NASA Blue Skies 2024

Deployable Unmanned Aerial System To Map and Detect Volcanic Ash Clouds

Chris Le, Nicholas Leung, Andrew Patnode, Miguel Villax

Team Advisor: Professor James Geiger

Supporting Technical Experts:
Dr. Eben Cross, Chief Scientific Officer, QuantAQ
Dr. Christopher Kern, USGS-USAID Volcano Assistance Program
Dr. Larry Mastin, USGS-USAID Volcano Assistance Program
Dr. Kenn Sebesta, Boston University RASTIC Director
Dr. Sheryl Grace, Boston University, Mechanical Engineering
Dr. Jeffrey Geddes, Boston University Earth & Environmental Department
Dr. Andrew Kurtz, Boston University Earth & Environmental Department
Dr. James Lawford Anderson, Boston University Earth & Environmental Department

GATEWAYS TO BLUESKIES

NASA Gateway to Blue Skies: Advancing Aviation for Natural Disasters

Natural Disaster Selection

- Research current natural disasters
- Categorize them to weigh them against each other

Concept of Operation

- Research necessary components and processes required for a potential solution

Phases of response

- Preparation: Damage minimization
- Response: Immediate action during a disaster
- Recovery: Assisting in the rebuilding and recovery post-disaster

Pathway to implementation

- Research current implementation processes
- Create an implementation plan for full deployment by 2035

Downselction to Volcanic Ash Dispersion

Downselected natural disasters based upon Occurrences, Economic Impact, Human Toll, Robustness of Existing Strategies and Impact on Aviation.

Volcanic Ash Dispersion

Economic Impact

The 2010 Eyjafjallajökull volcanic eruption in Iceland alone caused damages of **$1.7 billion in one week**

Aviation Impact

Planes cannot fly within volcanic ash clouds:
Combustion engines break down from silica, Exteriors damaged from abrasive particles, Lack of Sight in ash clouds

Robustness of Existing Strategies

Limited technologies able to assess volcanic ash clouds at initial states according to experts at USGS, especially remote areas

Pugh Matrix of Natural Disaster Selection

	Occurrences	Economic Impact	Human Toll	Robustness of Existing Strategies	Impact on Aviation	Totals
Weights	*2*	*3*	*1*	*4*	*5*	
Avalanche	-1	+1	+2	-1	-2	**-11**
Coastal Flooding	+2	+2	+1	-1	-1	**+2**
Cold Wave	+1	0	0	-2	0	**-6**
Drought	+1	0	0	-2	-1	**-11**
Earthquake	0	+2	+2	-2	-2	**-10**
Hail	-1	-1	0	+1	+1	**+4**
Heat Wave	+1	-2	0	-2	0	**-12**
Hurricane	+1	+1	+1	-2	+1	**+3**
Ice Storm	0	+1	+1	-1	+2	**+10**
Landslide	+1	+1	+2	+1	-2	**+1**
Lightning	+1	+1	0	+1	+1	**+14**
Riverine Flooding	+1	+2	+1	-1	-1	**0**
Strong Wind	+2	0	-1	+1	+2	**+17**
Tornado	-1	+2	+1	+1	0	**+9**
Tsunami	-2	+2	+2	-1	-2	**-10**
Volcanic Activity	-1	+2	0	+2	+2	**22**
Wildfire	+2	+1	+1	-2	-1	**-5**

Current Technologies and Trends

USGS
VOLCANOES

Background

Ground Based observation, Satellite imagery

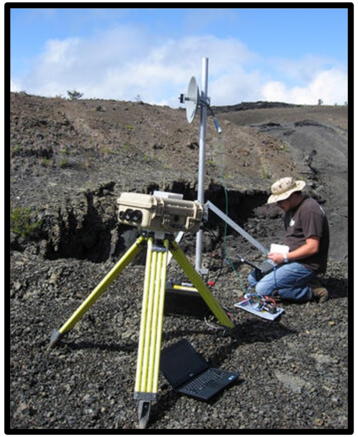
Constraints:

- Weather, Time-Response
- Lack of verification or Faulty sensors
- Lack of real-time data that characteristics initial volcanic parameters and location

Model Implementation

Dr. Christopher Kern: **Ash Dispersion Model**

- Uses historical and meteorological data
- Needs accurate real time data so assumptions aren't used when generating models



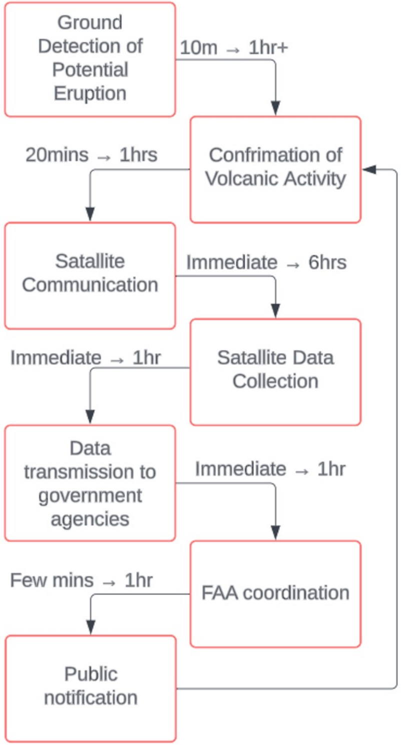
Current Trends

- USGS-USAID Involvement: Only US program specializing in Volcanos
- Discussions with Research Physicist Dr. Christopher Kern in Volcanic Emissions Project
- Current trends point to more satellite use, but still have limitations that airborne sensors could accomplish

Problem Areas

- Lack of confirmation and sensing of eruptions in remote locations
- Lack of initial real time accurate data of ash cloud parameters(Altitude, particle density, location)
- Lack of response to initial volcanic eruptions

How it works now



Ground Detection of Potential Eruption

10m → 1hr+

Confrimation of Volcanic Activity

20mins → 1hrs

Satallite Communication

Immediate → 6hrs

Satallite Data Collection

Immediate → 1hr

Data transmission to government agencies

Immediate → 1hr

FAA coordination

Few mins → 1hr

Public notification

Detection by Ground Sensors:

- Few minutes to a few hours depending on the sensor sensitivity and data processing speed.

Satellite Communication:

- This takes around 10 minutes to 1 hour depending on satellite availability and coordination protocols

Satellite Data Collection:

- The time taken for data collection is dependent on the next satellite pass, which could be between 6 to 12 hours.

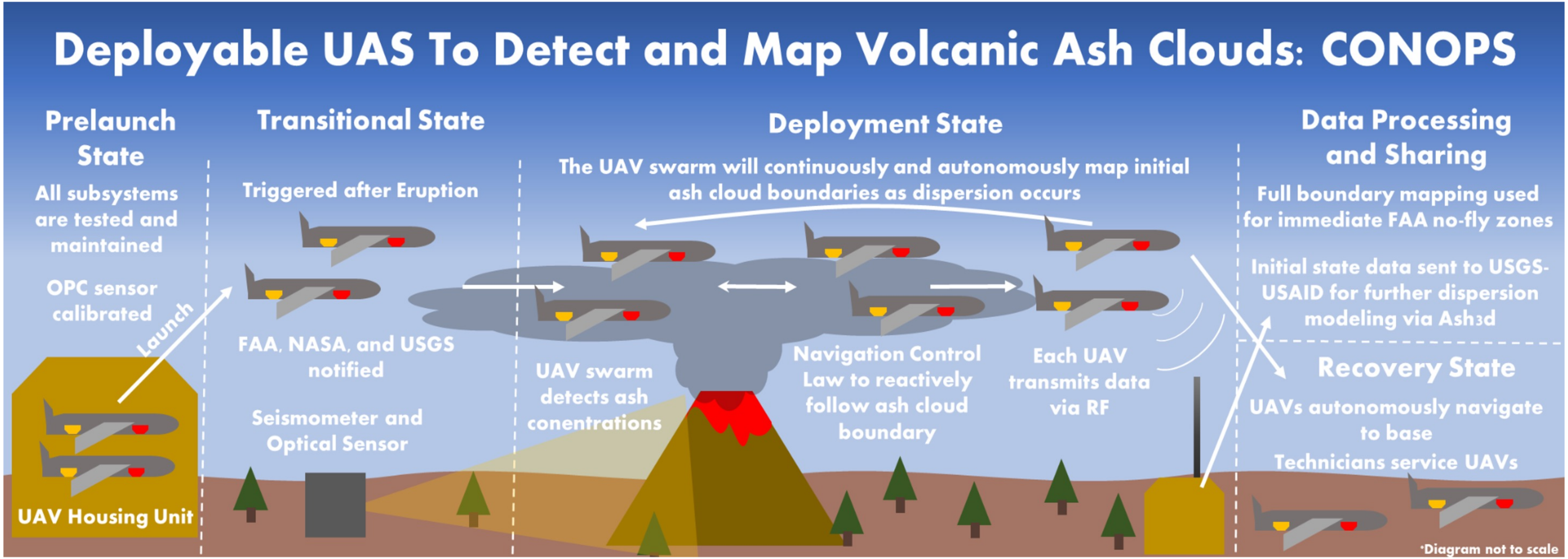
Data Transmission to Government Agencies:

- Data transmission can be almost instantaneous to within an hour if rapid-response protocols are in place.

FAA Coordination/ Public notification:

- The FAA assesses the impact on air traffic and issues advisories or restrictions. This step can take a few minutes to a couple of hours, depending on the complexity and severity of the volcanic activity and its impact on airspace
- Continuous monitoring is ongoing, with updates provided as new data becomes available from subsequent satellite passes .

Concept of Operations (CONOPS)



Deployable UAS To Detect and Map Volcanic Ash Clouds: CONOPS

Prelaunch State

All subsystems are tested and maintained

OPC sensor calibrated

Launch

UAV Housing Unit

Transitional State

Triggered after Eruption

FAA, NASA, and USGS notified

Seismometer and Optical Sensor

Deployment State

The UAV swarm will continuously and autonomously map initial ash cloud boundaries as dispersion occurs

UAV swarm detects ash conentrations

Navigation Control Law to reactively follow ash cloud boundary

Each UAV transmits data via RF

Data Processing and Sharing

Full boundary mapping used for immediate FAA no-fly zones

Initial state data sent to USGS-USAID for further dispersion modeling via Ash3d

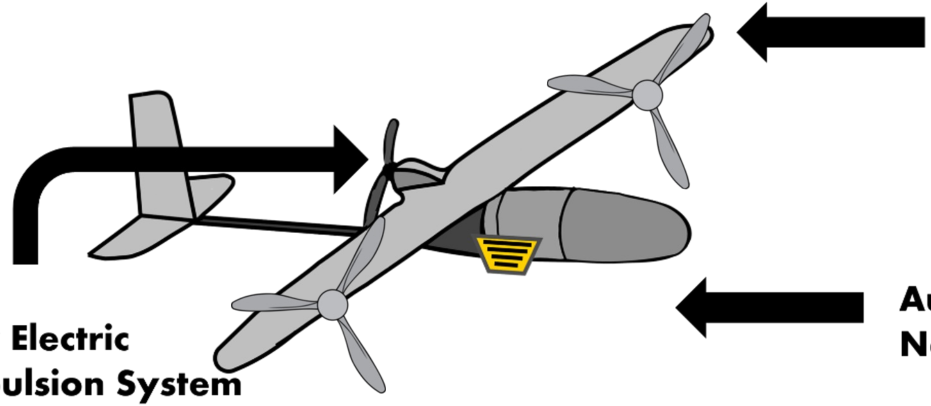
Recovery State

UAVs autonomously navigate to base

Technicians service UAVs

*Diagram not to scale

Key Technologies



Fixed Wing Design for longer airtimes and aircraft body cable of high temperatures with abrasives

Propellers for Vertical Liftoff

Autonomous Flight System with Navigation Control Law

Fully Electric Propulsion System (No Silica Intake from Combustion)

OPC (Optical Particulate Counter) Sensor for large particle sensing

3D Ultrasonic Anemometer for 3d wind speed / direction data and atmospheric conditions

Stakeholder & Technical Expert Consultations

Dr. Lawford Anderson, Dr. Andrew Kurtz, & Dr. Jeffrey Geddes

BU Volcano Field Scientists & Environmental Professors, with first hand experiences working with volcanic eruptions and tracking volcanic events

- There are significant time delays with obtaining accurate volcanic ash dispersion
- Satellite technology is most often used to track volcanic eruptions
- There are often signals through seismic activity when a volcano is likely to erupt prior to the event

Dr. Eben Cross

Co-Founder & Chief Scientific Officer of an Air Particulate Sensor Company

- Validated the use of OPC sensors for volcanic ash
- Suspects sensor would not clog during short flight times (<90 mins)

Dr. Christoph Kern & Dr. Larry Mastin

USGS: Research Physicist & Physical Volcanologist: Insight on important parameters needed for Ash3d's prediction model

- Wind Profile
- Topographic Variables
- Plume Height / Volume
- Plume flow rate

Dr. Sheryl Grace

BU Professor with expert knowledge in autonomous UAV / UAM development and flight systems.

- Electric Propulsion Systems within UAVs are viable for short timespans
- Vertical Liftoff can be viable within electric UAS systems

Dr. Kenn Sebesta

BU Director with expert knowledge in autonomous systems

- Control Law could be implemented to map volcanic ash boundaries
- System could likely successfully operate and deploy anonymously

Stakeholder Feedback from First Design Proposal

NASA Blue Skies

"Measuring meteorological variables (i.e., wind, pressure and humidity fields) is likely to improve the predictions as well"

"UAVs must be able to operate reliably in extreme conditions, with high temperatures, abrasive environment, and turbulent airflows."

"The solution identifies a much-needed resource for this type of disaster (volcanic eruption) and clearly defines the ROI."

USGS-USAID Ash3d Team

To achieve ash predictions using Ash 3d to within better than an order of magnitude would require additional parameters:

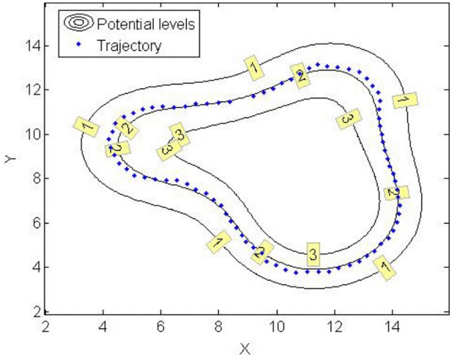
- Current mass eruption rate from the vent
- Range of heights at which the mass decouples from the plume and starts moving downwind
- 3D wind profile within 10km of the volcano

Systems Overview: Software

Software Systems

Navigation

- UAV can reactively navigate at a particular altitude to stay at a constant concentration of silica (cloud boundary)



ADCS

(ADCS) Attitude Determination and Control System

- Retains UAV orientation at correct altitude using Extended Kalman Filter
- Utilizes IMU (Inertial Measurement System) for a sensor fusion

Communications

- Communicate to ground station via RF
- Multiple Drones can communicate at one time
- Data of initial conditions passed onto air traffic control and USGS for further processing

Important Payload Components

Concentration

Optical Particle Counter (OPC):

- Meets min/max diameter specs
- Simple to attach on drone body
- Flight tested with drone technology

Wind Profile

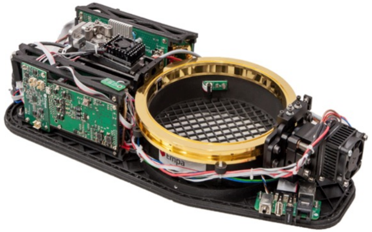
3D Ultrasonic anemometer (Wind Profiler):

- Accurate 3D wind speed and direction measuring
- Records multiple atmospheric characteristics

Altitude & Position

ADCS:

- Controls UAVs during flight
- Measures altitude and GPS position of UAVs



Measurement Systems: Instrumentation

UAV Additional Systems

OPC Sensor

Particulate Concentration Sensor:

- ~10 - 400 µm range
- Fast response time
- Simple output type that works well with given software (Digital Voltage)
- Lightweight and inexpensive

Wind Profiler

Airborn 3D wind Profiler:

- Highly accurate 3d air flow measure ash
- Fast sampling rate
- Lightweight and inexpensive

Support Systems

Seismometer

Seismic Activity Monitor:

- Constant readings
- Sends alert when critical range reached
- Can be powered via generator

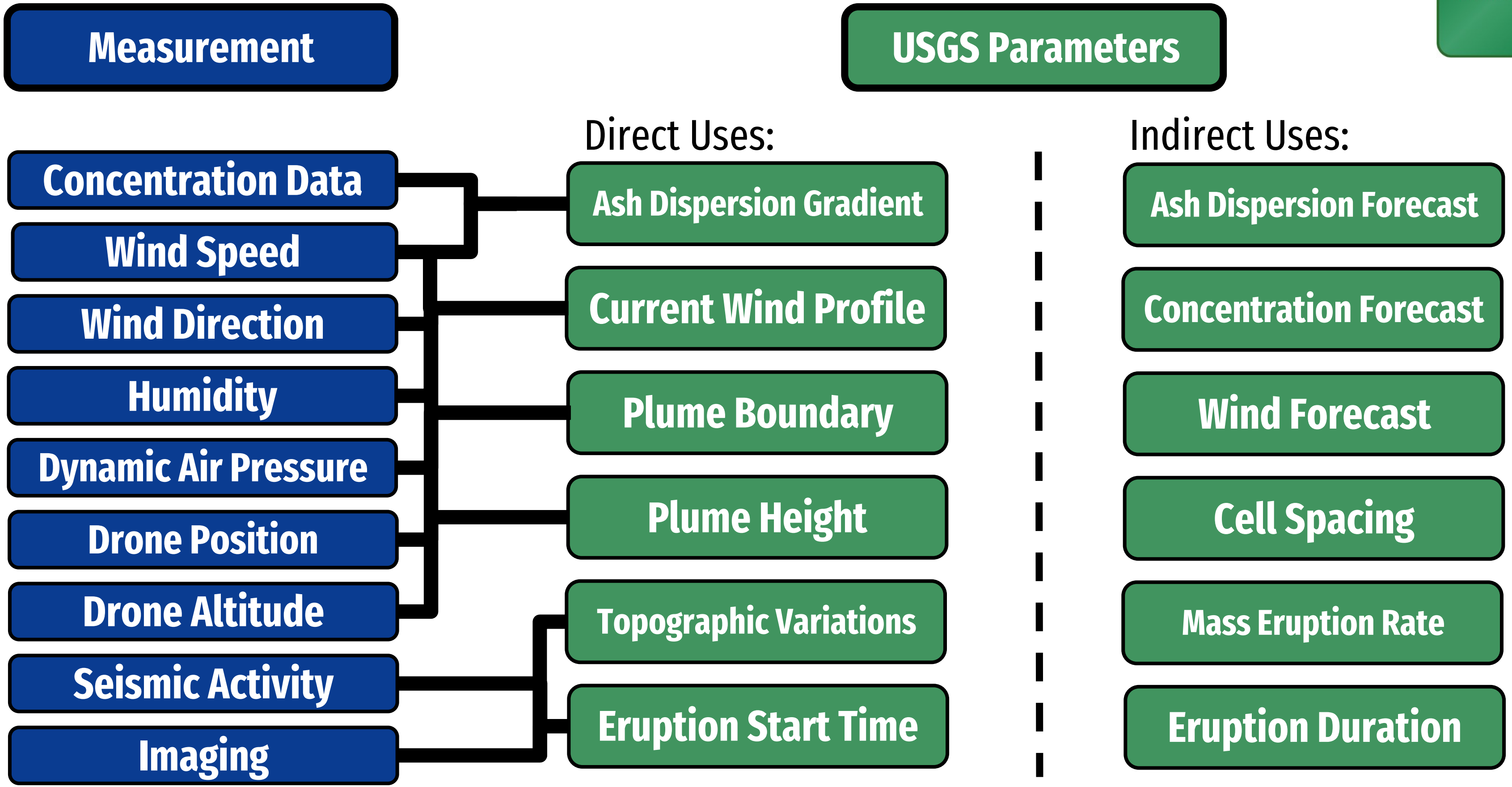
Optical Sensor

Video Monitor:

- Constant readings
- Be able to detect volcanic plume
- Powered via generator

Systems Flow: Measurement Usage

USGS
VOLCANOES



Measurement

USGS Parameters

- Concentration Data
- Wind Speed
- Wind Direction
- Humidity
- Dynamic Air Pressure
- Drone Position
- Drone Altitude
- Seismic Activity
- Imaging

Direct Uses:

- Ash Dispersion Gradient
- Current Wind Profile
- Plume Boundary
- Plume Height
- Topographic Variations
- Eruption Start Time

Indirect Uses:

- Ash Dispersion Forecast
- Concentration Forecast
- Wind Forecast
- Cell Spacing
- Mass Eruption Rate
- Eruption Duration

Implementation- Partner Organizations and Systems

Full System Integration

01

Initial Parameters

Using Real-time initial data measuring Volcanic Characteristics

02

USGS-USAID

Send initial conditions of volcano to Ash3D model

03

FAA

Send locations of immediate no fly zones

Implementation- Environmental / Policy Interfaces / Constraints

Certification

Adhere to aviation regulations and obtaining necessary permits for flying UAVs in certain airspace zones around active volcanoes.

Protocol

Clear protocol must be established to respond to emergency situations.

Must have protocol to handle accidents or malfunctions.

Safety

Ensure that UAV flights do not disturb not interfere with local wildlife oor nearby populations.

Implementation and Global system overview

Detection by Seismometers:

- The detection and confirmation process can take a few minutes.

Visual Confirmation by Cameras:

- Cameras are activated to visually confirm the eruption. This step can take around 5 to 15 minutes depending on camera positioning and image processing speed

Deployment of UAV Swarm:

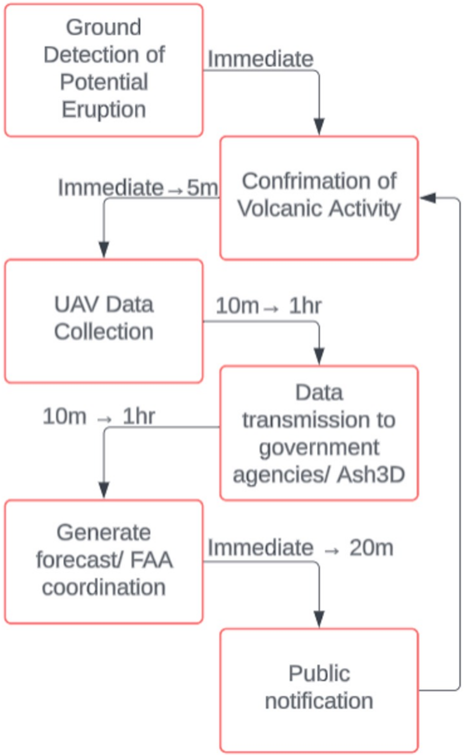
- UAV swarms are deployed to gather data. The deployment and initial flight to the volcanic site can take around 15 to 30 minutes.

UAV Data Collection:

- UAVs perform a flight around the volcanic area for approximately 1 hour, collecting initial parameters. Data is live-streamed to governmental agencies as it is received

Forecast and Data Transmission:

- Collected data is analyzed to generate a forecast. This forecast and data are transmitted to the FAA and other local bodies. This step can take around 15 to 30 minutes.



Technology readiness level

TRL: 9

“Flight Ready” Components:

- Fixed Wing UAVs in adverse conditions

-ADCS Sensors

-Abrasion resistant coatings

-Drone mounted 3D Wind profiler

TRL: 5 - 7

“Near Ready” Components:

- Optical Particle Counter

-Isoline Control Law

TRL: 3

Components needing more testing:

- Autonomous UAV storage

-Autonomous launching and return

Two-Phased Implementation Approach

Phase 1: (2024-2030)

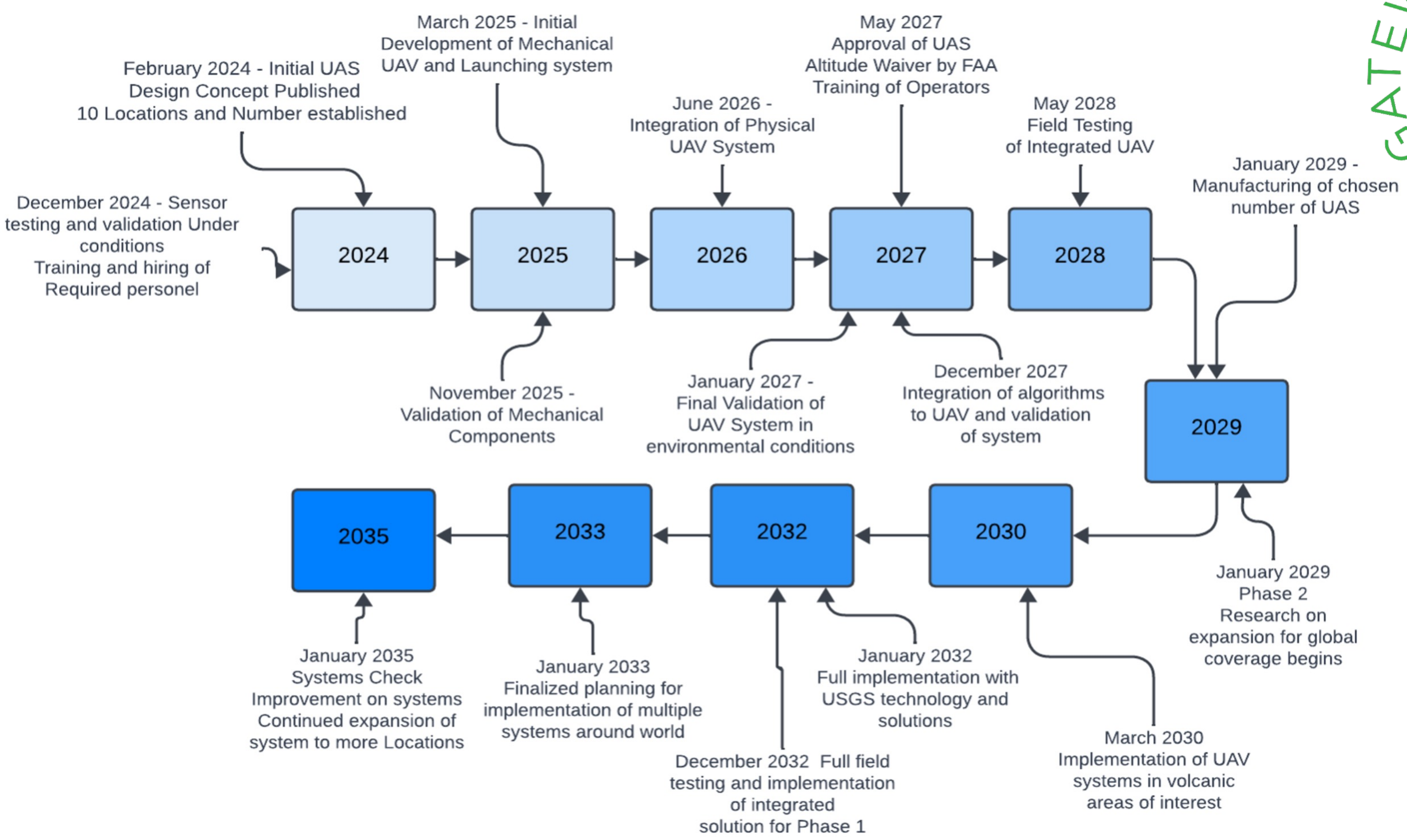
- **Three Locations:**
  - Mt. Saint Helens (WA)
  - Mt. Kilauea (HI)
  - Redoubt Volcano (AK)
- **Key Factors:**
  - Proximity to Airports
  - Eruption Frequency
- **Major Objectives:**
  - Design Testing
  - Accuracy increase testing

Phase 2: (2030-2035)

- **International Expansion:**
  - Targeting 10-20 “High Impact” Locations across globe
  - Key Areas: Italy, Indonesia, USA
- **Key Factors:**
  - Air Travel Impact
  - Eruption Frequency
  - Eruption Intensity
- **Major Objectives:**
  - Deployment for maximum impact
  - Expansion and Adoption of Tech

Charting a Path to Deployment by 2035

GATEWAYS TO BLUESKIES



February 2024 - Initial UAS Design Concept Published
10 Locations and Number established

December 2024 - Sensor testing and validation Under conditions
Training and hiring of Required personel

March 2025 - Initial Development of Mechanical UAV and Launching system

November 2025 - Validation of Mechanical Components

June 2026 - Integration of Physical UAV System

January 2027 - Final Validation of UAV System in environmental conditions

May 2027
Approval of UAS Altitude Waiver by FAA
Training of Operators

December 2027
Integration of algorithms to UAV and validation of system

May 2028
Field Testing of Integrated UAV

January 2029 - Manufacturing of chosen number of UAS

January 2029
Phase 2
Research on expansion for global coverage begins

March 2030
Implementation of UAV systems in volcanic areas of interest

January 2032
Full implementation with USGS technology and solutions

December 2032 Full field testing and implementation of integrated solution for Phase 1

January 2033
Finalized planning for implementation of multiple systems around world

January 2035
Systems Check
Improvement on systems
Continued expansion of system to more Locations

Expected improvements

- An estimated maximum of **84% Aviation Savings** is possible when system is applied alongside current solutions after a volcanic disaster
- Accurate detections in remote locations
- Direct near-real time interfacing with government organizations to accurately and safely map ‘no fly zones’, thus greatly reducing aviation disruption
- Significantly more accurate predictions of Volcanic Ash Clouds will affect more industries (aviation, agriculture, water) as well as human health management

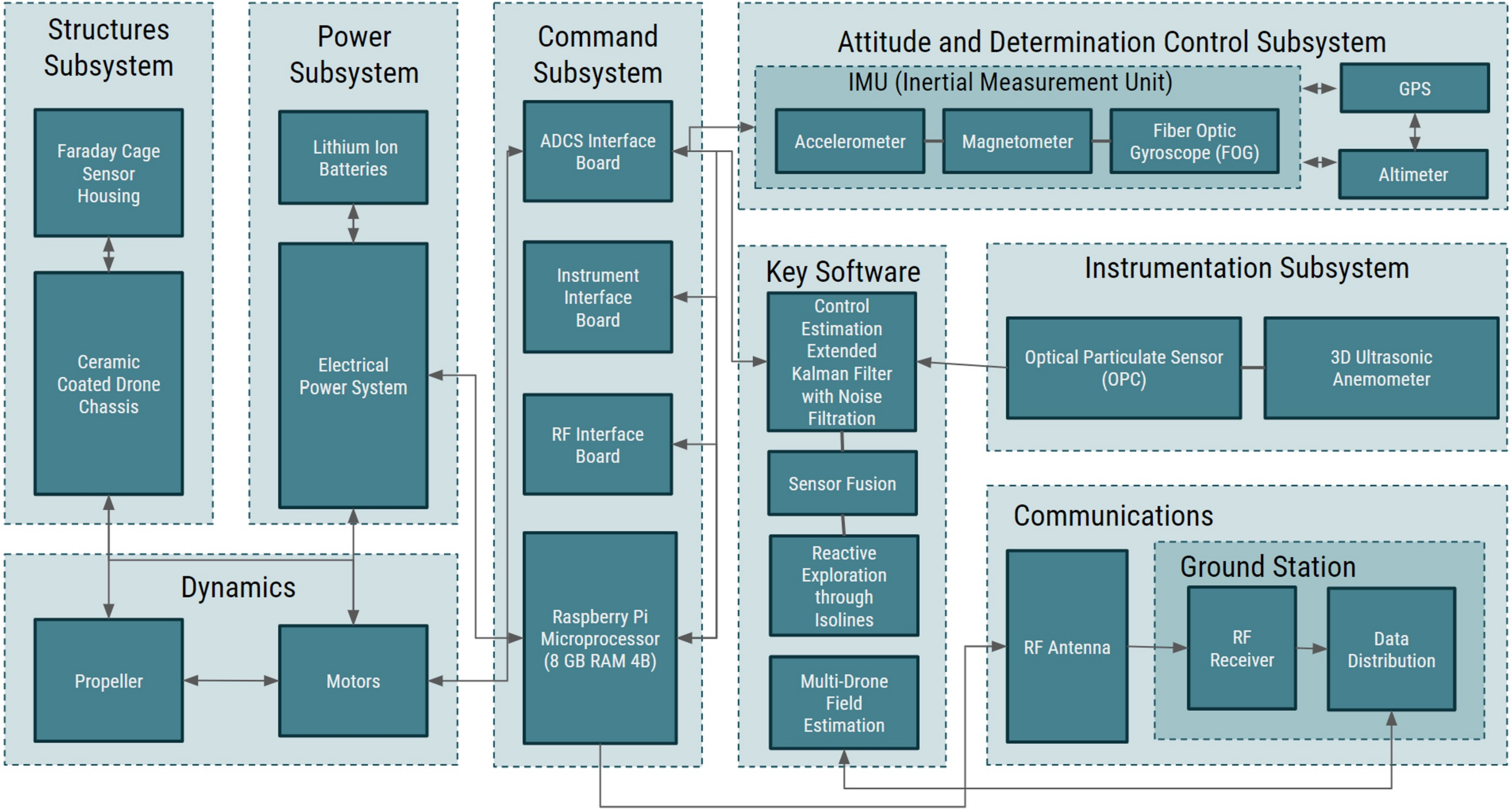
Phase 1 Total Costs: **10 Million USD**
Phase 2 Total Cost: **30 Million USD**
with **2 Million USD Annual** Operation

ROI expected after 2 years of full operation

GATEWAYS TO BLUESKIES

BOSTON UNIVERSITY

Back Up



Structures Subsystem

Faraday Cage Sensor Housing

Ceramic Coated Drone Chassis

Power Subsystem

Lithium Ion Batteries

Electrical Power System

Command Subsystem

ADCS Interface Board

Instrument Interface Board

RF Interface Board

Raspberry Pi Microprocessor (8 GB RAM 4B)

Attitude and Determination Control Subsystem

IMU (Inertial Measurement Unit)

Accelerometer

Magnetometer

Fiber Optic Gyroscope (FOG)

GPS

Altimeter

Key Software

Control Estimation Extended Kalman Filter with Noise Filtration

Sensor Fusion

Reactive Exploration through Isolines

Multi-Drone Field Estimation

Instrumentation Subsystem

Optical Particulate Sensor (OPC)

3D Ultrasonic Anemometer

Communications

RF Antenna

Ground Station

RF Receiver

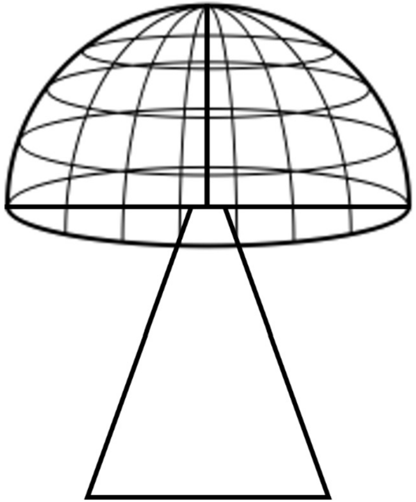
Data Distribution

Dynamics

Propeller

Motors

$$H_{p\_max} = 5\ km$$



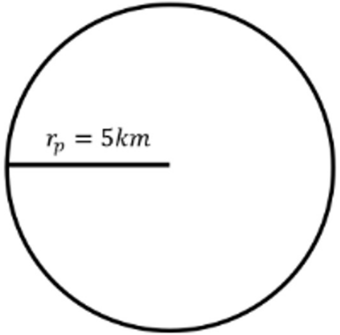
$$D_{p\_max} = 2r_{p\_max} = 10\ km$$

Assume that at very initial times, ash clouds expand is a approximately spherical nature. Given the plume height of a “severe” Volcanic Explosivity Index of 5 km, we can approximate the boundary of the ash cloud.

This mission concept is only interested in mapping ash at initial time series, so the maximum plume height is related to the maximum boundary surveyed

$$C_p = 2\pi r_{p\_max}$$

$$C_{p\_max} = 2\pi(5km) = 31.41\ km$$



Keeping the spherical assumption, we can take the circumference of the largest cross section of the ash cloud to get the largest 2D ash cloud boundary

$$v_{UAV} = 44\frac{m}{s} = .044\frac{km}{s}$$

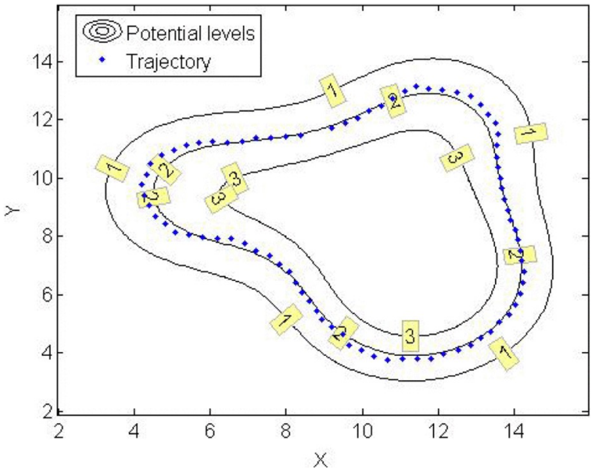
Take Average Velocity of UAV as 44 m/s

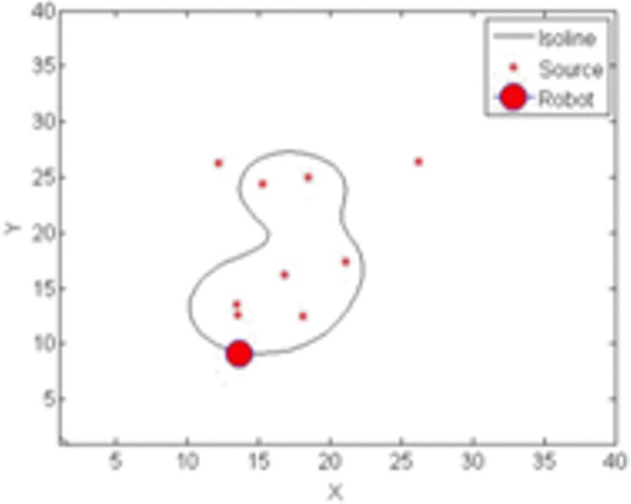
$$t_{UAV} = \frac{31.41km}{.044\frac{km}{s}} = 714\ s$$

Divide Ash Cloud Circumference by Velocity to find Time for a Singular Drone to cover the Entire Ash Cloud Boundary

$$t_{3\_UAV} = \frac{714\ s}{3} = 238\ s \approx 4\ min$$

If using three UAVs, divide this time by three to get approximately a full ash cloud boundary every 4 minutes. It is important to note that this is the maximum time this would take as the maximum ash cloud circumference was taken





Reactive exploration through following isolines in a potential field

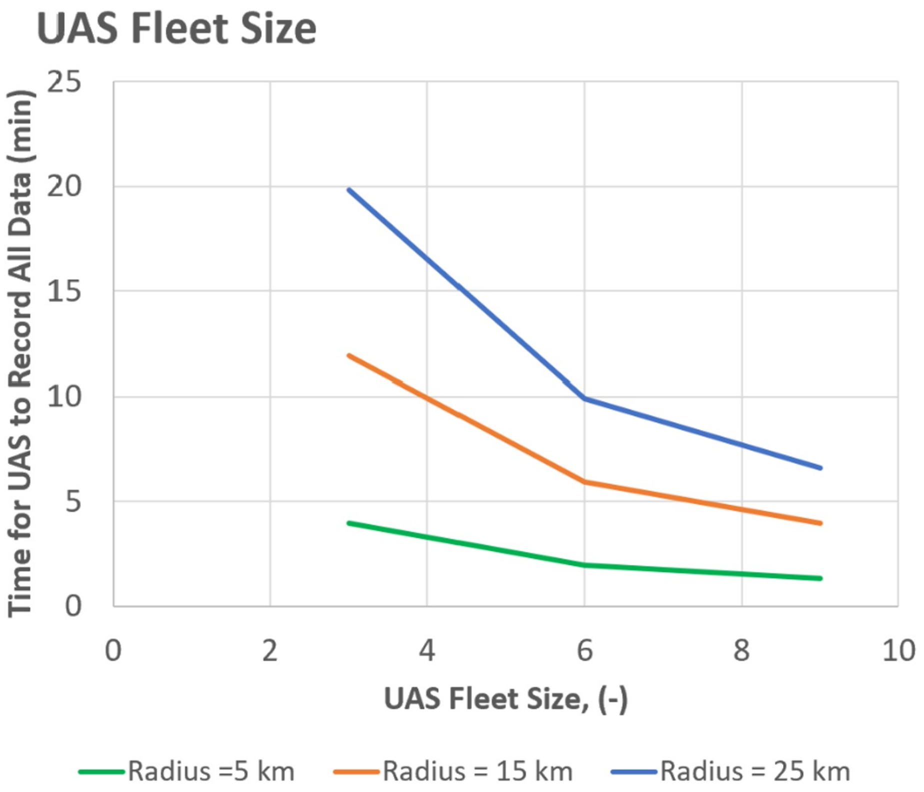
By Dimitar Baronov & John Baillieul

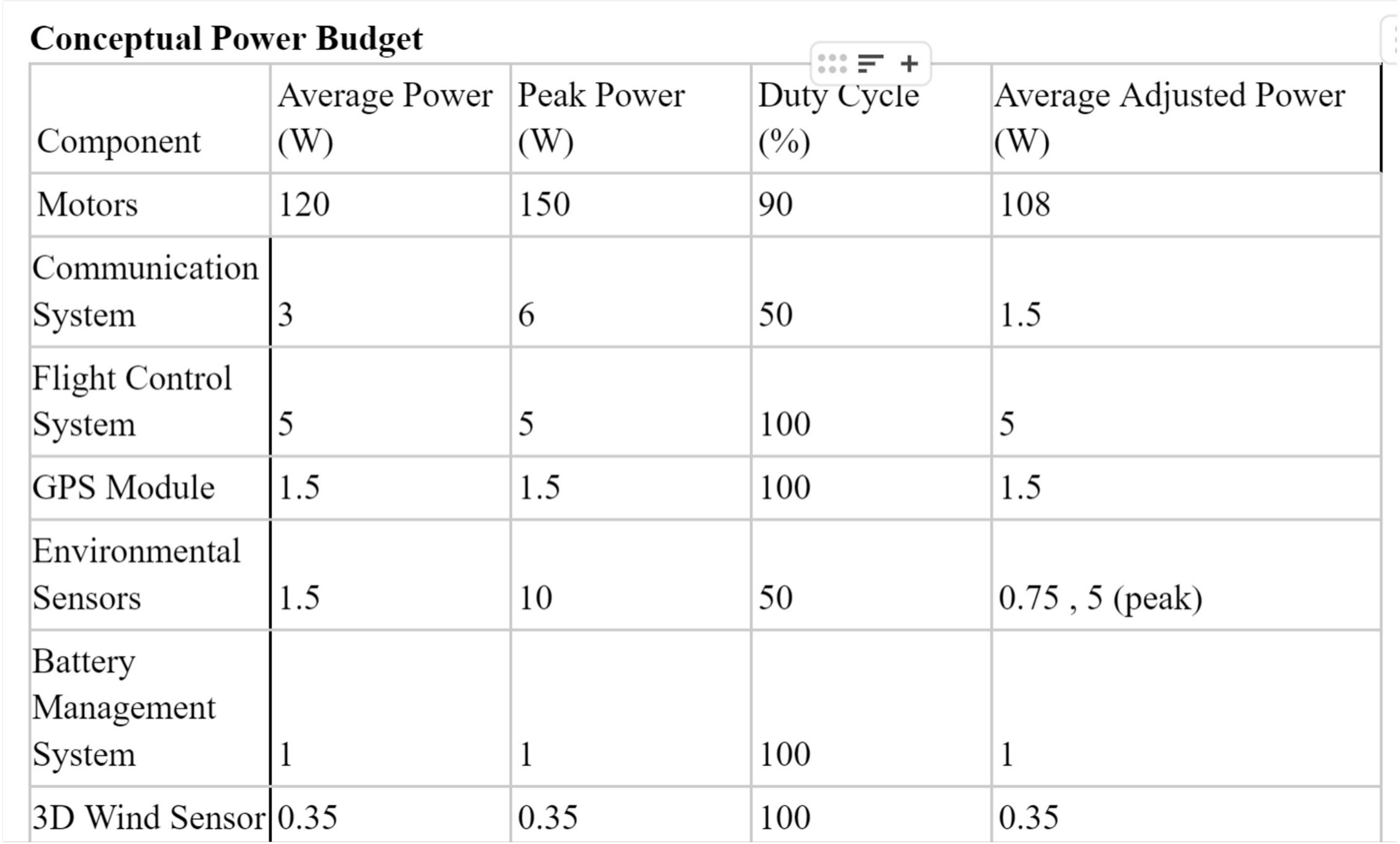
“ … determining the boundaries of the regions where a potential exceeds a given threshold [2], [8], [9]. These boundaries can be associated with the limits of a forest fire, the position of an oil spill, or the area in which the concentration of a contaminant exceeds the regulatory safety limits.”

- Fixed sensors are much more challenging to work with on a large scale like this, so the paper discusses how mobile sensing is feasible.

“The novelty of [this] control law…is that it does not rely on higher order characteristics of the field. In this way we are able to track an isoline with a single robot.”

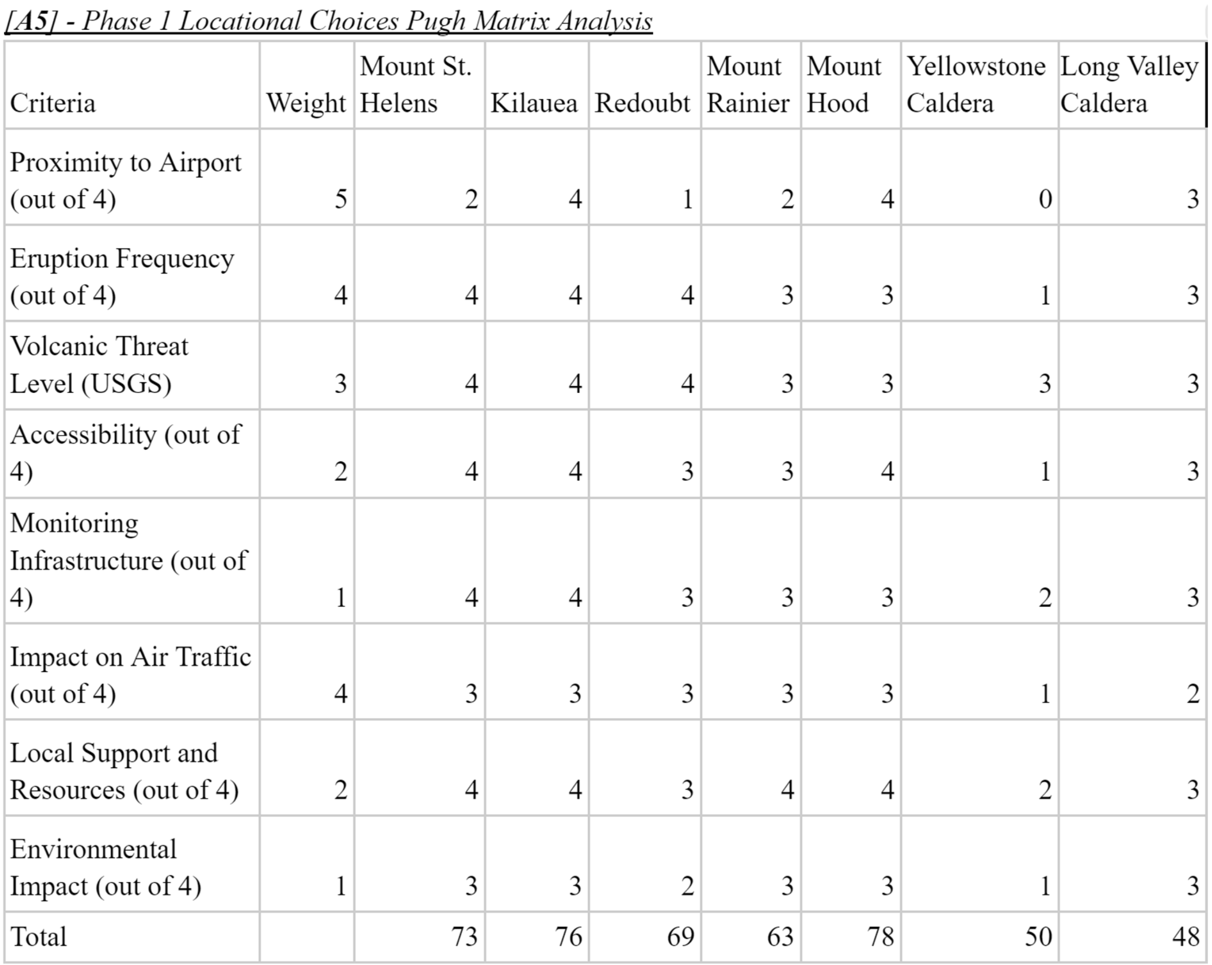
Parameter	**Units**	**Value**				
Flight Speed	m/sec	44				
Radius of Ash Cloud Circle	km	**5**	10	15	20	25
Circumference	km	31.4	62.8	94.2	125.7	157.1
Time to complete one (1) round trip	min	11.9	23.8	35.7	47.6	59.5
UAS Fleet Size	-	3				
Time to record data for entire circumference	min	**4**	7.9	11.9	15.9	19.8
UAS Fleet Size	-	6				
Time to record data for entire circumference	min	2	4	5.9	7.9	9.9
UAS Fleet Size	-	9				
Time to record data for entire circumference	min	1.3	2.6	4	5.3	6.6





Conceptual Power Budget

Component	Average Power (W)	Peak Power (W)	Duty Cycle (%)	Average Adjusted Power (W)
Motors	120	150	90	108
Communication System	3	6	50	1.5
Flight Control System	5	5	100	5
GPS Module	1.5	1.5	100	1.5
Environmental Sensors	1.5	10	50	0.75 , 5 (peak)
Battery Management System	1	1	100	1
3D Wind Sensor	0.35	0.35	100	0.35



[A5] - Phase 1 Locational Choices Pugh Matrix Analysis

Criteria	Weight	Mount St. Helens	Kilauea	Redoubt	Mount Rainier	Mount Hood	Yellowstone Caldera	Long Valley Caldera
Proximity to Airport (out of 4)	5	2	4	1	2	4	0	3
Eruption Frequency (out of 4)	4	4	4	4	3	3	1	3
Volcanic Threat Level (USGS)	3	4	4	4	3	3	3	3
Accessibility (out of 4)	2	4	4	3	3	4	1	3
Monitoring Infrastructure (out of 4)	1	4	4	3	3	3	2	3
Impact on Air Traffic (out of 4)	4	3	3	3	3	3	1	2
Local Support and Resources (out of 4)	2	4	4	3	4	4	2	3
Environmental Impact (out of 4)	1	3	3	2	3	3	1	3
Total		73	76	69	63	78	50	48

To find an estimated average savings forecast for the UAS System, an analysis of the current accuracy of the Ash3D model with the addition of measured initial data and the actual airspace that is closed, the difference in the areas is used to find the percentage of area reduction. This percentage decrease represents the area that was incorrectly labeled a ‘no fly’ zone, meaning that flights passing through shouldn’t have been cancelled. Using this information, an estimated savings percentage is calculated, and then applied to the Eyjafjallajökull eruption of April 2010 to show the impact of potential savings.

Area reduction calculations:

After review, the most accurate estimate was found to be an 84% increase in area certainty. All calculations will be made using this value.[1] [1]

Eyjafjallajokull (April 2010)

Total economic loss: >100,000 flights cancelled -> $1.7 Billion

Total savings from Eyjafjallajökull eruption:

Increase in area certainty = Increase in airspace availability

Total economic loss * % increase in airspace availability

$1.7 Billion * 0.84 = $**1.445 Billion**

Average annual savings (based on average losses between 2018-2022)

Total economic loss: $480 Million
Expected savings: $480 Million * 84% = **$403 Million** per year [6]

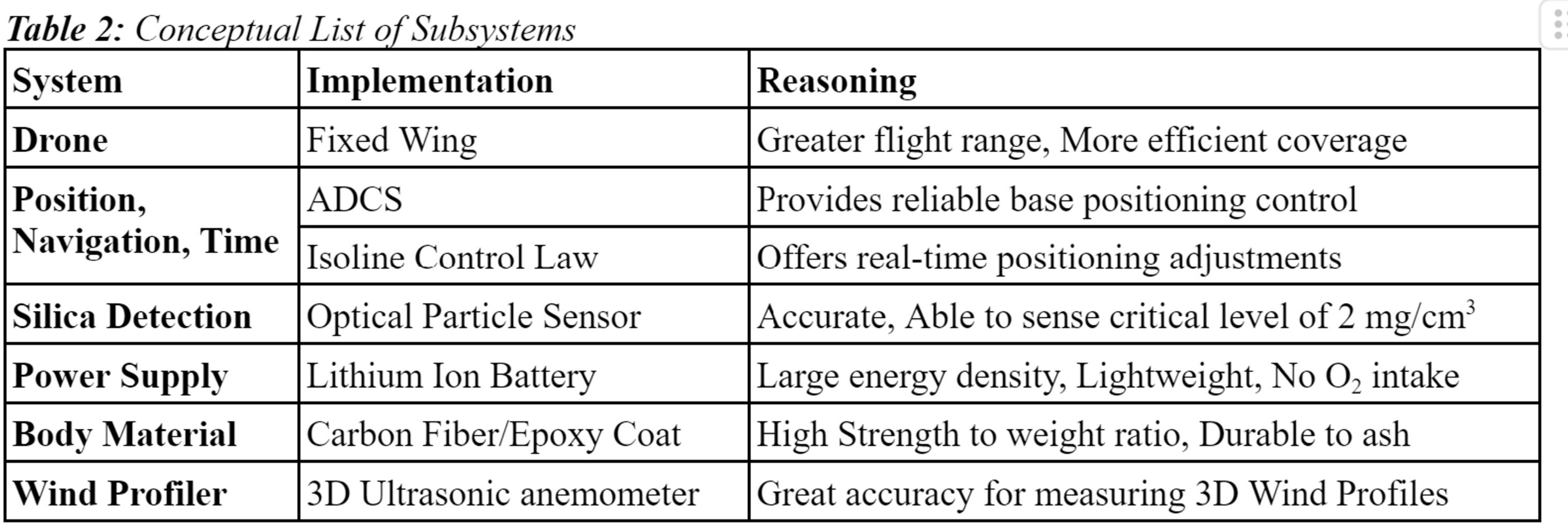
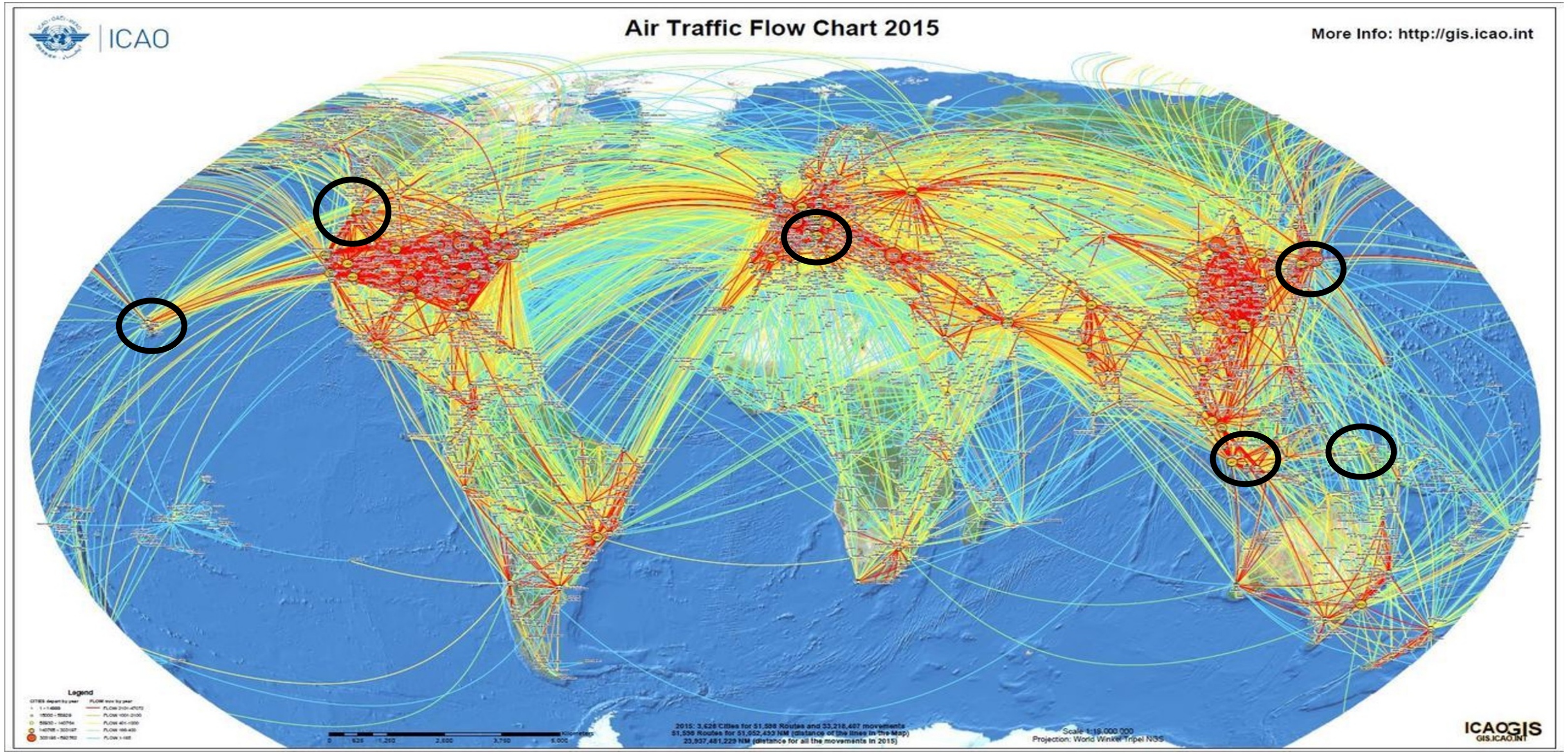
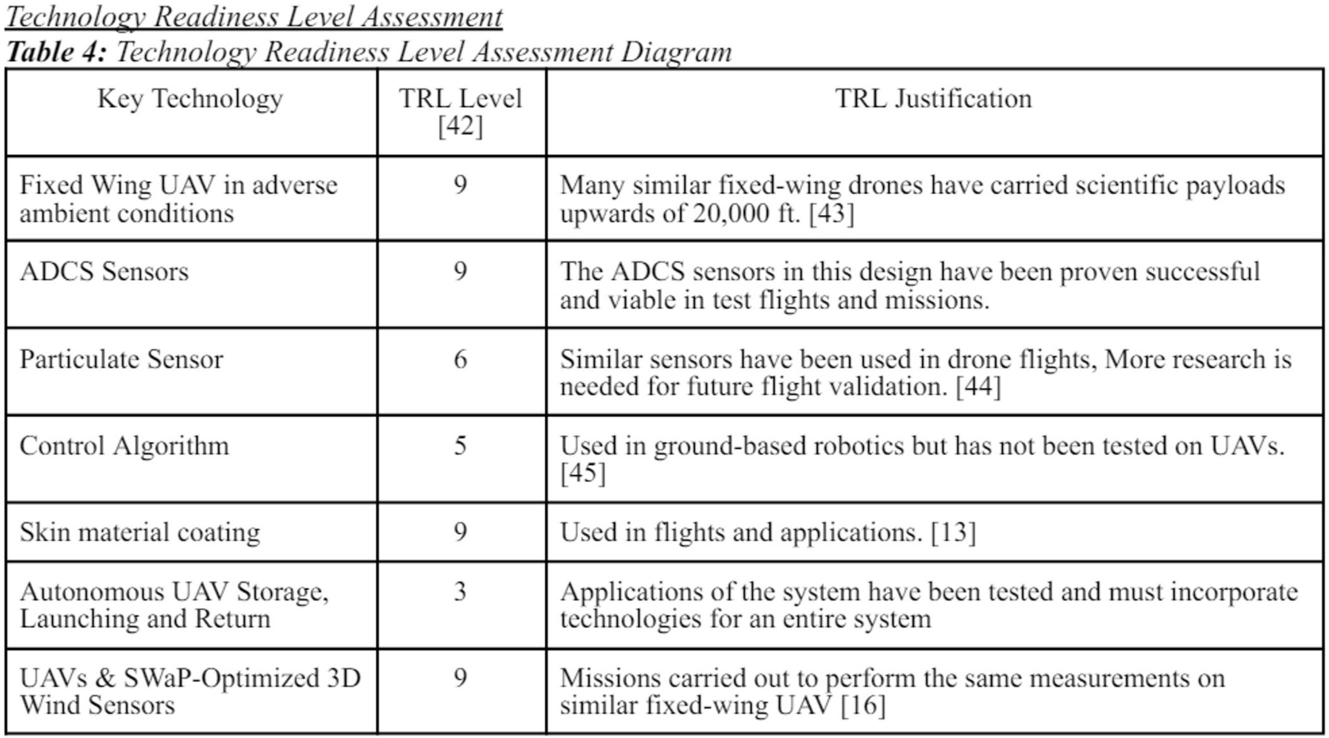


Table 2: Conceptual List of Subsystems

System	Implementation	Reasoning
Drone	Fixed Wing	Greater flight range, More efficient coverage
Position, Navigation, Time	ADCS	Provides reliable base positioning control
	Isoline Control Law	Offers real-time positioning adjustments
Silica Detection	Optical Particle Sensor	Accurate, Able to sense critical level of 2 mg/cm^3
Power Supply	Lithium Ion Battery	Large energy density, Lightweight, No O_2 intake
Body Material	Carbon Fiber/Epoxy Coat	High Strength to weight ratio, Durable to ash
Wind Profiler	3D Ultrasonic anemometer	Great accuracy for measuring 3D Wind Profiles



- Volcano Information: Global Volcanism Project, Smithsonian Institution
- Flight Map: International Civil Aviation Organization (ICAO)



Technology Readiness Level Assessment

Table 4: *Technology Readiness Level Assessment Diagram*

Key Technology	TRL Level [42]	TRL Justification
Fixed Wing UAV in adverse ambient conditions	9	Many similar fixed-wing drones have carried scientific payloads upwards of 20,000 ft. [43]
ADCS Sensors	9	The ADCS sensors in this design have been proven successful and viable in test flights and missions.
Particulate Sensor	6	Similar sensors have been used in drone flights, More research is needed for future flight validation. [44]
Control Algorithm	5	Used in ground-based robotics but has not been tested on UAVs. [45]
Skin material coating	9	Used in flights and applications. [13]
Autonomous UAV Storage, Launching and Return	3	Applications of the system have been tested and must incorporate technologies for an entire system
UAVs & SWaP-Optimized 3D Wind Sensors	9	Missions carried out to perform the same measurements on similar fixed-wing UAV [16]