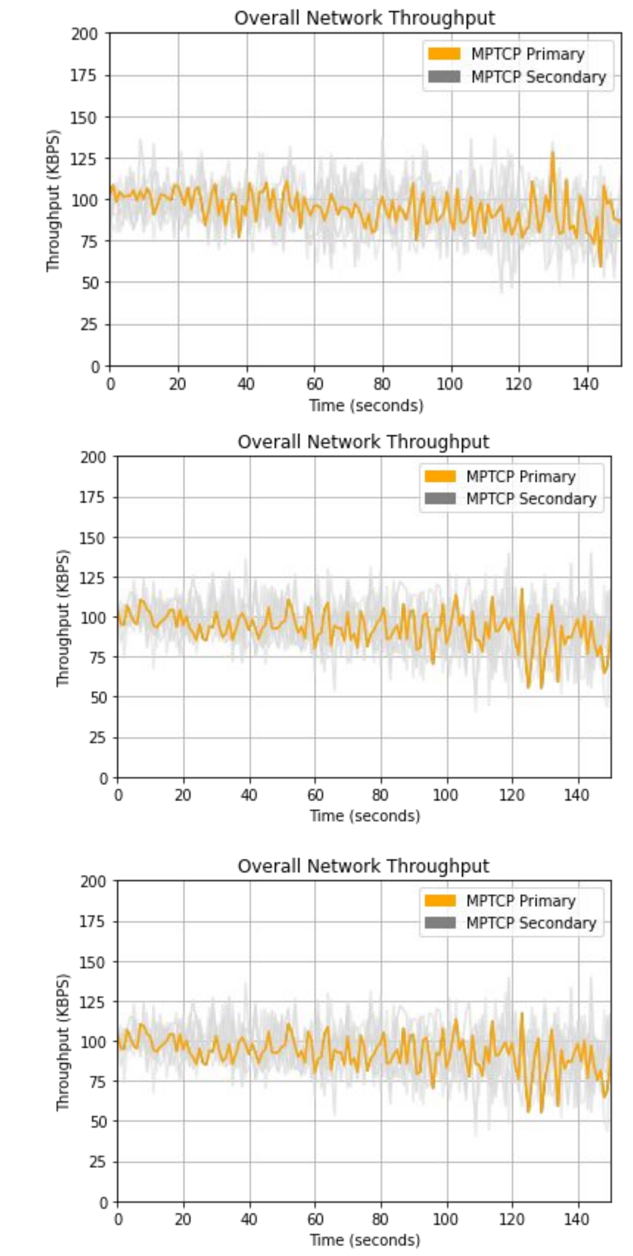


Fig. 25: Average throughput across all network devices (NS3). 101.3 Kbps at minimum loads; 78.1 Kbps on max.

$$R_b = SF * \frac{\left[\frac{4}{4+CR}\right]}{\left[\frac{2^{SF}}{BW}\right]} * 100$$

Fig. 24: Equation Resulting in LoRa Module Connection Data Rate, Using Spreading Factor (SF, Plausible: 6-12), Code Rate (CR, Plausible:1-4) and Bandwidth (BW, 10.4, 15.6 20.8, 31.25, 41.7, 62.5, 125, 250, 500)

Handovers case in point :

When handover (when one satellite comes into the signalling range while the other leaves) occurs, the ground terminal locates both satellites and will begin to apply the unused interface associated with A2. Which will now prepare to establish new subflows to B1 while the previous two subflows are still maintained. A will first send an ADD_ADDR message to inform B of the new address, and then the messages will somehow arrive at S' and forwarded to the controller. The second algorithm in the image above is now run to handle the message, doing more stuff that will find the path that is not only disjoint from existing paths but also as short as possible.

During this handover, the link between (A2,B2) will be turned into backup mode, with data transmission not available until the link of A and S1 is down and leads to the failure of (A1,B1). Data is immediately sent through (A2,B2) which will ultimately mean that MPTCP connection is never interrupted.

Engineering Criteria

To address the three criteria established in the beginning of the project, reliability, performance, and full-stack integration, four crucial categories are selected for analysis. The flowchart in the following represents the overall satisfied expected results of Project TetraNet:

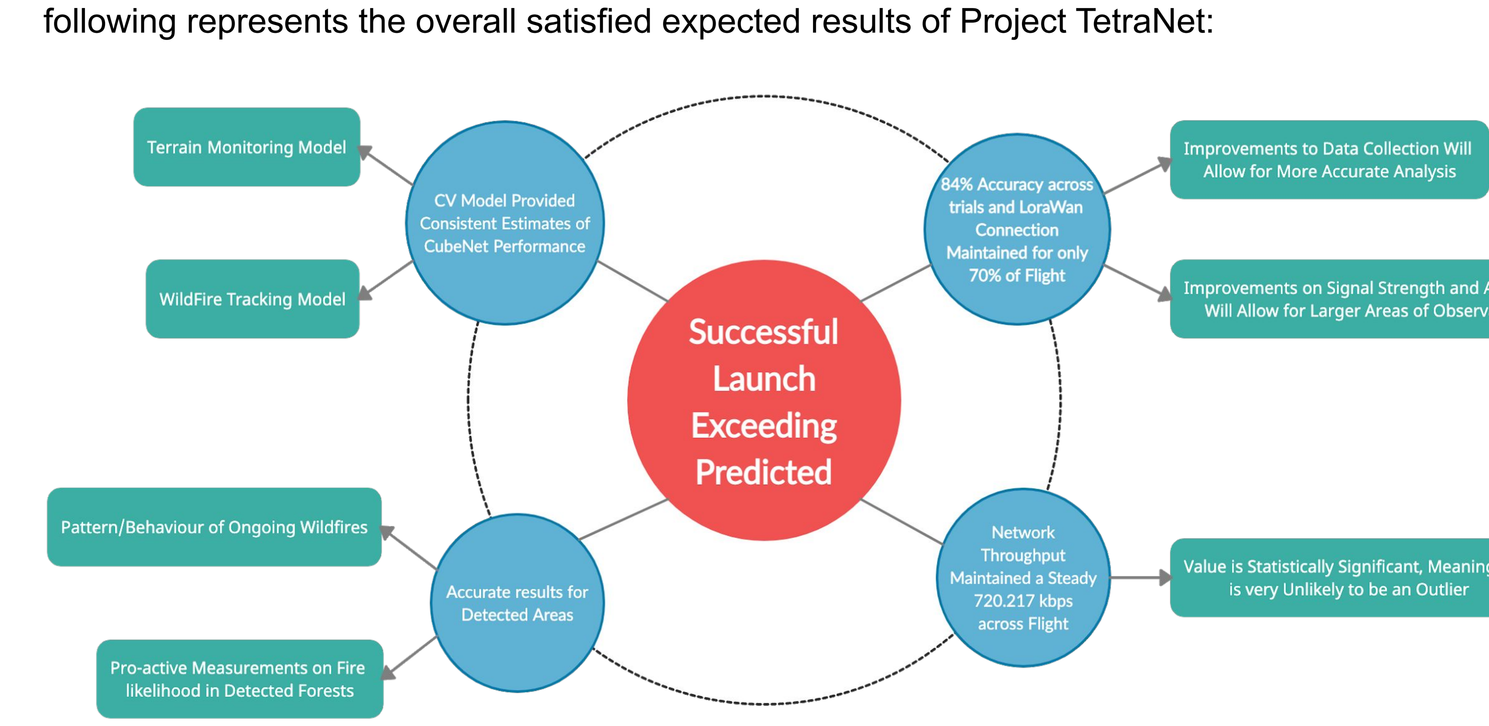


Fig.26: Graphical Representation of Data Results' Fundamentals. Subsequent Trials to be Focused on Increased Area of Effect and More Precise Readings. Looking forward,

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