Autonomously Coordinated Multi-HAPS Communications Network: Failure Mitigation in Volcanic Incidence Area Coverage.

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***Abstract*—This paper investigates the coordination of multiple autonomous High Altitude Platform Stations (HAPS) in a volcanic cloud emergency scenario for aerial communications coverage. Deploying unmanned(pilot-less) HAPS over areas impacted by volcanic ash clouds is proposed in this work. Volcanic ash clouds stretching over distances can be challenging and requires resilient wireless communications infrastructure. In this work a self-organising solar-powered HAPS network is presented and its resilience tested in the event of the failure of a participating HAPS in the swarm. The future of implementing swarm of unmanned HAPS for communications services requires autonomous capabilities as demonstrated in this paper. A swarm intelligence based algorithm developed for this work is applied to coordinate a swarm of HAPS for communications coverage. The paper highlights the demands of such self-organising infrastructure and how failure may impact communications coverage, especially in emergency scenarios where high availability and reliability of the supporting communications infrastructure is critical.**

I. Introduction

A. Overview of Volcanic Incidence Environment

Volcanic eruptions are natural phenomena that can have devastating impact on humans, animals and the environment [1], [2]. There are about 575 historically active terrestrial volcanoes, and an annual eruption of about 12 volcanoes affecting "cruise altitude" airspace [1]. Such eruptions can produce enormous ash clouds injecting substantial amounts of gas, aerosol and ash into the troposphere, and even up to the stratosphere in some cases [1]. The impact of the resulting volcanic plumes, volcanic clouds, and associated climatic effects will vary depending on the mass of the eruption, and local atmospheric factors. It may also result in the volcanic cloud spreading over thousands of kilometers, constituting grave danger to aviation traffic by reducing visibility and increasing risk of engine failure [1], [3]. For instance, the 2010 Eyjafjallajokull eruption in Iceland (see figure 1), resulted in the largest air traffic shutdown in recent times [1], demonstrating the devastating impact of volcanic incidences. In other instances, airplanes have had direct encounter with volcanic ash with severe consequences e.g. 1982 Galunggung volcano incident in Indonesia resulted in significant engine damage to 2 Boeing 747s [4]. Due to its critical nature, the aviation industry maintains records on volcanic ash incidences and has a formal severity index to categorise encounters [5]. However, the monitoring and proactive response to volcanic incidences rely heavily on satellite observation and effective communications [6], [7]. The use of Geo-Stationary satellites for earth monitoring and observation is covered in literature [7]; the use of satellites for earth observation will remain relevant, especially with improvements in infrared spectral imaging [1]. There has also been proposals to use Unmanned Aerial Systems (UAS) to support volcanic research through collection of in-situ data and related activities within these hazardous and extreme environments [8], though not for emergency response which this work considers.

This work, however, focuses on providing HAPS based communications coverage in the event of a volcanic emergency, where terrestrial or satellite infrastructure is degraded or nonexistent. The need for resilient aerial communications infrastructure to support volcanic emergencies, which are typical extreme environments are needed. In this work, self-organising High Altitude Platform Stations (HAPS) are proposed as an optional and less expensive infrastructure to provide area communications and sensor coverage over the affected region.

Fig. 1. Volcanic Ash from the 2010 Eyjafjallajokull eruption in Iceland [9].

B. HAPS as an Aerial Communications Infrastructure

High Altitude Platforms (HAPS) are aerial vehicles that operate in stratospheric altitudes ranging from 17 to 50Km above mean sea level [10]. At this altitude wind profile is described as mild and suitable for hosting platforms with minimal station keeping requirements. These platforms can be implemented as heavier than air (HTA) platforms e.g. fixed-wing aircraft. The use of unmanned aerial vehicles (UAVs) as a communication infrastructure is covered in literature and continues to be considered an active area of research [11]–[15]. However, HAPS are actually distinct from low altitude platforms (LAPS) UAVs [16], which typically operate within the troposphere, with lower endurance capabilities and footprints. HAPS by design operate from the stratosphere and is considered a platform for providing persistent communications coverage to mobile and fixed users, with inherent technical strengths of terrestrial and satellite communications systems combined [17]–[19]. HAPS offer large footprints with signal latency similar to terrestrial systems. Furthermore, they can be easily recovered and redeployed to meet changes in demand, a new capability that neither satellite nor terrestrial systems can offer effectively. This is particularly relevant in this case as volcanic ash can spread over thousands of kilometers [1], and will require larger footprints to cover. Furthermore, due to non-ingestion of air as electric vehicles they are less vulnerable to the effects of volcanic particulates. HAPS potential for multi-day persistence and its low cost and risk (for the pilotless option) makes it a good technology option for volcanic emergency coverage. A typical HAPS platform is the Airbus Zephyr (see figure 2), a solar aircraft with the world endurance record for flying 25 days continuously without refueling. This work will investigate how multiple solar-powered HAPS can be autonomously coordinated to provide coverage and how the swarm will react to failure (e.g. of a platform) in a volcanic cloud environment.

Fig. 2. Airbus Zephyr - Typical HAPS Platform [20]

In this paper, section I gives an overview of volcanic environments and HAPS communications infrastructure. Section II, describes the problem scenario, modeling and simulation methodology for the work. In section III, simulation results and analysis are presented. Finally, section IV draws conclusions on the work and considers future work.

II. Problem Scenario, Modeling and Simulation Background

A. Overview of Problem Scenario

The scenario simulated is a swarm of four HAPS providing area coverage over a region devastated by volcanic activity and with volcanic ash spreading over hundreds of kilometres beyond the eruption area. The HAPS swarm also includes a "cold standby" spare platform which is activated in the event of the failure of any active HAPS in the network, see figure 3. It is expected that due to the extreme nature of the environment, a HAPS platform may fail and require replacement. The swarm of HAPS are autonomously coordinated and should be able to react to this failure by self-organisational capabilities inherent in the system. The ability of the swarm of HAPS to react to the failure of one or more HAPS and to autonomously adjust to the addition of a spare HAPS is the level of resilience desirable for a wireless communications infrastructure in an extreme environment. In the conceived scenario; the swarm of HAPS forms the main network access infrastructure as terrestrial and satellite systems are assumed unavailable.

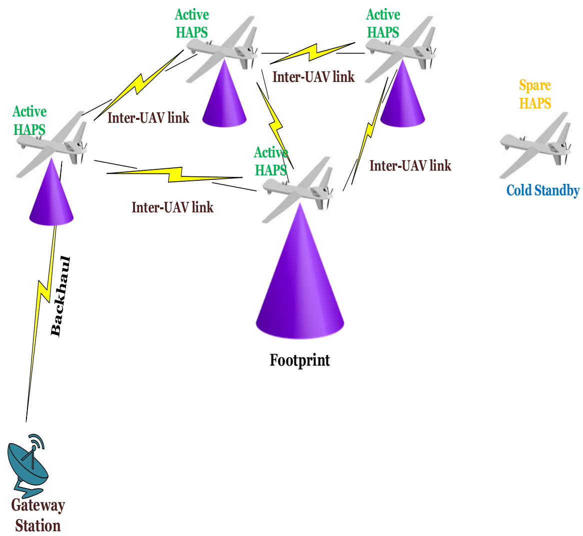

Fig. 3. HAPS Network showing Active and Spare Platforms

B. Modeling and Simulation background

To investigate this problem, a software model of key system segments were developed using Matlab and simulated to investigate the problem. Simulated HAPS models and subsystems were based on standard aerodynamic and communication link equations [21]. A parameterised model of the HAPS was used in this work and is typical of related models in its class e.g. the Airbus Zephyr referenced earlier. However, due to propriety and commercial concerns, data for specific parameters are not publicly available, leading to making assumptions and approximations based on theoretical analysis.

The parameters in table I, describes the HAPS system communications and link budget parameters which ultimately defines the profile of the service segment e.g. HAPS communications payload power and link data rates. The link budget is based on a payload power of 80 Watts, with the simulated HAPS network supporting about 500 users spread over a large area (typical coverage density profile for HAPS). In such thinly populated scenarios, terrestrial networks would not be economical and satellites may be too expensive and ineffective. The available power is expected to be shared between the communications and sensor payloads. Such payload use strategy is relevant in emergency scenarios where first responders(fewer in number) may request priority for sensor payloads to understand the environment. As events progress, there may be need to shift priority to communications payload as the need for communications outweigh sensor feedback. Dynamics of this nature are desirable and should be considered in designing HAPS communications infrastructure.

TABLE I
HAPS SYSTEM COMMUNICATIONS AND LINK BUDGET PARAMETERS

S/N	Item	Specification	Justification
1	Half Power Beam Width (HPBW)	145 degrees	Specific to Model
2	Normalised Signal to Noise Ratio (Eb/No)	10 dB	Assumed for Link
3	EIRP	Depends on Slant Range	Power to support 1 subscriber at edge of cover
4	Data Rate	100 Kbit/s	Desired Link Data Rate
5	HAPS Transmitter Antenna Efficiency	0.75	Assumed for Model
6	Ground Receiver Antenna Gain	1	Assumed for Model
7	Signal Frequency	7 GHz	Assumed for Model
8	System Noise Temperature	350K	Standard

C. HAPS Autonomous and Swarm Coordination Algorithm

This work considers implementing swarm of semi or fully autonomous aerial vehicles with self-organising capabilities. Autonomy is defined within the context of decision making, and self governance capabilities of the HAPS, however, levels of autonomy exist and may depend on design, functions and specifics of the mission [22]. It is expected that aerial vehicles of the future will be managed by fully autonomous algorithms maintaining network connectivity, data rate and coverage as mission objectives [14]. Autonomy in this regard can also refer to the ability of the HAPS to make local decisions with limited or no global knowledge and still achieve network-wide objectives cooperatively in this case [21]. For a swarm of HAPS with the mission of providing communications coverage for volcanic cloud emergency conditions, self-organisation and swarm coordination is very crucial. A swarm intelligence based algorithm is developed for this problem scenario and leverages the strengths of swarm self-organising capabilities. The participating HAPS in the swarm exchange essential data as they explore the environment akin to foraging. By exchanging critical data and using swarm techniques the HAPS provide persistent and resilient coverage over the area of interest. Figure 4, shows the flow chart for the applied swarm algorithm developed for this work.

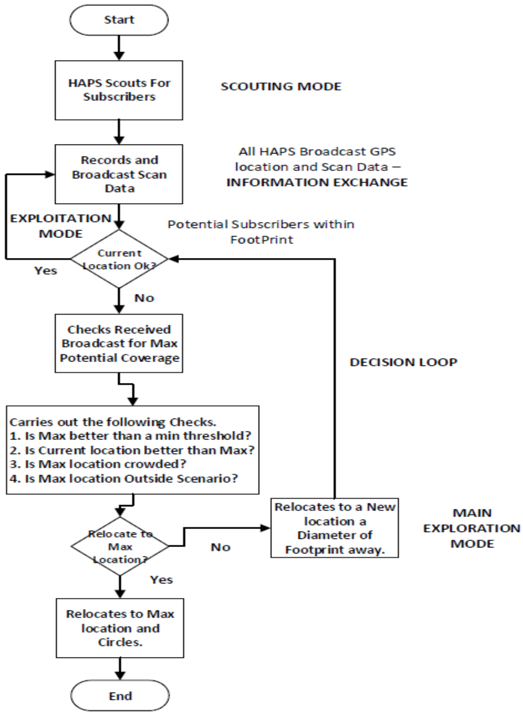

Fig. 4. Swarm Intelligence Algorithm Flow Chart

III. RESULT AND ANALYSIS

The simulation was run with four (4) HAPS covering an area extending over some Indonesian islands and the Java sea. This region was selected for the high volcanic activity around the area and its unique location within the “Ring of Fire” home to 75% of the world’s volcanoes and 90% of its earthquakes [23] and associated tsunamis. The active HAPS in the swarm as shown in figure 3 above provide fixed data rate of 100kpbs (within rate for emergency service [24]) to about 500 users, scattered over the area of interest. One spare HAPS is maintained in cold standby mode to be activated when an active HAPS fails. The simulation was run for slightly above 6 hours, which is reasonable as convergence for an emergency based solution is time sensitive. A 6 hour window provides a reasonable constrain to test convergence and also isolate any user density issues associated with random walk models. The following assumptions are made in order to manage the complexity and scope of the work.

- The HAPS swarm can activate local positioning systems if GPS fails; valid for current technologies [25]).
- The HAPS swarm has multi-mode transmission (RF, mmWave and Optical) for Inter-HAPS and HAPS-User links [21], since volcanic ash can sometimes impact RF signals, e.g. disruptions from interference to radio transmission due to atmospheric conditions [2].
- The Swarm can activate sensor-based communications if required.
- The HAPS network can operate as fully ad-hoc network or part of an infrastructure based network if required [21].

A. *Coverage Performance without Replacement HAPS*

In the first scenario, the HAPS swarm was not equipped with a replacement or spare HAPS. This was important to establish a baseline and a means of validating the performance of the coordination algorithm; the main concept of this work. It is expected that the coordination algorithm should re-organise the swarm and maintain or improve coverage amidst the failure without the spare HAPS. As shown in figure 5, HAPS 1 failed at about 11.30am and its local coverage dropped to zero. The remaining three HAPS worked to fill this gap as shown in figure 6 as global coverage dropped from 46 users to about 39. However, within 30 minutes, the global coverage rose to about 49 as the HAPS self-organised to cover more users. The swarm intelligence algorithm applied within this scenario responded to the failure of the HAPS and maintained recovery and positive improvement trend over the remaining time of the simulation.

The performance of the coordination algorithm without a replacement HAPS highlights the self-organising capacity that is desirable in an extreme environment where human intervention may not be possible or safe. The baseline for measuring the algorithm has been established and will be used to validate the next scenario, where replacement HAPS is introduced after failure.

During the HAPS circling and relocation, the algorithm also manages the horizontal separation of the HAPS as shown in figure 7. This does not suggest any form of collision avoidance but highlights another dimension to self-organisation. In figure

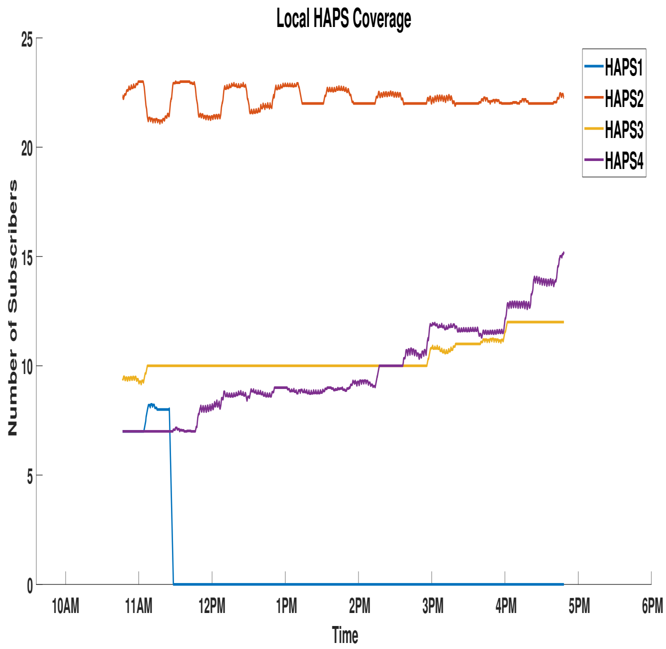

Fig. 5. Local HAPS Coverage - Failure Scenario without Spare HAPS

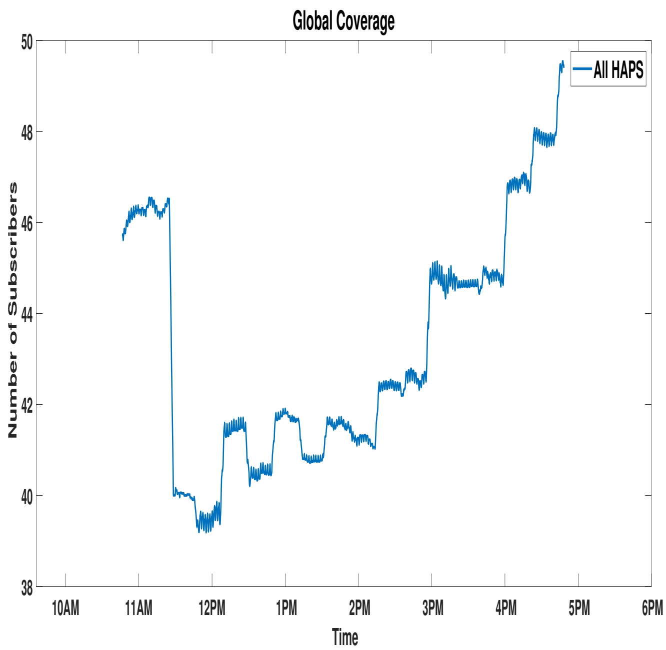

Fig. 6. Global Coverage - Failure Scenario without Spare HAPS

7, HAPS 2 was used as a reference, and the horizontal distance to each HAPS was measured all through the simulation. A minimum horizontal separation distance of 5000m was set for this simulation; 5500 to 9260m [26], is recommended in some jurisdictions for manned aircraft but not established for UAS. Achieving a neat separation profile is very critical in HAPS aerial formations and service availability.

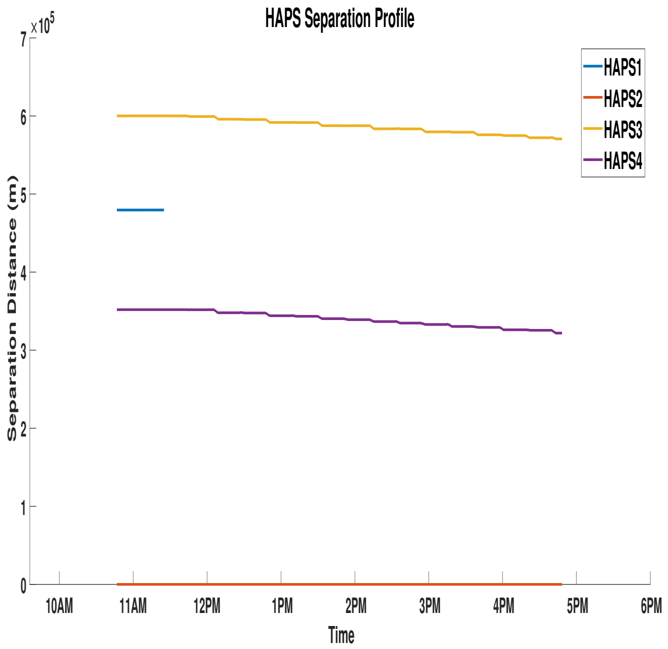

Fig. 7. HAPS Horizontal Separation - Failure Scenario without Spare HAPS

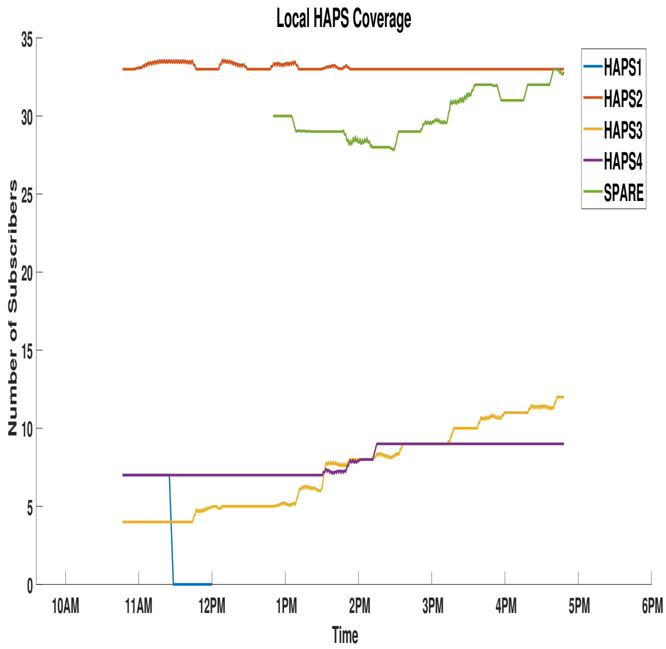

Fig. 8. Local HAPS Coverage - Failure Scenario with Spare HAPS

B. Coverage Performance with Replacement HAPS

In this scenario, all parameters and conditions are the same as the previous experiment except that the spare HAPS is introduced after failure. The impact of the replacement HAPS is noticed after failure of HAPS 1 at about 11.30am, see figure 8. In about 1 hour the spare HAPS provided the needed boost in the global coverage performance as coverage improved from about 45 to 85 users as shown in figure 9. The trajectory of improvement remained positive as the HAPS swarm "foraged" for users within the area.

The addition of the spare HAPS clearly provided coverage improvement but more importantly the self-organising capability as indicated in figures 8 & 9, which is key to autonomous coordination especially in extreme environments. The number of users, was constrained by the high EIRP required for the link as defined by the link budget. Reducing the EIRP by either using a lower E_b/N_o or data rate will accommodate more users but at the detriment of service quality.

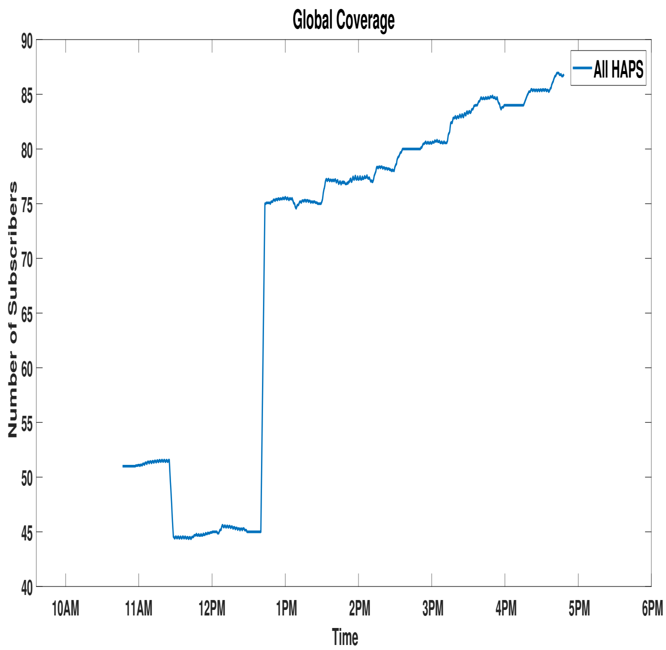

Fig. 9. Global Coverage - Failure Scenario with Spare HAPS

IV. Conclusions and Future Work

This paper has attempted to highlight the application of autonomous solar HAPS for providing communications area coverage where swarm coordination is needed for emergency support. Resilient aerial communications infrastructure is needed in the absence of terrestrial or degraded satellite systems. Volcanic cloud emergencies impact aircraft but HAPS are immune to ingesting particulates making them suitable for such environments. Though there may be concerns with solar panel obscuration by ash clouds; the low cost and low risk potential is significant. The work has demonstrated that self-organisation and coordination is key to meeting emergency services demand in such extreme environments. With the multi-day persistence capability and the concept of dual communications and sensor payloads; HAPS may be crucial in managing and coordinating first responders and general emergency efforts during volcanic cloud incidences.

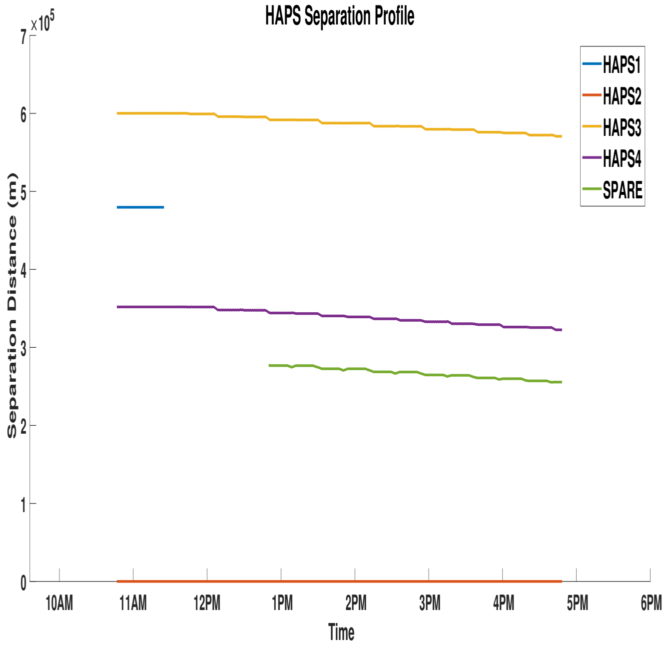

Fig. 10. HAPS Horizontal Separation - Failure Scenario with Spare HAPS

A network of persistent and self-organising HAPS over the "Ring of Fire" region can make a difference in early warning and emergency management efforts.

Future work will consider how to improve the performance of the solar-powered HAPS swarm for sensor and communications coverage in volcanic cloud environments. Focus will be on practical application issues; for instance, extending HAPS persistence for providing communications coverage by battery powered descent under the ash clouds at night and ascent during the day/clear skies to charge its batteries. Such meticulous algorithmic management of energy will extend its communications coverage capabilities and improve availability and reliability.

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