

Global Communication Coverage Using Cubesats

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Abstract—Cubesat constellations may become the next generation of communication backbone architecture to provide future worldwide communication services. In this paper, we investigate the feasibility of deploying Cubesat constellations with inter-satellite links (ISL) for the delivery of global continuous communication. Cubesat constellation designs for various mission scenarios are proposed and verified using a simulation toolkit commonly used by space engineers.

Index Terms—Cubesat, inter-satellite links, binary phase shift keying, code shift keying, low earth orbit, pilot symbol, sensor, M-ary frequency shift keying, M-ary phase shift keying, quadrature phase shift keying, Systems Tool Kit, unmanned aerial vehicle.

I. INTRODUCTION

CUBESATS, being a cheaper alternative to traditional satellites, are gaining popularity as the next generation of satellite system by virtue of the hardware miniaturization effect made possible by technological advancements. Cubesats have changed the communication outlook from long-range point-to-point propagations to a multi-hop network of small orbiting nodes. Numerous Cubesats, when grouped together as a constellation, can form a wireless sensor network, and the inter-satellite links (ISL) between the Cubesats in the constellation are one potential area to be researched. In the network architecture, a robust communication channel is a cardinal requirement for reliable data transfer between nodes. For ground nodes that are operating within the area of interest where there is a clear line-of-sight (LOS), radio communication techniques can be employed. However, when the area of interest is large and the ground nodes are located beyond line-of-sight (BLOS), there is a need to rely on other communication techniques such as satellite communications. For this case, a satellite functions as a repeater in space to transfer data from one geographic location to another, as shown in Figure 1. In our paper, a Cubesat is employed as the BLOS repeater solution for communication between the space and ground segments. Since a Cubesat has a small payload and operates at low earth orbit (LEO), the footprint coverage is limited with a single Cubesat. Moreover, based on the orbital movement for satellites deployed in LEO, the satellite coverage is constantly moving and its dwell time over a designated area is limited [1]. Thus, Cubesats must be deployed in constellations to enable continuous coverage over the designated area. Furthermore, if there is a need to have continuous global coverage, we have to rely on ISL between

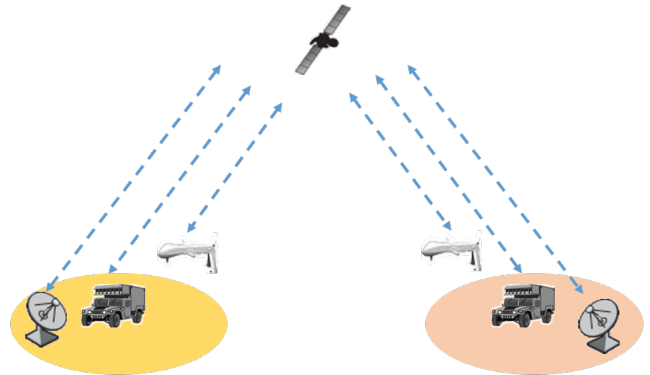


Fig. 1. System Overview using Conventional Satellite as a Repeater

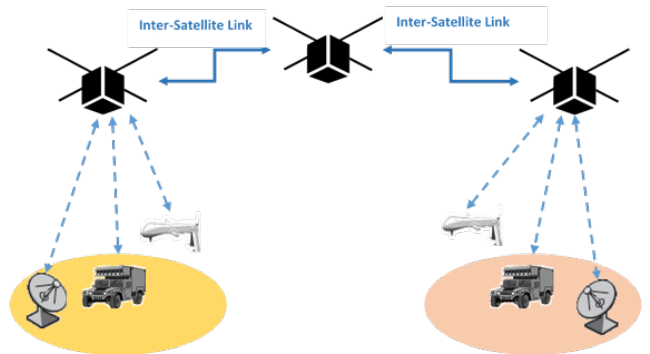


Fig. 2. System Overview using Cubesat with ISL

Cubesats to provide a seamless communication channel in the space segment. The mission scenario for our analysis is shown in Figure 2.

The objectives of our paper are to design Cubesat constellations with ISL to act as the backbone communication architecture with continuous global coverage; to propose suitable Cubesat constellation architectures for different mission profiles; and to ensure that the Cubesat constellation design is well optimized to deliver the highest data rate available to the nodes without compromising the mission requirement. In our mission scenario, Cubesats function as space repeaters, and the information collected is relayed to terrestrial nodes,

which consist of Unmanned Aerial Vehicles (UAV), mobile vehicles, and ground stations. Noting the high number of Cubesats deployed to achieve continuous global coverage, we must ensure there is a minimum separation distance between the Cubesats to avoid collision. Collisions in space are catastrophic situations, highlighting the importance of collision avoidance as a constellation design consideration.

In [2], [3], researchers investigated the possibility of using Cubesat to relay information to an existing satellite constellation. Challenges for Cubesat ISL and the digital communication scheme were discussed in [4]. The authors in [5] studied the feasibility of implementing networking transport protocols, Transmission Control Protocol and User Datagram Protocol, in a QB50 Cubesat constellation. The authors in [6] simulated and verified that Cubesats can be used as communication relays for a small fleet of UAVs in an area of operations. In [7], [8], the authors looked into using Cubesats to provide global coverage that minimized the maximum revisit time. The method to obtain global coverage for a LEO satellite network and the necessity of having overlapping footprints were discussed by the authors in [1]. From the previous works, it can be observed that the Cubesat constellation is primarily used for observational or surveillance missions that do not require continuous global coverage. The feasibility to employ Cubesat ISL has been proven by past researchers, but the discussions have been generally restricted to non-continuous global coverage. In this paper, we build on the previous research findings and propose Cubesat constellations that are capable of providing continuous global coverage.

The paper consists of three sections. Section II provides an overview of Cubesat constellation design. Simulation procedures to determine the coverage of the proposed constellation and trade-off analysis are discussed in Section III. The conclusions are provided in Section IV.

II. OVERVIEW

To date, the operational Cubesat constellations have been used for observational or surveillance missions. These constellations demonstrate the feasibility of deploying Cubesats at a large scale to perform specific missions. Deploying large scale Cubesat constellations as a network of communication nodes and using them for ISL will undoubtedly be challenging due to their small form factor and power limitations.

A. Designing a Constellation

With the small form factor and power limitations, it is paramount that we design the satellite constellation in a manner where the number of satellites deployed is optimized without compromising the fulfillment of the mission requirements. The ultimate satellite constellation design will be dependent on parameters such as the orbital height, inclination angle, and separation distance. The main parameters and the corresponding mission impacts to be considered for the design of a satellite constellation are shown in Table 1.

To date, existing satellite constellations in LEO have been deployed with similar profiles, whereby the satellites operate

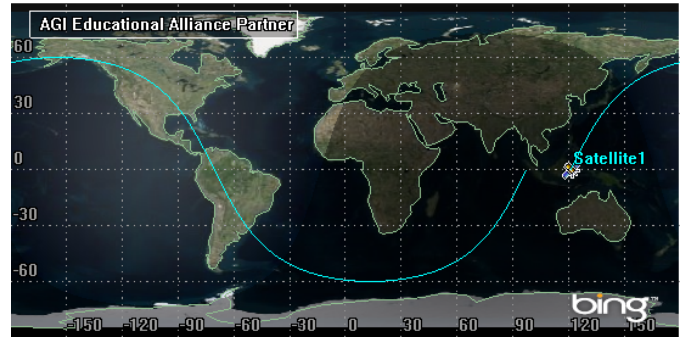


Fig. 3. Path of the Satellite with Inclination Angle at 60°

at the same height, inclination angle, and orbital velocity. The purpose for such a deployment style is to lower the overall deployment cost and enhance ease of implementation. Space engineers will also design satellite constellations that require the minimal number of orbital planes and fewest satellites to meet mission objectives. Moreover, with the same profile, satellites will have the same atmospheric effect and orbital velocity, and therefore the satellites will have the same decay rate. This will allow us to determine the mission supportable lifespan of the Cubesat constellation easily, and thus, satellites with the same profile are preferred.

B. Constellation Architecture for Global Coverage

There are two common constellation architectures for generating a large number of satellites for global coverage, namely Walker and Street of Coverage (SOC). The constellation of satellites using Walker's pattern has the same latitude and inclination; it is also symmetrical. Using Walker's notations, the satellite constellation can be defined by the parameters T, P, F and i [10], where T is the total number of satellites in the constellation, P is the number of commonly inclined orbital planes, F is the relative phasing parameter, and i is the common inclination for all satellites. To achieve the symmetry required for Walker's pattern, the satellites in each inclined plane are equally spaced, and the orbital planes are separated equally around the Earth [10].

Based on Walker's concept, the inclination angle will constrain the upper and lower latitudinal bound limits of the footprint coverage region. Thus, there will not be any coverage at the latitudinal zones beyond the inclination angle. An example of a satellite's path with an inclination angle at 60° is shown in Figure 3. Note that coverage only exists between 60° North and 60° South.

The SOC architecture [10] is based on the concept of having several overlapping trailing satellite constellations where the satellites are located at the same altitude and orbital plane. This trail of circular satellite footprints will translate to a zone of continuous satellite coverage, termed a street. To obtain global coverage, we need to determine the number of streets required, and thus, the number of orbits needed.

1) *Polar Orbit Constellation Using Walker's Concept:* For missions that require continuous global coverage in high-

TABLE I
SUMMARY OF PARAMETERS [9]

Parameters	Mission Impacts
Number of Satellites	Affects the coverage and the principal cost.
Number of Orbital Planes	Varies based on coverage needs. Highly advantageous to have a minimum number of orbital planes as transfer between the orbits increases the launch and transfer costs.
Minimum Elevation Angle	Must be consistent with all satellites. Determines the coverage of single satellite.
Altitude	Increases the coverage and the launch, transfer cost when altitude is increased. Decreases the number of Satellites. For communication applications, increase/decrease in altitude can correspondingly change latency.
Inclination	Determines the latitude distribution of coverage and selected based on coverage needs.
Plane Spacing	Results, when plane spacing is uniform, in continuous ground coverage.
Eccentricity	Determines the type of orbit of the satellite.

latitude areas or the polar region, we can consider using Walker's concept. Having the same satellite profile for all the Cubesats, its design and implementation will be less complicated and less costly. However, the trade-off for this concept will be poorer coverage at the equatorial region. An example of a polar orbit constellation using the Walker concept is shown in Figure 4.

2) *Inclined Orbit Constellation with Modified SOC Concept*: For missions that require continuous global coverage with emphasis on the equatorial region or the low latitude zones, we recommend using a modified SOC concept. This is performed by deploying Cubesats at different inclination angles, where the orbital planes will be equally spaced apart over 180° . The trade-off for this design is the longer time needed to deploy the satellite constellation, and the need to have multiple launch sites to deploy the satellites into the different inclination planes. Moreover, with the satellites deployed at different orbits, the decay lifespan will vary. This phenomenon makes it difficult for continuous sustainment of the satellite constellation as the effort to track and replace the deorbited satellites will be significant. An example of an inclined orbit constellation using a modified SOC concept is shown in Figure 5.

III. PERFORMANCE EVALUATION

In this section, the proposed Cubesat constellation architecture needed to meet different mission requirements is stimulated using Systems Tool Kit (STK). STK is a commercial software product available from Analytical Graphics Inc. that is widely used by satellite engineers and developers to model complicated networked systems on the ground and in space. STK is a very powerful tool that allows satellite engineers to easily analyze and visualize results obtained from the simulation. With the aid of STK, the proposed constellation for the various missions in this paper is determined. The detailed link budget analysis, primarily focusing on the inter-Cubesat links, and modulation techniques to improve the bit rate are also discussed in this section. We make use of the Walker tool built into STK to create Cubesats on single and multiple planes. The Walker's constellation is selected since it is most symmetrical and the angular phase separation distance between the satellites can be automatically generated.

A. Simulation Scenarios

1) *Determination of Orbital Height and Collision Avoidance*: Collision avoidance is a critical factor to consider in any space deployment. There are two key types of space collisions, namely collision with space debris and collision with existing satellites. With the increasing amount of space debris and congestion of satellites in LEO, it is important to ensure that the orbital attitude of the deployed Cubesats is free from debris. Collisions could render the affected orbital slot useless. According to [11], a majority of satellite collisions occur in sun synchronous orbits at inclinations of 98° and 82° with an orbital height of 480 km to 1100 km. A suitable range for the deployment of our Cubesats was determined to be at an orbital height from 200 km to 450 km as it is less populated and lower the risk of collision.

The number of satellites or space debris that is trackable, specifically those that have a size that is larger than 1 cm, is plotted in [11]. The satellites or space debris lie in the range of 200 km to 2000 km with the peak of the space debris in the range of 700 km to 1000 km, and the amount of debris increases each year. This data further reinforces our selection of the orbital height at 200 km to 450 km, whereby the probability of collision with both existing satellites and space debris is remote.

Collision avoidance between Cubesats in their own constellation also has to be considered. The Cubesat has to stay within an operational box to prevent collisions, and it is also recommended that a combined analysis be performed with other neighboring satellite service providers to ensure that every satellite is operating within its design specifications. Conjunction is a term used to refer to a situation whereby a space object is approaching the operation box at a close distance.

Currently, space engineers conduct conjunction analysis for LEO satellites with a 25 km x 25 km x 2 km box [12]. The International Space Station has a more stringent requirement whereby maneuvers will be performed when space objects come close to the operation box of 25 km x 25 km x 0.75 km for orbits at the attitude between 330 km to 435 km [13]. Based on these examples, we propose that the separation distance for each Cubesat in its own constellation be at least 25 km.

In the Cubesat constellation, there are two distinct regions

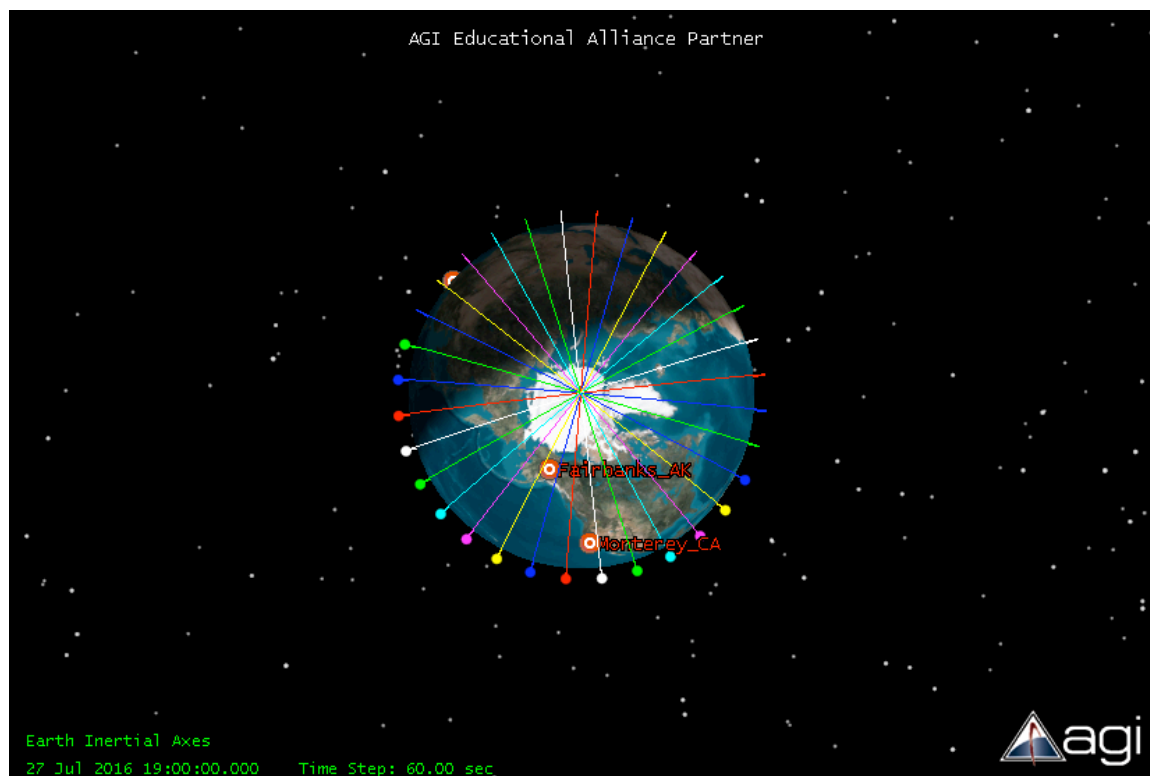


Fig. 4. Polar Orbit Constellation

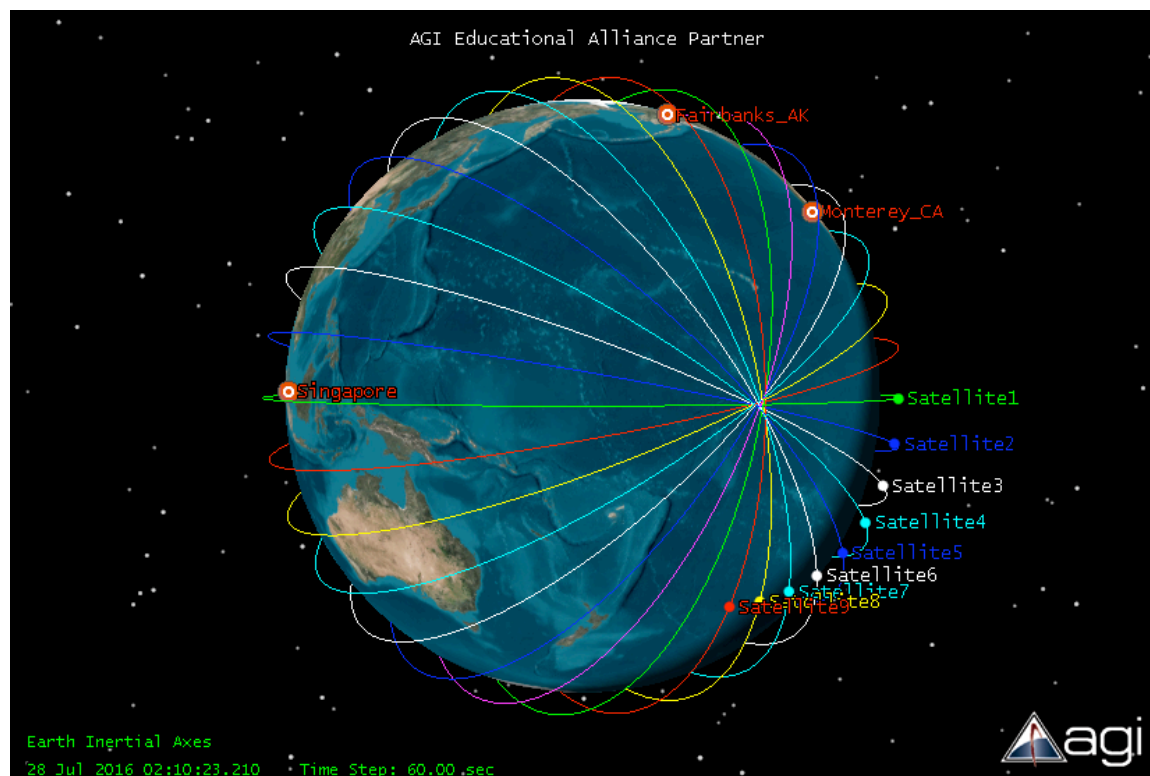


Fig. 5. Inclined Orbit Constellation

TABLE II
DECAY LIFETIME OF CUBESAT

Orbital Height (km)	Decay Lifetime from STK	Decay Lifetime Adapted from [14]	Decay Lifetime Adapted from [15]
180	< 1 day	< 2 days	-
200	1-3 days	2 days	-
250	7-14 days	5 days	-
300	28-49 days	18 days	29 days
350	81-158 days	58 days	-
400	155 days - 1.5 years	167 days	256 days
450	2.6 - 5.1 years	1.1 years	-
500	1.3-7.4 years	2.4 years	4 years
550	268 days - 11.8 years	7 years	-
600	6.2 - 22.5 years	15.1 years	20 years
640	> 25 years	> 25 years	-

where all the planes converge. This point, known as the convergence point, is either at the equatorial or the polar region, depending on the constellation design. Conversely, the diverged region refers to areas where the Cubesats are located further apart. As the Cubesats are highly concentrated at the convergence point, there is a need to maintain a minimum separation distance between the Cubesats for collision avoidance.

2) *Decay Lifetime and Corresponding Orbital Height Selection:* The decay lifetime of all satellites is dependent on numerous variables, such as the drag force, solar flux, orbit configuration, satellite mass, drag coefficient, and cross-velocity area [14]. As a result, the decay lifetime of a Cubesat is highly variable, and there are many models in the market to perform the predictions. According to [10], the Jacchia 1971 model is widely used to represent the atmospheric density. We use that model in STK to generate the decay lifetime of a Cubesat starting from 180 km, which is the minimum height for a LEO satellite. The results will be verified with statistics acquired through open literature [14], [15]. A summary of the decay lifetime is shown in Table II.

Based on stimulated results and considering the standard guideline that limits the lifespan for small satellites to 25 years [16], the maximum orbital height of the Cubesat should not exceed 640 km. The analysis also showed that the most ideal orbital height would be 450 km as the decay lifetime coincides with the lifespan of typical electronic components and offers a reasonable time frame for the mission. If mission requirements call for short durations, the orbital height from 200 km to 300 km can also be considered.

3) *Number of Planes and Number of Satellites per Plane:* The methodology to obtain the optimal number of satellites per plane and the number of planes is described in the following section. The illustration of the geometry of a satellite with respect to the Earth is shown in Figure 6.

From this geometry, we first have to determine the footprint of the Cubesat, or the satellite coverage radius on Earth's surface; the coverage radius r is given by

$$r = h \tan \alpha \quad (1)$$

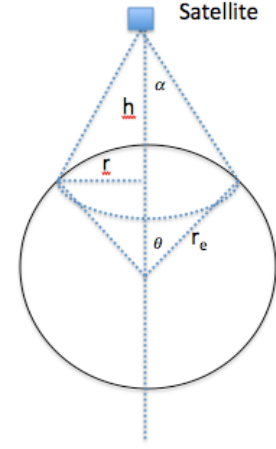


Fig. 6. Viewing Geometry of a Satellite

where h is the satellite orbital height and α is the satellites field-of-view angle. The Earth's central angle of coverage θ can be expressed as

$$\theta = \frac{360}{2\pi} \sin^{-1} \left(\frac{r}{r_e} \right) \simeq \frac{360r}{2\pi r_e}, r \ll r_e \text{ (degrees)} \quad (2)$$

where r_e is the radius of the Earth. We can obtain the number of non-overlapping satellite footprints per plane with the expression $360^\circ / (2\theta)$. For the purpose of the analysis, we assumed a 20% and 25% increase in the additional Cubesat footprints required to achieve the overlapping coverage. This assumption will be verified in the STK simulations. As Cubesat launches are dependent on p-pods that have been designed to have three Cubesats per pod [17], we will have the number of Cubesats per planes in multiples of three.

Last, as the number of planes is equally distributed around the Earth's hemisphere, i.e., half the Earth's circumference, this can be expressed as $180^\circ / (2\theta)$. Similarly, for the purpose of the analysis, the same assumption of a 20% to 25% increase in the number of planes to achieve the overlapping coverage will be applied. The parameters in Table III are used in the simulations to determine the selection of the Cubesat constellation deployment in the next section.

4) *Coverage of the Constellation:* Coverage is defined by the duration where there is LOS between the Cubesat and ground station or the time that the ground station has access to at least one satellite. As the footprint of each Cubesat overlaps the oncoming Cubesat, the ground station will always have continuous coverage, i.e., there is handshake from one Cubesat to another Cubesat. For locations not in the desired area of interest, there are intermittent periods when there is no coverage as the LOS with the Cubesat is lost. However, the next coverage period will commence once LOS is established with the Cubesat from the next nearest plane.

Coverage of a location is the key consideration when determining the optimal Cubesat constellation. Thus, we have selected three locations, Singapore, Monterey, and Fairbanks,

TABLE III
PROPOSED PARAMETERS FOR STK SIMULATION

Orbital Height (km)	Footprint Radius of Cubesat (km)	Number of non-overlapping Cubesats per plane	Number of overlapping Cubesats per plane		Proposed number of Cubesats per plane	Proposed number of planes
			20 %	25 %		
450	779	26	31	32	30, 33	15, 16, 17
300	520	39	46	48	45, 48	22, 23, 24
200	346	58	69	72	69, 72	34, 35, 36

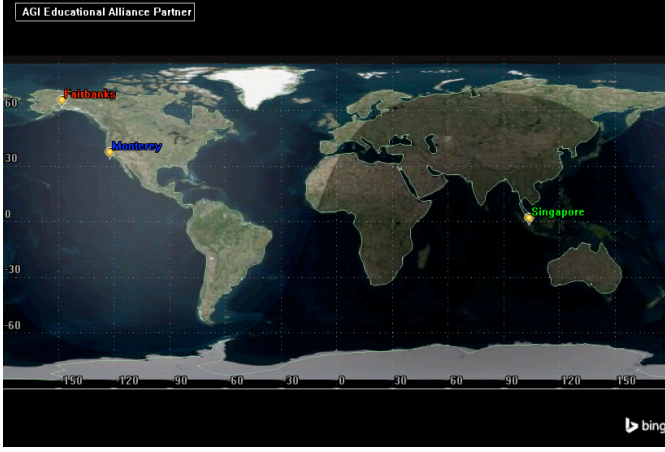


Fig. 7. Locations Selected for Simulation

with varying latitudes to determine the constellation coverage. Singapore, at a latitude of 1.29° , represents the coverage at the equatorial region. Monterey, at a latitude of 36.60° , is ideally located to represent coverage in the median latitude region. Lastly, Fairbanks at a latitude of 64.84° , which is close to the Arctic Circle (66.57°), is selected as it provides a good representation of the coverage in the polar region. An overview of the locations selected is shown in Figure 7.

After these locations are inserted into STK, we proceed to insert the Cubesat. We utilize the Walker tool to generate the constellations required for simulation. Sensors need to be attached to each satellite to emulate the Cubesat's field of view and its footprint. We configure the sensor type as 'Simple Conic' and set the cone half-angle to be 60° . This angle is the practical beamwidth of a Cubesat omni antenna. An representation of a ring of footprints generated by the Cubesat constellation on a single plane is shown in Figure 8.

An example of a polar constellation configuration with multiple planes to achieve continuous global coverage generated through STK is shown in Figure 9.

A final example of an inclined constellation configuration that is used in the simulation scenarios is shown in Figure 10.

IV. CONCLUSIONS

In this paper, studies have been carried out to investigate the best constellation design to provide continuous global coverage. One of the principle contributions of this work was

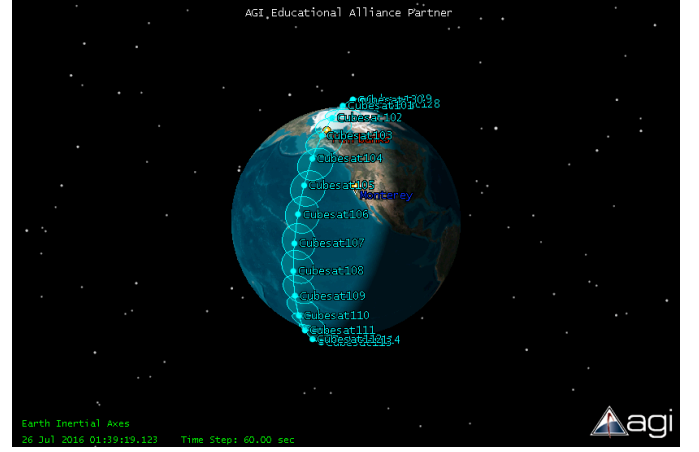


Fig. 8. Footprint Generated by a Cubesat Constellation



Fig. 9. Polar Constellation of 17 Planes with 33 Satellites per Plane

the affirmation of the feasibility of using a Cubesat constellation as an alternative communication backbone to achieve continuous global coverage. From a suite of space parameters of orbital mechanics, we identified the key elements required to determine the optimal height of our Cubesat constellation while meeting our mission requirement. These parameters are namely collision avoidance, Cubesat decay lifetime, and footprint.

Next, we proposed the use of polar and inclined constellations based on Walker's and modified SOC designs, respectively. Both the polar and inclined Cubesat constellation designs were then generated at three different orbital heights.

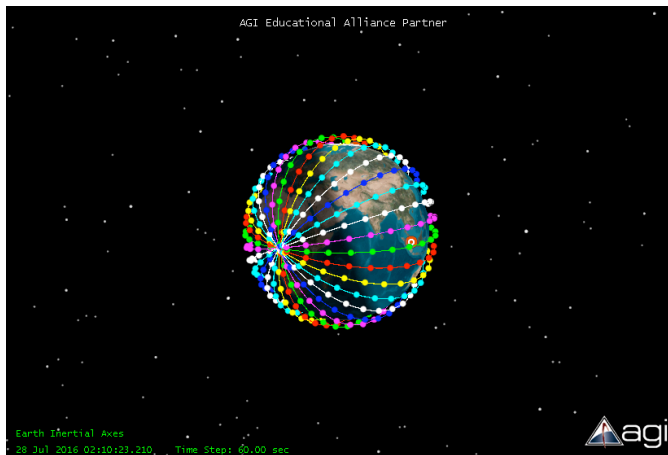


Fig. 10. Inclined Constellation of 16 Planes with 30 Satellites per Plane

From there, we determined a methodology based on the optimal number of planes and total number of satellites needed in the Cubesat constellation; this methodology was verified using the STK simulation program.

The Cubesat constellation at 450 km is recommended as it requires the least number of satellites, and it also has the longest decay lifespan. A Cubesat constellation of 17 planes with 33 satellites per plane is proposed for the polar constellation design while 16 planes with 33 satellites per plane is proposed for the inclined constellation design.

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