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CUBESAT CONSTELLATION DESIGN FOR AIR TRAFFIC MONITORING

Sreeja Nag

NASA Ames Research Center, Bay Area Environmental Research Institute, CA USA, sreeja.nag@nasa.gov

Joseph L. Rios¹, David Gerhardt², Camvu Pham³

¹NASA Ames Research Center, CA USA, joseph.l.rios@nasa.gov

²Gomspace ApS, Denmark, dge@gomspace.com

³San Jose State University, CA USA, camvu.pham@sjsu.edu

Suitably equipped global and local air traffic can be tracked. The tracking information may then be used for control from ground-based stations by receiving the Automatic Dependent Surveillance-Broadcast (ADS-B) signal. In this paper, we describe a tool for designing a constellation of small satellites which demonstrates, through high-fidelity modeling based on simulated air traffic data, the value of space-based ADS-B monitoring and provides recommendations for cost-efficient deployment of a constellation of small satellites to increase safety and situational awareness in the currently poorly-served surveillance area of Alaska. Air traffic data were obtained from NASA's Future ATM Concepts Evaluation Tool, for the Alaskan airspace over one day. The results presented in this study were driven by MATLAB and the satellites propagated and coverage calculated using AGI's Satellite Tool Kit.

I. INTRODUCTION

The Automatic Dependent Surveillance^{1,2} or ADS system is an effort to detect airplane states using a communicative on-board unit, instead of relying solely on traditional radar-based surveillance systems³. ADS is defined by initiatives in the US through the NextGen program and in Europe through the SESAR program. It is currently functional under the Broadcast (ADS-B) and the Contract (ADS-C) protocols. The ADS-B signal is emitted from the aircraft's Mode-S transponder to provide surveillance data. The *surveillance* data includes aircraft position, velocity, and altitude, as determined from a Global Navigation Satellite System (GNSS), as well as additional elements of navigational intent and meteorological data. The aircraft information is *automatically* transmitted periodically (at least once every second) without flight crew or operator input. Other parameters in the transmission are preselected and static. The transmission is *dependent* on proper operation of on-board equipment that determines position and velocity and availability of a sending system. ADS-B⁴ applications broadcast the data to anyone listening and, like surveillance radars, allow Air Traffic Control (ATC) to automatically and periodically access data from all suitably equipped aircraft and both use and re-broadcast it to suitably equipped aircraft within range. ADS-C, also known as ADS-Addressed or ADS-A, applications generate and transmit data in response to a request within the terms of the ADS contract held by the ground system. The contract constrains the type of data to be transmitted and the conditions of transmission.

The ADS-B/C signals are currently tracked by ground-based receivers but not over remote oceans or sparsely populated regions such as Alaska or the Pacific Ocean. Lack of real-time aircraft time/location information in remote areas significantly hinders optimal planning and control because bigger "safety bubbles" (lateral and vertical separation) are required around the aircraft until they reach radar-controlled airspace. Moreover, it presents a search-and-rescue bottleneck. Aircraft in distress, e.g. Air France AF449 that crashed in 2009, took days to be located or could not be located at all, e.g. Malaysia Airlines MH370 in 2014. Satellite constellations can aid ADS-based air traffic monitoring not only by providing accurate state information to the airplanes via GPS, but also in relaying that information from airplanes to ATC via a space-based communication network. Such a network will need to cover airspaces of interest for continuous monitoring. Constellations have recently been proposed for many aspects of earth observation such as reduction of revisit time between measurements⁵, achievement of global coverage as well as continuous monitoring of specific regions^{6,7}. This paper will use the tools and algorithms developed for distributed space mission design⁸ to design and evaluate constellations for ADS-B or ADS-C signal relay from airplane to ground, given an airspace of interest.

II. PROBLEM AND SOLUTION DEFINITION

II.1 Ground-Based Air Traffic Tracking

ATC has traditionally used ground radar based systems as the surveillance system of choice. A radar system typical consists of primary surveillance radars (PSR) and secondary surveillance radars (SSR), and both

have worked complementarily with radio systems since the 1950s⁹. Due to exponential increase of air traffic (32% in the last decade¹⁰), radar systems are getting saturated and more sophisticated and advanced systems are being developed. Radar sensing is also noisy and prone to interference and garbling¹¹.

ADS-B and C systems saturate slower than radars because mode S can resolve two aircraft when they are at the same geographical position and can also discretely interrogate single aircraft transponders. They have higher visibility and increased efficiency versus radars because their digital signals do not deteriorate with range like radars. If aircraft are also equipped with commands to listen, ADS-B technology allows all the airplanes in the airspace to know where the others are and use these data in their collision prevention systems.

Ground-based air traffic control, whether it is with a radar or ADS system, is faced with the challenge of poor coverage in remote areas and over the oceans where ground towers cannot be installed. HF (High Frequency) voice and data links have been used over oceans because HF has the advantage of complementing ground wave and sky wave propagation, unlike VHF¹². However, it too suffers poor link quality due to deterioration with range.

II.II Air Traffic Tracking using Satellite Communication

Satellite communication is indispensable for relaying aircraft signals in remote and oceanic areas. Current ADS-B systems have only been demonstrated as monoliths (single spacecraft) and their deployment as constellations have only been discussed, but never demonstrated.

In 2013, ProbaV became the first space platform (140 kg) to carry an ADS-B transponder into space and DLR – the German Aerospace Center - was subsequently able to receive, decode and forward all Mode-S downlink telegram formats using its ADS-B over Satellite in-orbit demonstrator¹³. The mission, in spite of being a demo, was able to identify 44,665 aircraft and detect 149,568 messages. Shortly after that, Denmark's Gomspace ApS launched its 2U CubeSat GOMX-1^{4,14} which went on to collect over 3.5 million Mode S ADS-B frames in the 6 months it was operational. While the satellite operates normally in all other respects, the ADS-B payload has not responded to queries since May 2014. The Canadian CanX-7 mission, primarily a drag sail mission¹⁵ that has not yet launched, will carry an ADS-B receive antenna into orbit to track air traffic in the Northern Atlantic. It builds on the Canadian FLOAT experiment¹⁶ that carried a receive-only ADS-B detector on a self-bursting

stratospheric sounding balloon and spent 48 minutes over 60,000 feet.

A limited number of satellite relay networks for aeronautical applications exist and can be reflective (except for frequency conversion) or regenerative. Inmarsat was originally targeted as a maritime service for safety, but soon became available for aircraft and mobile users¹². The geostationary constellation currently supports Air Traffic Services (ATS) and Airline Operational Communication (AOC) services. The MTSAT system, operated for the Japanese Civil Aviation Bureau (JCAB), offers the same services to airlines in the Asia Pacific area and again uses geostationary satellites. However, geostationary satellites by virtue of being placed around the Equator are unable to cover the poles and associated remote locations such as Alaska, Siberia and the Northern Pacific. Further, due to cost, demand and equipment requirements, many airplanes elect to use Inmarsat's ClassicAero Service which provides very broadbeam coverage as opposed to its SwiftBroadband system which uses multiple of smaller spot beams. Incidentally, Malaysia Airlines Flight MH370 used ClassicAero, whose Aircraft Communications Addressing and Reporting System (ACARS) can be switched off. Since the aircraft was not mandated to keep ACARS on over the Asian routes, it did not report its state information. However, ClassicAero on the aircraft pings Inmarsat's network at regular intervals to synchronise timing information, switches notwithstanding, as long as the aircraft is powered on. Inmarsat's team had to infer the aircraft locations on large arcs from its Burst Frequency Offset (BFO)¹⁷, causing large uncertainty and delay in locating the aircraft after it stopped transmitting.

II.III Improving Air-Sat Communication

Faster, more reliable air traffic control can be enabled by improving the air-satellite network connectivity using multiple satellites and improving the air-sat communication protocol. This paper attempts to address *only* the former by using existing models for current protocols.

Designing constellations

While it is estimated that 70% of the current commercial aircraft fleet (80% in Europe, 55% in the US) is ADS-B equipped, this number is approximately 20% for general aviation. Recent decisions, taken by EUROCONTROL and FAA, mandate that ADS-B be compulsory equipment on all high performance aircraft from 2015 and 2020 respectively. Simultaneous technology development on the spacecraft, to match those occurring on the aircraft side, will facilitate very minimal delay in aircraft information and tracking. So far, only single satellite^{4,18}, space-based ADS-B

capability has been flight-demonstrated which is insufficient for exhaustive monitoring even regionally. A fully deployed constellation will allow significant reduction in inter-airplane spacing, reduce fuel consumption (and emissions) with informed optimization of routes, reduce flight time, and increase usable airspace leading to a predicted 16-fold increase in trans-oceanic flights¹⁹. Nav Canada has reported the reduction of required “safety bubbles” from 60×80 statute miles to 5×5 statute miles over the Hudson Bay, leading to predicted annual fuel savings of \$9.8 million/year¹⁹. ADS-B has been demonstrated (in simulation) to aid collision avoidance planning using dynamic programming²⁰ and can be used to support Traffic Alert and Collision Avoidance Systems (TCAS).

The Iridium Constellation (NEXT), currently under development, will host ADS-B receivers on its 66 satellites and is scheduled to start operations in 2018²¹. Its inter-sat links are in the K_a band while user links are in the L band. However, no public information is currently available about its cost or availability to government or commercial users. Section III and the rest of the paper assumes Iridium to provide 100% coverage continuously and discusses the development of a constellation design for air-sat network connectivity that meets absolute performance metrics in terms of coverage and delay.

Better Transponder Algorithms

The first vulnerability for ADS-B transmission is the risk of GPS failures and information integrity²² at the aircraft. If the aircraft does not know its true state, it cannot relay the correct state.

The second vulnerability is at the spacecraft receiver. When several messages arrive at the ADS-B antenna onboard the satellite at the same time, they overlap and cannot be decoded by the ADS-B receiver^{4,13}. The risk of garbling or packet collision increases as more airplanes are in the field of view of the receiver. Multi-beam approaches as well as clever data processing algorithms are currently being researched to mitigate these risks. They will be modelled statistically in this paper, with no claim to improve current methods.

ADS-B vs. ADS-C Protocol

ADS-B, due to being a broadcast application that was designed to promote broad use by using inexpensive equipment, is plagued with security issues. First, ADS-B comes directly from the aircraft and is freely available to anyone with a 1090 MHz receiver without passing through any agency for filtering or control. This allows malicious tracking of specific airplanes with possible intent to destroy (e.g. suicidal terrorism, bombs on model planes) and without-consent tracking of private planes

leading to loss of competitive advantages of businesses*. Second, studies have shown that ADS-B messages can be generated using very inexpensive hardware such as the Universal Software Radio Peripheral (USRP) as the radio frequency (RF) front end and GNU radio as the development toolkit to build the software defined radio (SDR) application for signal processing¹⁰. Junk ADS-B packets generated in this manner can be used to flood the airspace causing a jam in the receiver due to overflowing data collision. For example, the Department of Defense (DOD) intentionally jammed TCAS and ADS-B channels for part of the Eastern U.S. in September 2015[†]. Rogue ADS-B transmitters also have the ability to create ghost airplanes on pilots’ display screen to confuse them. Given the lack of any interoperability between ADS-B and legacy radar systems, it is difficult to cross-check identities of airplanes appearing on the display screens.

The Broadcast protocol is thus very susceptible to malicious intent. Since ADS-C applications are contract-driven, they are more difficult to hack. Contracts are of three types: periodic (time interval and groups specified), on demand (of ATC) and on event (e.g. waypoint change or lateral deviation change). ADS-C applications also support emergency alerting, wherein the flight crew can send out a report highlighting an emergency situation to ATC manually, indirectly or covertly.

The values of constellation design variables used in this paper are either the same between ADS-B and C or similar enough that results are not expected to be affected. Further, the design tool presented is modular and scalable, such that more details of either ADS system, depending on which one is chosen after protocol/algorithm/antenna assessment, can be modelled as they become available.

III. SOLUTION EVALUATION METHOD

Aircraft locations in remote areas can be retrieved with minimum delay by using an optimized constellation of small satellites in low Earth orbit that will receive ADS-B signals from aircraft and relay it to ground stations. So far, a 2U CubeSat is the smallest, free-flying unit to have demonstrated space-based ADS-B. GOMX-1, developed and operated by GomSpace ApS (Denmark), will serve as an ideal theoretical first unit for

* ADS-B: terrorist’s Dream, Security’s Nightmare - <http://www.airsport-corp.com/adsb2.htm>

† Online news article: <https://www.intelliconnect.com/alert-air-traffic-collision-warning-systems-locators-down-off-east-coast-and-5-states-until-oct-1/>

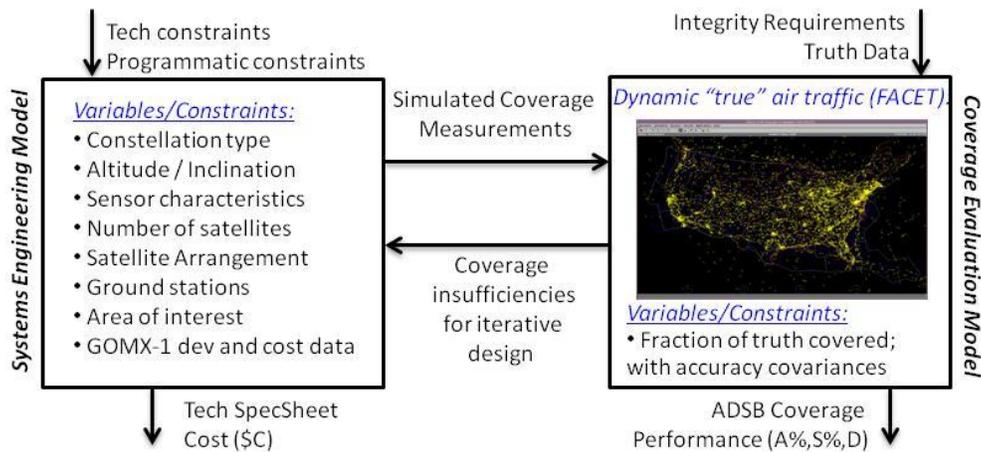


Figure 1: Coupled constellation design (driven by Model Based Systems Engineering or MBSE) and evaluation (driven by science-inspired Observing System Simulation Experiments or OSSEs) tool for designing an air-traffic monitoring sensor network in space

a CubeSat constellation with some parameters borrowed from PROBA-V¹³ and the Thales Alenia design for Iridium NEXT²¹. Satellites bigger than and not adherent to the CubeSat standard may be used, if required by the instruments.

Constellation design for ADS-B reception is a complex problem dependent on the following design variables as seen in the left box of Figure 1: area of interest (e.g. Alaska), simulated air traffic (e.g. from models or TCAS) and ADS-B receiver characteristics (e.g. field of view - FOV, signal attenuation, signal interference probability, congestion, SNR). The design variables are: Constellation type (e.g. Walker, precession type, ad-hoc), number of satellites, orbital parameters (e.g. altitude and inclination), and available ground stations. An architecture is defined as a unique combination of values for the mentioned design variables. A MATLAB-driven STK-based tool has been developed that is automated to generate hundreds of architectures and evaluate them based on the metrics shown in the right-hand box of Figure 1. They are: Percentage of airplanes and routes covered within the area of interest (A%), certainty of aircraft states (S%), delay in relaying the information to ground (D) and cost per packet (\$C). We have simulated the air traffic in the area of interest using a high-fidelity airspace simulator (Future ATM Concepts Evaluation Tool or FACET) developed at NASA Ames Research Center to obtain aircraft states that will serve as the “reference” or true airplane population. ADS-B receiver characteristics, signal integrity/interference, single satellite cost and cost to build multiple copies have been obtained from GomSpace and included within the performance

simulation. Ground stations from NASA’s Near Earth Network (both government-owned and commercial) have been considered. Costs for typically available launches as a function of constellation will be used, as explained in Section IV.IV.

Section IV will show the performance (A% covered at S% with D) and cost (\$C) for a few selected architectures, with an explanation of why they have been showcased. A% metrics refer to the percentage of airplanes covered at any instant of time and the percentage of any flight route covered. In air flight literature, these values are called the probability of target acquisition¹³. S% metrics represent the probability of the satellite system detecting an airplane that it has successfully covered or acquired. Probability of detection is a function of range between a satellite and airplane; and the risk of dropped packets due to interference. The presented simulations assume that if an airplane is within the field of view of a satellite, it can be identified with the same probability as detected.

The developed tool also has the capability to show performance vs. cost trade-offs between multiple architectures so that decision makers can evaluate these trade-offs for any location and select a few options that theoretically demonstrate critical functions within programmatic constraints. The airspace in the U.S. state of Alaska has been selected as a representative location. Alaska's terrain is too mountainous and weather too seasonal to build, and more importantly, maintain ground stations for ADS-B reception and relay. The proposed constellation shows comparable coverage to Iridium NEXT (100%

continuous coverage) at possibly cheaper costs than NEXT's expected subscription. The constellation design variable generation has been inspired by model-based systems engineering while the metric calculations compared to a reference or truth, inspired by the concept of observing system simulation experiments in Earth Sciences²³. Preliminary constellation design using such an approach has been demonstrated successfully for global Bi-Directional Reflectances²³ and albedo estimation and Earth radiation budget estimation²⁴.

III.I Constellation Types

Three types of constellations have been selected for the modelling exercise.

Among the uniform ones, Walker constellations with uniform phasing (where phase is half or less than half of the number of orbital planes) will be shown to provide the most uniform continuous coverage of Alaska with the least number of satellites. Streets of Coverage (SOC) uses a lot more satellites and when the number is minimized, the SOC design converges to the same design as Walker because the optimal inclination for the constellation was found to be at 90°. To initiate a Walker constellation, many separate launches will be required. Alternatively, a rocket (for example, Falcon-9) with multiple relight capability in orbit can be used. Plane changes are very expensive – a 2-plane design will need >10 km/s – thus, a large rocket will be required. Separation of satellites within the same plane can be achieved by the deployer's propulsion or by atmospheric drag manoeuvring using satellite attitude, and may take between a few days to many months⁷ respectively.

Among the non-uniform constellations, ad-hoc constellations are those where satellites are launched as and when secondary launches become available. PlanetLabs Inc.²⁵, a start-up based in San Francisco aiming to image the globe daily, provides an excellent example of ad-hoc constellations because they launch their 3U CubeSat imagers (called Doves or Flocks) on secondary launches, many at a time. Ad-hoc launches are separated in time, causing a delay in full operations.

The third constellation type can be launched using a single rocket that drops off each satellite at a slightly higher altitude and inclination compared to the previous, by performing impulsive burns in between drop-offs. The burns may be carried out by a rocket (for example, Orbital ATK's Pegasus) or by a propulsive adapter (for example, Spaceflight Inc.'s Sherpa). The differential altitude and inclination will

cause the satellites to precess at different rates and, over time, cause the planes to spread out without needing any propulsion. However, once maximum spread has been achieved, the planes will merge back together and continue doing so periodically. Operations requiring maximization of airspace coverage are best performed over periods of higher spread, as will be shown in the results.

Uniform constellations will need to be maintained (either propulsively or with atmospheric drag manoeuvres) to keep them so^{8,26}. Non-uniform constellations don't need to be maintained, except to avoid potential collisions.

III.II Sensor Characteristics

ADS-B differs from mode S in that the message is 112 bits, 120 μ s long and uses extended squitter messages²⁷ (not interrogated). The Half Power Beam Width (HPBW) of the GOMX-1 sensor⁴ is 20° and provides a maximum gain of 10dB. Prior work has shown that LEO satellites can detect ADS-B signals with net receiver gains of 0-5 dB and GEO satellites need 30 dB¹⁶. The Doppler effects in both are negligible. A 20° Field-of-View (FOV) will need hundreds of satellites in a constellation to continuously cover Alaska because the ground footprints are <500 km. At least 90 satellites will be needed per plane to form a continuous train along track.



Figure 2: GomSpace's GOMX-1 sensor as obtained from their website:

<http://gomspace.com/index.php?p=products-platforms>

ProbaV's antenna HPBW¹³ had an elevation axis of around 73° and an azimuth axis of around 33°, for a maximum gain of 11.2 dBi. The FOV can be assumed to be a maximum of 120° (less than 2×73°, to be conservative) thus better than GOMX-1 in terms of coverage. Thales Alenia's simulations of the antenna being developed for Iridium NEXT²¹ shows the options of off-nadir pointing up to 63° (or FOV 126°) for full coverage, between 13° and 63° for medium coverage and between 26° and 59° for

reduced coverage. CANX-7's antenna simulations²⁸ show more than 60° off-nadir tilting for >5dBi gain, allowing for 120-130° FOV. All ADS-B receiver antenna designs^{21,28} specify a null in the nadir direction, so the airplane cannot be detected from directly overhead for a few seconds.

Antennas for a CubeSat sized payload that offer more coverage than that demonstrated by GOMX-1 are possible. However, we have kept the trade open for larger satellites to account for an advantage in antenna gain. The results presented in this paper assume limb-to-limb sensing (133°-137° FOV) and represent an upper limit on performance, given by an omni-directional, single-beam, uniform gain antenna. Due to the geometric constraints of a 2U or 3U CubeSat, no more than two helix antennas (one shown in Figure 2) may be used and the coverage is not scalable. Antenna development is thus critical to the constellation's success. Future work will take into account a realistic antenna with the few degrees of nadir null, its gain dependence on angle and the signal strength dependence on the satellite-airplane range.

III.III Area of Interest

FACET (Future ATM Concepts Evaluation Tool[‡]) has a physics based model of the US airspace and is capable of quickly generating and analyzing thousands of aircraft trajectories^{29,30} based on real traffic data. FACET is extensively used in over 40 organizations and has more than 5000 users. A 24 hour slice with 60,000 flights takes 15 minutes to simulate on a 3 GHz, 1 GB RAM computer³⁰.

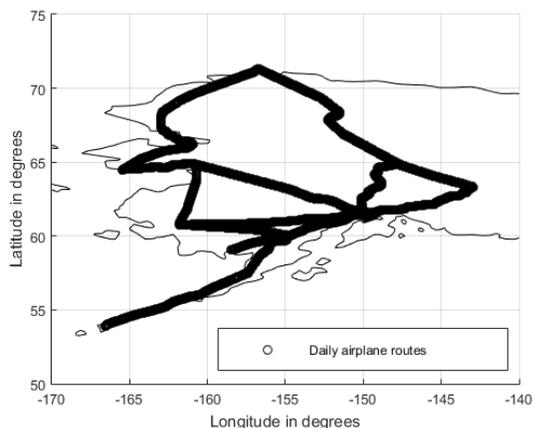


Figure 3: The ground projection of 600 flights (22 flight paths, 30 flights per path) over one day in Alaska, received as the output of NASA's FACET simulation

[‡] NASA ARC webpage on FACET: <http://www.aviationsystemsdivision.arc.nasa.gov/research/modeling/facet.shtml>

For this study, FACET is used to propagate the trajectories of expected flights between Alaska's airports forward in time and simulate air traffic over a day starting from June 6, 2015 at 13:00 UTC, an Alaskan morning. The airports considered are: ANC, PAL, WAS, FAI, SKW, GUL, TOK, POR, KIN, ILI, BET, DIL, UNA, NOM, KOT. Twenty two edges or flight paths were simulated between the fifteen airports and FACET produced thirty flights per path, amounting to 660 flights in all over one day. Figure 3 shows the flight paths in black, corresponding to 7679 unique latitude/longitude points. While these routes are not exhaustive, the airports and their connections serve as outer geographic bounds for expected Alaskan traffic. The performance numbers quoted in this paper are, therefore, representative of the full, true airspace. More routes for smaller, shorter flights, which are expected to be more toward the interiors, may be added to increase fidelity.

The NASA NEN³¹ is benchmarked as the ground station network, with receptors at 14 locations worldwide. Alaska has 3 antennas within the state (PF, USAK and ASF). Using them for downlink will cause negligible delay in relaying the aircraft states to the ground, once the satellite gets the ADS-B packet. GOMX-1 used an omni-directional antenna that did not need active pointing, but was limited to 9.6 kbps downlink due to frequency licensing constraints⁴. The link could be increased 10-fold, depending on the link budget and available band. If directional antennas are used, the Alaska (AK) ground stations will be difficult to use because the comm. antenna will need to be pointed to the dish, possibly disturbing the primary mission which is to keep the ADS-B antenna pointed nadir to track maximum airplanes. The feasibility of pointing such an antenna can only be determined once the bus has been designed or point independently of the bus.

III.IV Data or Packet Collision

ADS-B packet collision occurs when two or more arrive at the receiver at the same time, therefore the packets cannot be decoded. Message reception can be modelled using probability theory, as demonstrated by NASA Langley Research Center³² and the CanX-7 team in Canada³³ using a simplified version of the Aloha Protocol. The original protocol transmitted a message when ready without checking if the channel was busy. If it collided with another transmission, indicated by an absence of an acknowledgment, it re-sent the message – which ADS-B does not do. The simplifying assumptions made were that messages were not resent, all messages were assumed of equal length and all colliding messages were discarded. The

load is modeled as a Poisson process with rate $G = M_{att} * T$ where T is the length of a message (120 μ s) and M_{att} is the number of messages attempted (1 to 3.1 per second^{27,28}). A collision occurs if a message starts within the current or previous time frame. The throughput rate or reception rate is then given by Equation 1³³, where exp^{-2G} is the probability of a single successful transmission (no collision in $t=2$ time frames) and $G * exp^{-2G}$ is the transmitted load. Since the message rate (G) depends on the number of flights per coverage area, the probability of detection drops with increasing traffic volume.

$$M_{rx} = \frac{G * exp^{-2G}}{T}$$

Equation 1

The success rate of message transmission at any time instant is the ratio M_{rx}/M_{att} . Since the decoding of an ADS-B message (did the signal collide or not?) is a binary state, we can apply the binomial probability distribution. The probability of consecutive collisions is given by Equation 2. The probability of at least one successful transmission every x time steps (the equations remain the same across equal units of time) is $1 - P_x$, where:

$$P_x = [1 - M_{rx}/M_{att}]^x$$

Equation 2

The data collision model is assumed to be the same in the ADS-B or C protocol. Loss of signal integrity as a function of airplane-to-satellite range has not been considered in this study because GOMX-1's antenna was able to successfully detect planes up to the horizon at >2000 km. Thales Alenia has investigated the use of a multi-beam antenna design (1, 4 or 7 elements) where one reception beam corresponds to one processing channel. Packets from aircraft within an antenna's beam can then be divided into different channels, reducing collision probability.

In future studies, detected power from planes (75-200W transmitted) as a function of range and more detailed modelling of messages of different lengths³² may be important to consider. When a realistic antenna model is available (Section III.II), a trade space of multiple beams can also be explored.

IV. SIMULATION RESULTS

Performance and cost results for a selected few constellation designs will be presented in this section. The constellation types and variables will be evaluated on the basis of Percentage of airplanes covered within the area of interest (A%) and delay in relaying the information to ground (D). Since the

selected designs have no overlapping ground spots among the satellites and the sensor is assumed to be a single beam, certainty of aircraft states (S%) as a time series is the same for all architectures. The cost of development and launch (\$C), as a function of varying number of satellites and different constellation types, will also be discussed together.

IV.I Walker Constellations

A Walker constellation is one where all satellites have the same altitude, inclination, circular orbit, with varying and uniformly distributed TA (true anomaly) and RAAN (right ascension of the ascending node)³⁴. It has been extensively studied to provide global coverage, uniform revisits and specific latitudinal coverage³⁵. The upper and lower limit to altitude in the Walker constellation for this study is chosen as 600 km and 500 km respectively. Orbits above 600 km usually take more than 25 years to de-orbit naturally in the atmosphere, and will need propulsive de-orbiting to meet the UN requirement. Orbits less than 500 km may de-orbit in less than 3 years. Since the constellation may take many months to initialize, depending on launch availability and drag maneuvers, altitudes below 500 km are not considered to allow at least a few years of operations.

The number of satellites needed to cover the along-track ground swath over one plane can be analytically calculated as $360^\circ/\lambda$ where λ is the Earth centric angle subtended by their sensor's FOV. Eight and nine satellites are needed when the altitude is 600 km and 500 km because the limb-to-limb FOV subtends a λ of $\sim 48^\circ$ and $\sim 44^\circ$, respectively. A trade study of varying inclinations showed that two planes of FOV-to-FOV satellites are sufficient for near continuous coverage of Alaskan airspace only if the inclination is between 85° and 95° . Sun-synchronous secondary launches at 97° may be used if coverage gaps are acceptable or three launch planes are available.

Access durations to the southern-most point in Alaskan airspace [53.89° - 166.54° 762.5m], of all satellites in a 16-sat constellation at 600 km with 2 uniformly distributed planes for a 90° (top) and 70° (bottom) inclination, are seen in Figure 4. Coverage of regions further north significantly improve for the 90° constellation (poles are covered better) and diminish for the 70° constellation (lower inclinations miss the poles more). The latter shows a gap between time 13:00 to 17:00 UTC where the Alaskan point is not covered by any satellite, because for 5 hours it lies in the 90° RAAN gap between the two planes. The 90° constellation shows that the Alaskan point is

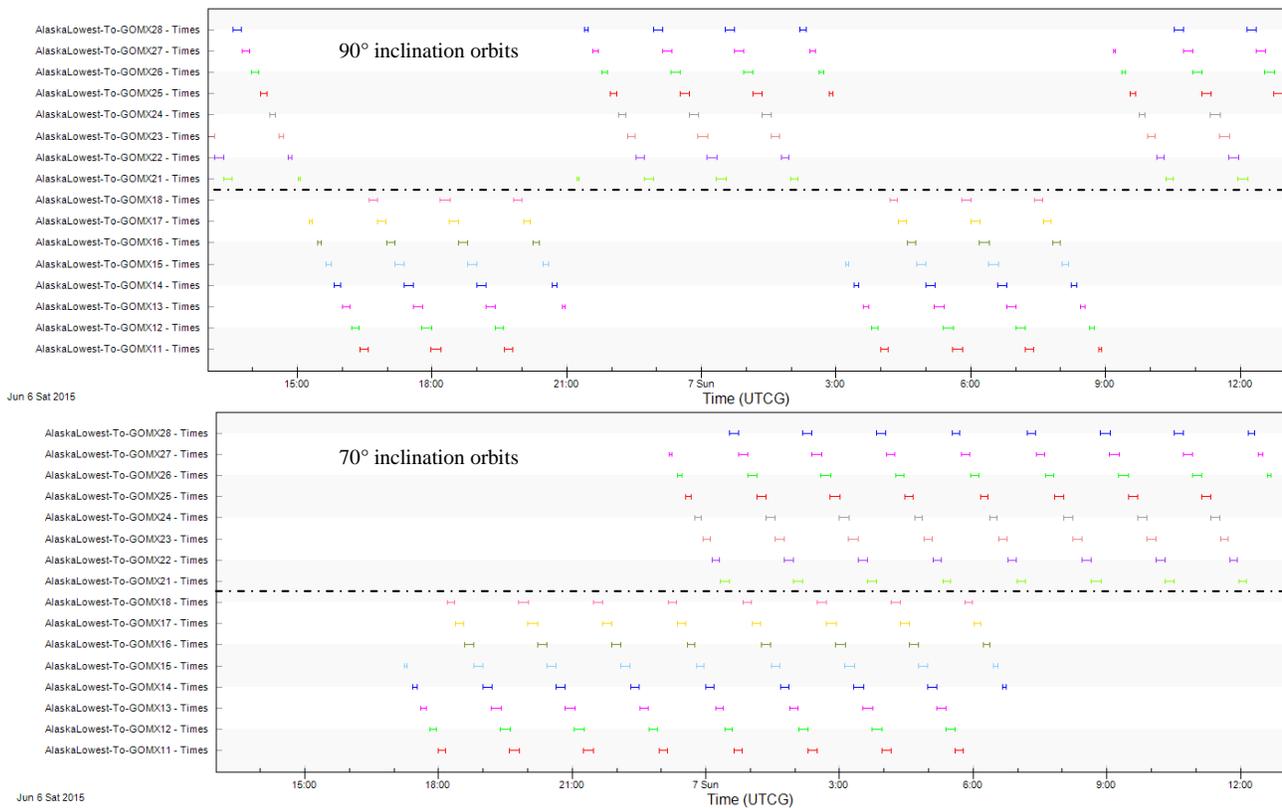


Figure 4: Access duration for every satellite (rows) in a 16 satellite constellation arranged in two planes over a period of 24 hours (X-axis) when the satellites are at a 90° [Top] and 70° [Bottom] inclination. Access is calculated for the point in Alaskan Airspace with lowest latitude, as obtained from FACET simulations. The lack of a colored horizontal bar across a vertical line drawn from a time step indicates that the Alaskan point is not covered by any satellite at that time.

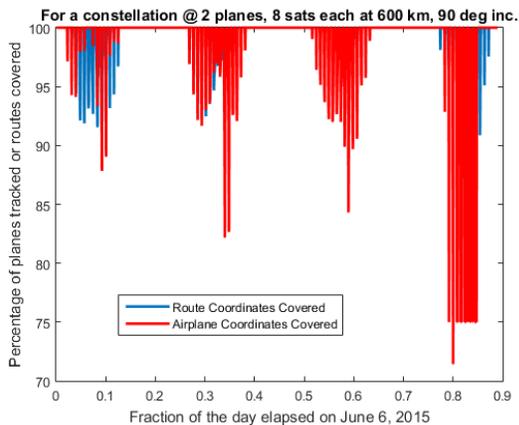


Figure 5: Instantaneous percentage of airplanes (red) covered by a 16-sat Walker constellation, where the true airplane population over Alaskan routes are simulated by FACET over one day. Percentage of Alaskan airspace coordinates covered (blue) irrespective of having airplanes on them, has been shown as comparison.

mostly covered by at least one sat at every instant and gaps are not visually noticeable (will be quantified subsequently).

The access duration distributions also show the necessity of multiple planes for continuous coverage. The satellites in the 2 planes are separated by the dashed, black line. If only one of those row sections existed (one plane only), there would be over 10 hours of no coverage per day for the southern region of Alaska. If another section of rows (third plane) were added, it would cover the small gaps at 21:00 and 9:00 UTC in Figure 4[top]. The third plane becomes necessary for more than 99% coverage when FOV is less than 132° and altitude less than 600 km.

Airplane coverage (A%) as a performance metric is quantified in terms of (a) the instantaneous percentage of airplanes that a constellation architecture covers at any instant of time over the simulation, and (b) the percentage of airplane routes covered. For every architecture, satellites are

propagated using AGI STK’s High Precision Orbit Propagator (HPOP) and coverage of the ‘true’ airplane states (time-dependent FACET output) calculated using MATLAB-driven STK. Coverage reports are post-processed to calculate the performance metrics. For every time step in the simulation, metric (a) is calculated as the ratio of the airplane dynamic states within any satellite’s FOV to the number of airplanes in Alaskan Airspace, as populated by FACET. Figure 5 shows the results for a 2-plane, 8 sat-per-plane Walker constellation at 600 km, 90° inclination. The average airplane coverage over time is 99.05% and median of 100% (non-normal histogram). The last 10% of the day has no flights (Alaskan night), therefore not plotted.

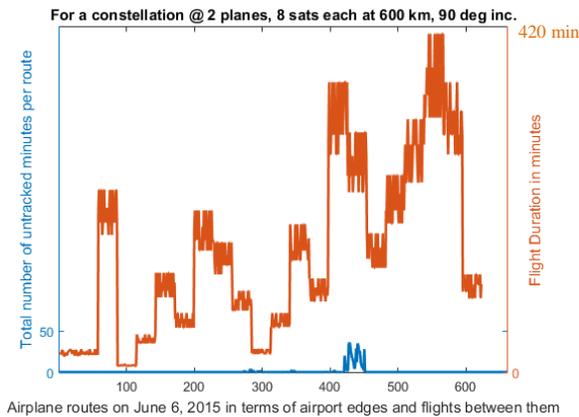


Figure 6: Total time per route (blue), of 660 routes populated by FACET over a day, that an airplane is not covered by any satellite in a 16-sat Walker constellation. The time is the complement of percentages in Figure 7 multiplied with the flight time for that route (orange).

For every flight route in FACET’s output, metric (b) is calculated as the total number of minutes or time steps (orange minus blue in Figure 6) when the airplane is within the FOV of at least one satellite in the constellation divided by the flight time for that route (orange in Figure 6). The ratio is shown in Figure 7 and is an average of 99.68% and median of 100% for the 600 km constellation. In comparison, if the sensor FOV is smaller by a few degrees or the constellation altitude is 500 km (earth centric angle of 22° instead of 24°), 9 satellites per plane are required to cover each plane instead of 8. Cross-track coverage, however, is compromised due to the lower FOV. A 2-plane 18-sat constellation provides 97.8% mean instantaneous coverage (a) and 98.8% mean route coverage (b). Thus, as a realistic antenna design becomes available or a different launch altitude is required, the tool can easily show impact on the above performance metrics.

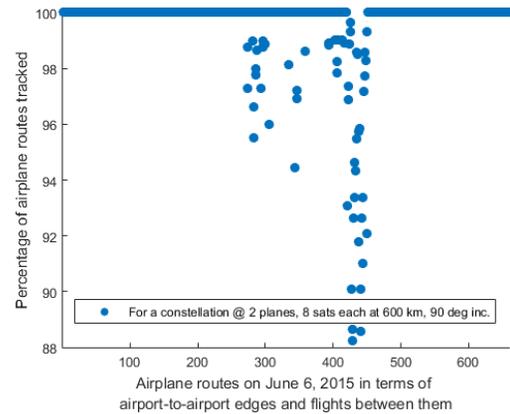


Figure 7: Percentage of routes, among the total 660 populated by FACET over a day, covered by a 16-sat Walker constellation at 600 km.

The absolute number of minutes any airplane is not covered indicates the total time period when its state is unknown to ATC, and is an important metric reflecting temporal coverage of the airspace. It must be considered in addition the percentage values in A% (metric (b)). More pertinently, the absolute number of *continuous* minutes that any airplane is not covered or the tracking *gap* indicates the minimum delay (D) in ATC’s knowledge of the airplane’s state. Member States of the International Civil Aviation Organization (ICAO), in February 2015 in Montreal, recommended[§] the adoption of a new 15 minute aircraft tracking Standard. In the context of this paper, the maximum delay (D) should be 15 minutes. For every airplane route, the tracking gap is plotted in Figure 6. The average tracking gap (red) is well below 5 minutes for the 500 km or 600 km constellation. However it is the maximum tracking gap (blue) that should meet the new ICAO standard. As seen in Figure 8, the gap is 6 minutes for the 600 km design and 28 minutes for the 500 km design. The factor-of-four difference (compared to a 1% difference in coverage) shows clearly that tracking gap (delay D) is the most sensitive metric to constellation architecture.

The tracking gaps indicated in Figure 8 represent the delay in state transmission from airplane to satellite. The delay in transmission to ATC also includes the time needed for the satellite to downlink to the closest ground station (GS). If the AK ground

[§] United Nations Specialized Agency (ICAO) website: <http://www.icao.int/newsroom/pages/states-recommend-new-flight-tracking-performance-standard-at-icao-high-level-safety-conference.aspx>

stations are considered or a TDRSS (Tracking and Data Relay Satellite Systems) link is used, the downlink will be immediate. The distance between the 500-600 km orbit satellites and the closest TDRS varies between 35,000 km and 40,000 km, and this communication link may enforce a higher power and communication subsystem requirement on the CubeSat.

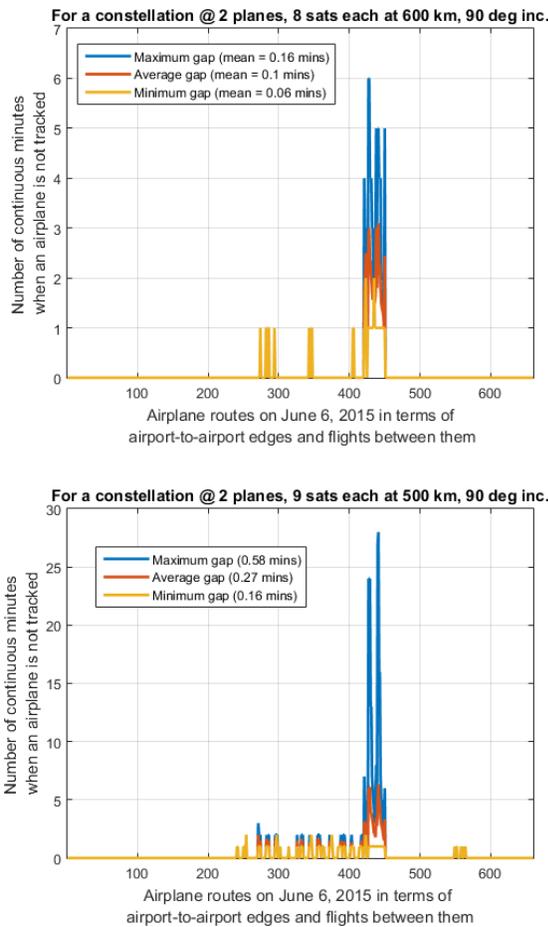


Figure 8: Coverage gap time - maximum, minimum and average - per route, among the 660 populated by FACET over a day. A gap is a continuous stretch when an airplane is not covered by any satellite in a Walker Constellation at 600 km [Top] and 500 km [Bottom].

If TDRSS is unavailable and spacecraft pointing constraints do not allow the 3 NEN stations in Alaska to be used, Figure 9 shows the distribution of gaps of different lengths (in minutes) between a satellite's access to airplanes on Alaskan airspace and then to the closest NEN GS. The simulation is run for 24 hours, for 2 different initial conditions for the ADS-B satellite, resulting in 58 closest, post-coverage GS

accesses for 58 orbits. Only eleven GS accesses (22% of the accesses to all NEN stations) are within 10 minutes of coverage ops, as required to meet the ICAO 15-minute standard after the 6-minute air-to-sat delay. The mean sat-to-GS delay is 30 minutes. The results are very similar within the 500-600 km altitude range. Without loss in generality, we can safely assume that the histogram will be similar for different launch epochs and satellite initial RAAN and TA. Therefore, additional non-governmental ground stations or the use of the AK stations will be required to reduce the time needed to downlink to the ground. AK stations can be used with an omnidirectional antenna, an appropriate non-amateur frequency allocation and a link budget that ensures reasonable data rates.

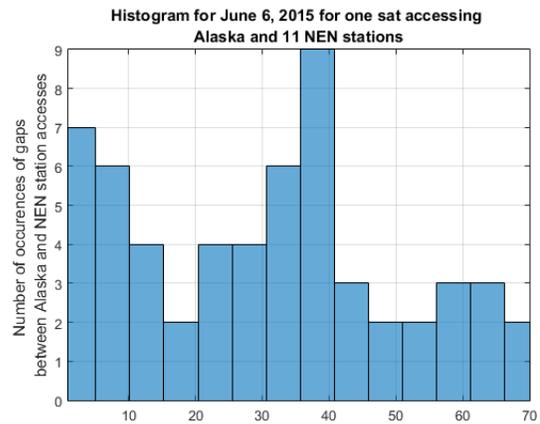


Figure 9: Frequency of gaps between when a satellite covers the Alaskan Airspace and when it accesses the next closest ground station in the NEN network.

The 600 km, 90°, 16-sat Walker constellation is found to meet the performance threshold for all metrics while minimizing the number of satellites. When a plane is subtracted from this design, i.e. 8 satellites in one plane are used, the mean instantaneous and route coverages are 74.7% and 67.8% respectively. Maximum delays in routes can be up to 5.5 hours and minimum delays as high as 2.5 hours, causing the 1-plane design to be very insufficient. When another plane is added to the proposed design, i.e. 24 satellites arranged in 3 planes are used, the coverage (A%) is 99.998% and mean delay per route drops to zero. Adding a plane increases launch costs by up to 50% (\$5-\$20 million as will be seen in Section IV.V). Unless decision makers have a stronger performance threshold, the 0.9% increase in coverage may not be worth the cost. The 500 km, 90°, 18-sat Walker constellation can be a good alternate design if the 7 of 660 (1%) routes

that have maximum tracking gaps >15 minutes can be ignored. If a plane is added to this design, the 27-sat constellation provides 100% coverage and no delays. However, as before, the cost may not be worth the improvement.

Multiple planes in Walker constellations need to be initialized using separate launches (or a large rocket with relight options) and satellites per plane can be separated using air drag or propulsion. Figure 10 shows the ΔV and time required to spread 8 satellites uniformly on a plane using as little as 5 m/s per satellite. The altitude bounds of 300 km and 800 km represent the lowest and highest altitudes considered in this study, from which an baseline of 500-600 km was chosen. The CYGNSS mission achieves and maintains this separation using drag⁷. Propulsive adapters such as Spaceflight Inc.’s Sherpa may also be used to provide the required ΔV .

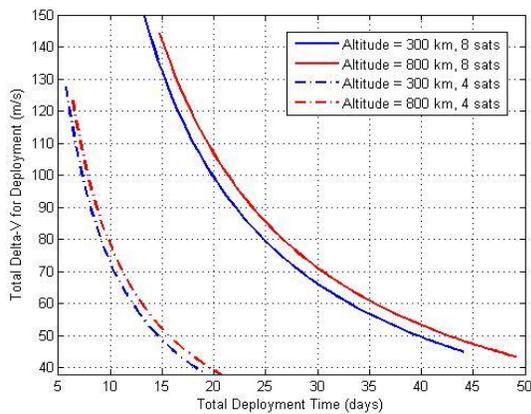


Figure 10: Trade-off between total ΔV (proxy for required fuel) and deployment time required to propulsively deploy 4 or 8 uniformly spaced satellites in the same plane. Time is a function of the phasing orbit.

Periodic maintenance is also needed to ensure the uniform spread of satellites in any plane and uniform phasing of satellites across planes. Maintenance can be done using drag manoeuvres or propulsion to correct for differential TA perturbations due to unpredictable gravity harmonic effects⁸. Maintenance ensures that the ground below any orbital plane is continuously covered by the theoretical number of satellites needed ($360^\circ/\lambda$). Previous studies have shown the monthly ΔV for maintenance to be 1-6 m/s depending on the available maintenance time (5 days to a few hours)⁸. Adding more satellites than the theoretical value relaxes the coverage requirement, but weekly maintenance will still be needed to avoid collision.

IV.II Ad-Hoc Constellations

Since Ad-Hoc constellations are formed by launching satellites as secondary launches become available, the current Planet Labs fleet of satellites are used as a representative example. Planet Labs has been launching 3U CubeSats in groups of up to 28 from the International Space Station (sent up with resupply vehicles) or from secondary rockets²⁵. The most current states of their satellites, from the Flock 1a-f constellation at the time of this writing, is available online at: <http://ephemerides.planet-labs.com/>. Thirty two satellite states were extracted as of summer 2015, in keeping with the epoch of FACET’s simulation. The altitude/inclination ranged from 318 km/51.6° for the ISS launches (21 Doves) to 606 km/97.95° for the SSO secondary launches (11 Doves).

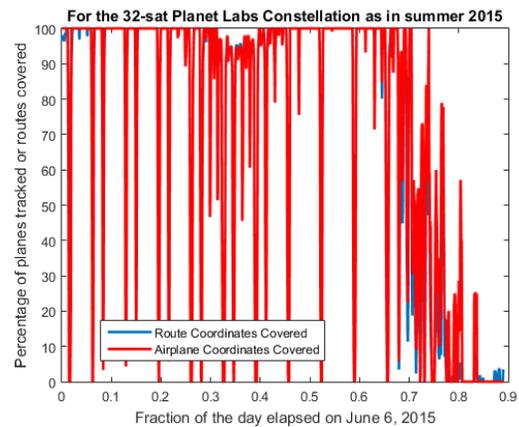


Figure 11: Instantaneous percentage of airplanes (red) covered by the current set of 32 Planet Labs satellites. Compare to the percentage of Alaskan airspace coordinates covered (blue) irrespective of having airplanes on them.

Since the Alaskan airspace ranges from 54° to 71° latitude (Figure 3), the 51.6° Doves will cover very little of the airspace even with the 36° earth centric angle sensor, corresponding to limb-to-limb sensing at 320 km. Moreover, since the constellation is neither uniformly deployed nor maintained in RAN and TA like a Walker constellation, coverage frequently drops to zero due to orbital gaps. Figure 11 shows the instantaneous coverage of the airplanes over a period of a day. The intermittent lows and nulls are clearly visible, as expected, and the average coverage is 74.7% in spite of double the number of satellites than the chosen Walker constellation. As mentioned before, the last 10% of the day has no flights (Alaskan night), therefore not plotted.

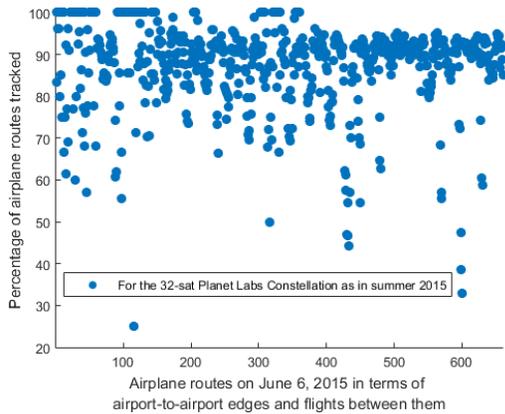


Figure 12: Percentage of routes, among the total 660 populated by FACET over a day, covered by the current set of 32 Planet Labs satellites.

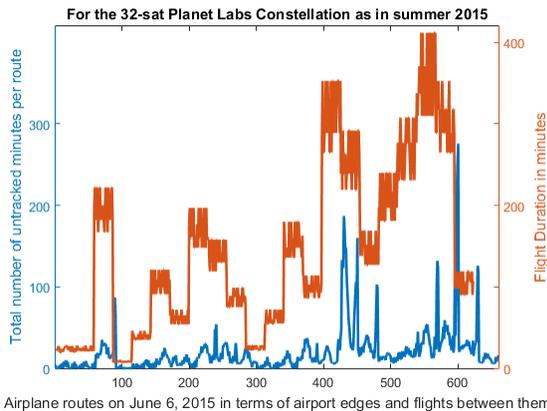


Figure 13: Total time per route (blue), of 660 routes populated by FACET over a day, that an airplane is not covered by any current 32 Planet Labs satellite.

The plot of route percentage coverage in Figure 12 averages to 87.8%. The route metric shows more optimistic results than the instantaneous coverage metric because coverage is mainly hit by the sudden nulls, which bring down the average but which constitute only a few minutes of null time for most routes. It is for the same reason, that the tracking gap time (D) is less than 15 minutes for 95% routes but peaks of up to 90 minutes are observed for a few routes - Figure 14. The maximum, total, untracked time per route can be well over 3 hours.

The delay (D) and route coverage (A%) (b)) metrics show that the Planet Labs constellation or, in general, the ad-hoc constellation design holds great potential for ADS-B monitoring, *only if* the satellites are well spread in TA and RAAN and active manoeuvring mechanisms (using drag or propulsion)

are used to maintain the uniform spread, just as in the Walker design.

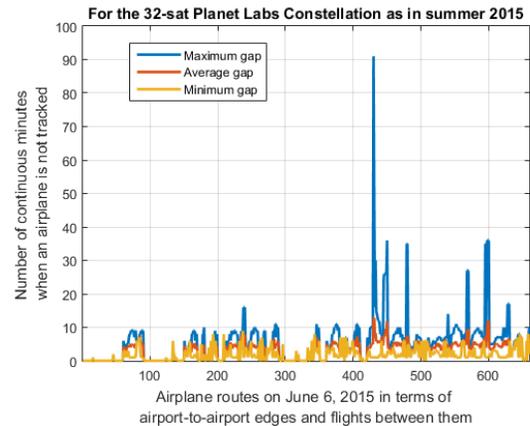


Figure 14: Coverage gap time - maximum, minimum and average - per route, among the 660 populated by FACET over a day, caused by the current 32 Planet Labs satellite constellation.

IV.III Continuously Precessing Constellation

Unlike Walker and Ad-Hoc constellations which use different launches to achieve a RAAN spread, followed by launched propulsion or air drag to achieve TA spread, precessing constellations use differential inclinations and altitudes to achieve both.

If the first satellite is dropped off at a 500 km altitude and 85° inclination, then the higher and more inclined the second satellite is, more will be its differential precession rate with respect to the first. The RAAN spread between the two will increase from zero at drop-off to maximum (acute 90°) depending on the differential rate. Figure 15 shows the time taken by two satellites to achieve a 90° separation in RAAN as a function of the differential altitude and inclination between them. The contours show the ΔV required to achieve the initial differential in alt/inc. 85° has been chosen as the starting inclination so that the highest point in Alaskan airspace can be optimally covered (Figure 4) and 500 km as starting altitude so that the satellites do not de-orbit in less than 3 years. Clearly, it takes almost a year to achieve the planar separation demonstrated in the 2 successful Walker designs until which there will be nulls in coverage as seen in Figure 4 [bottom] or Figure 11.

The differential altitude and inclination, and associated ΔV , per satellite needed to initialize a 16 satellite constellation in less than 6 months is seen in Figure 16. At least 3.5° of inclination plane change is

needed between the two extreme satellites, even at 100 km apart, to achieve this speed of initialization. Unfortunately, small primary launchers with multiple relight capabilities such as Orbital ATK's Pegasus rocket³⁶ with the HAPS module for insertion accuracy, do not have enough fuel to achieve that plane change. Large, secondary launches such as the Falcon-9 do not have enough relight options to launch 18 satellites differentially. The HAPS currently has 300 m/s of ΔV availability for LEO deployments, taking into account its mass, adaptor mass, mass of 18 ADS-B satellites and a maximum of 60 kg of fuel. The black contours in Figure 16 show the extent of Keplerian separation that fuel can get us – only half the required spread.

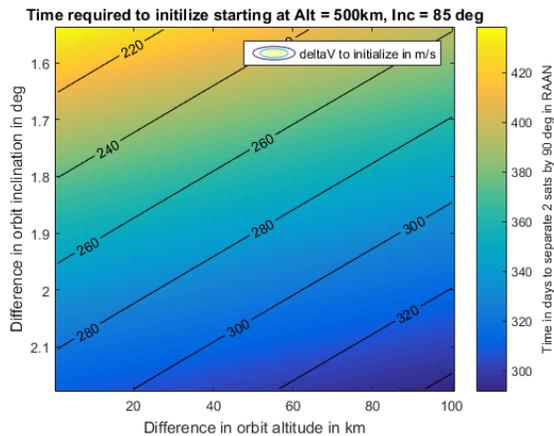


Figure 15: Time- ΔV trade-off for moving 2 satellites from zero to 90° apart in RAAN as a function of differential altitude and inclination, using chemical propulsion. The colors indicate time in days and the contours are ΔV in m/s.

The lack of a cheap, current launch vehicle to deploy a constellation of satellites, with plane changes in between, currently rules out a precessing constellation as a viable option to start mission operations within 6 months. Since it is the extent of plane change, not the number of satellites distributed in between, that drives the fuel and time, adding satellites to such a constellation would not help either. Moreover even if it were possible to launch, the planes would diverge and converge every 6 months, resulting in periodic nulls in coverage along track. The true anomaly spread from 0 to 180° is faster to achieve because satellites separated by 100 km (500-600 km altitude) diverge by 7.7° per orbit, along track. Any number of satellites spread uniformly within 500-600 km altitude at negligible true anomaly apart will diverge and converge with a period of 36-38

hours due to orbital period phasing resulting in periodic nulls in track. ADS-B tracking for a specified region is thus better performed with a uniform constellation.

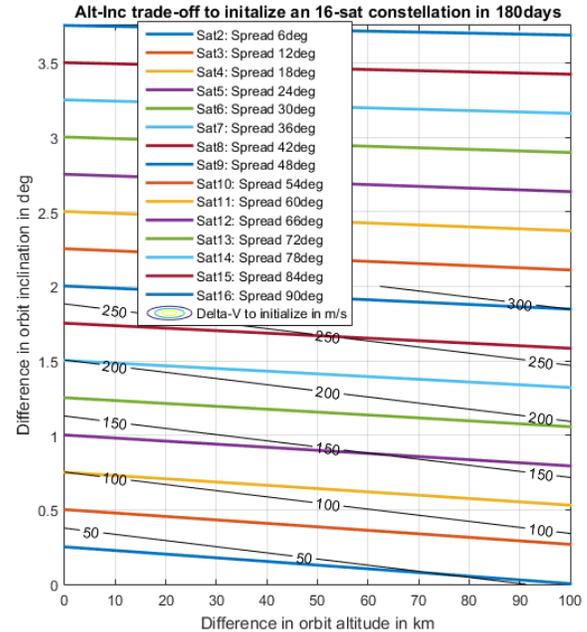


Figure 16: Trade-off between differential altitude and inclination required for spreading 16 satellites uniformly between zero to 90° in RAAN within 180 days. Each color represents a different sat's trade-off. ΔV required for initializing the different alt/inc is shown as black contours within available Pegasus HAPS fuel.

IV.IV Signal and Transmission Reliability

The certainty of aircraft states (S%) can be evaluated in terms of aircraft to satellite range and probability of packet collision. The Alaskan airspace spans ~25° in longitude and 20° in latitude and the sensor constellations proposed in this paper subtend 44°-46° of Earth Centric Angle (λ). Thus, within this study, the airspace is covered by none, one or two sensor FOVs at any instant of time. Figure 17 shows the probability of packet collision, as calculated using Equation 1 and its explanation, within any satellite's FOV when it is solely (blue) or jointly (red) covering the airspace at any instant over a day. The airplane population output by FACET over that day is plotted in yellow. It starts at 6 am, peaks during the 'office hours' and then drops off after sunset. More airplanes decrease the probability of successfully receiving a packet, nonetheless it is always better than 92% even when the coverage is transitioning from one satellite to another. The calculated probabilities are time unit independent and will remain the same if FACET

populates the airplane states every second instead of the currently simulated 60 seconds.

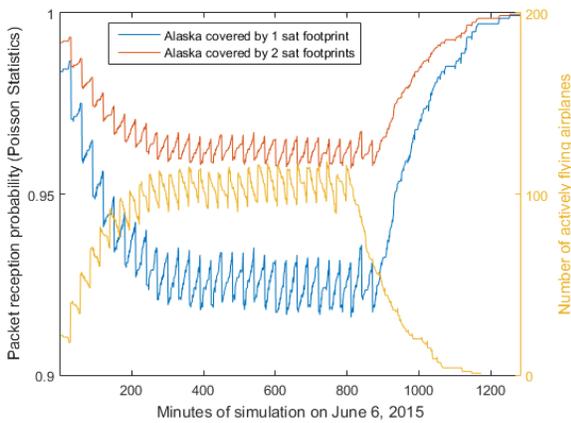


Figure 17: Probability of successfully transmitting a packet from an airplane to a satellite that reliably covers it as a function of time of day, airplane population within the FOV and number of FOVs covering the space

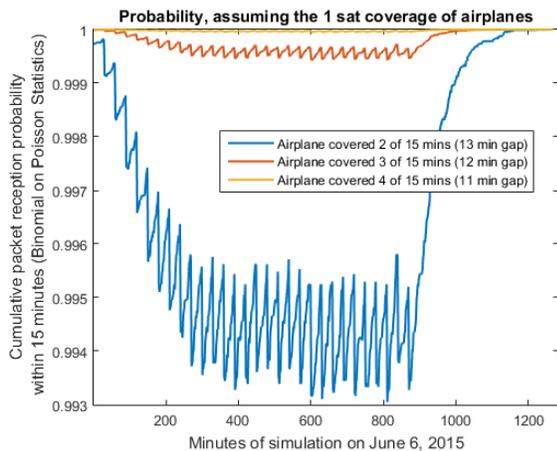


Figure 18: Probability of successful packet transmission from airplane to any satellite in the constellation in spite of sending as low as one packet a minute and 11 to 13 minutes of gap in coverage.

Since the ICAO recommends tracking of all airplane states every 15 minutes, the constellation must ensure that it successfully receives an ADS-B packet from an airplane in less than 15 minutes, in spite of nulls in coverage and data collision possibility. Equation 2 is used to calculate the probability of successful packet transmission within 'x' time steps. When transmission is considered every second, the probability of unsuccessful transmission for 30 seconds is between 1e-30 to 10e-90 while

failure for a full 60 seconds is between 1e-70 to 1e-190. Statistically speaking, for the Alaskan airspace simulated in this paper, the packet collision problem can be considered negligible within a minute's time frame.

If an airplane is able to establish contact with a satellite only once per minute, the ICAO 15-minute standard is well met. The probability of successful transmission within $x = 1$ minute is shown by the blue curve from Figure 17, assuming worse case probability. When $x = 2$ to 4 minutes, the results are shown by the curves in Figure 18. The probability increases very exponentially with time allowed for transmission, is ~ 1 if the airplane has at least 4 minutes of coverage from any satellite. Thus, even if the constellation has a gap in providing coverage to any airplane for up to 11 of every 15 minutes, it can still obtain the airplane state at greater than 99.999% probability in the remaining time. The proposed Walker design has a maximum air-to-sat gap of 6 minutes and possible 5 minute gap to downlink to a ground station, allowing sufficient time for non-colliding transmission.

The air traffic simulated over Alaska by FACET is mainly represented by the big aircraft that form the geographic bounds of the airspace. When small aircraft, of which Alaska has many, and the inter-continental flights crossing Alaska are added to this traffic, the aircraft population is expected to increase and the overall routes expected to be different. While this is not expected to affect coverage and delay results, it will affect signal collision. The maximum number of airplanes at any instant is 113 in the current simulation, corresponding to a maximum, instantaneous, collision probability of 0.9194. When the aircraft population is increased by 2-, 4-, 10- and 20-fold, the instantaneous probability drops to 0.85, 0.71, 0.43 and 0.19 respectively. Assuming transmission every second, successful reception at a satellite is possible within half a minute at more than 99% probability, even if the air traffic is 20 times that of our FACET simulations. Note that this number corresponds to increase in probability of failure by an order of 30. If transmission were to occur every minute (as shown in Figure 18), the probability of successful reception at the satellite, after an 11 minute gap, would be only 55.55% at 20 times the air traffic, compared to the currently simulated 99.999%. Thus, increased air traffic load can be mitigated by more frequent packet transmission, at a rate that is well within current ADS-B capabilities.

Future work entails a detailed study of the ADS-B receive antenna and modelling its hardware-dependent success in processing received packets, in keeping with signal dilution due to space loss and atmospheric noise²⁸.

IV.V High-Level Cost Estimation

CubeSat constellation cost prediction is an extremely difficult prediction for this study because of not having a reliable first unit cost, learning curve or operations/maintenance cost model³⁷. From a very high level estimate from GomSpace’s sales team, it would cost \$350k (USD) for one fully flight ready ADS-B satellite, reducing to \$275k as the number of satellites approach 50. We add an additional \$100k for the theoretical first unit (TFU) for development of a higher FOV antenna than GOMX-1. The learning curve parameter (b) is then found to be 93.84% - higher than NASA’s predicted 85% and JHU APL’s 67%, as inferred from their published data³⁷. Development cost of a constellation of variable number of satellites can be calculated from TFU and learning curve parameter “b”, and is shown in black in Figure 19.

Three launch options are considered for the constellations described in this paper – all satellites as a primary payload such as Orbital ATK’s Pegasus³⁶ (Precession constellation), secondary payload on multiple, big launches (Walker and Ad-Hoc constellation) such as SpaceX’s Falcon-9 and primary payload on multiple launches from small, start-up companies such as Rocket Labs^{**} (Walker constellation). We estimate Orbital ATK’s Pegasus with the HAPS module to cost \$45 million and be able to carry a maximum of 200 kg into LEO. This allows sufficient space for up to 27 ADS-B satellites of 7 kg each, as simulated in the precession case and is shown as a red star in Figure 19. Secondary launches have been modelled at \$140k per kg – a rough upper-limit estimate inferred from conversations with Space Flight Services^{††} and in keeping with the Pegasus data point. Secondary launch costs are likely to be much lower. Finally, new start-ups, with much lower Technology Readiness Level (TRL) than the above options, are proposing to deliver small satellites to commercial orbits at high temporal frequency. For example, Rocket Lab’s

Electron rocket^{‡‡} proposes to take 110 kg to a 500 km circular orbit for less than \$5 million. Their website advertises \$50k per 1U. The secondary and start-up launches, when added to the development cost, are shown in red and blue respectively in Figure 19. Other start-up alternatives for launch are also becoming available, such as the Super Strypi rocket which proposes to put 606 kg into a 400 km circular orbit at \$15 million per launch^{§§}.

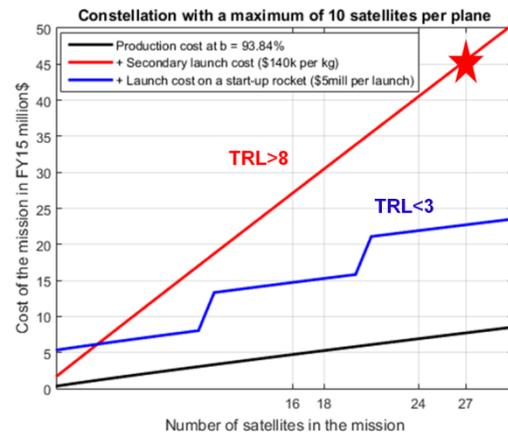


Figure 19: Development and launch costs

Since our proposed 16-sat, 2-plane Walker constellation needs 2 launches, the high-level cost is estimated to be \$15 million using Electron. Maintenance, ground station usage and operations costs have not been included. Operations support will need both scheduling of downlinks as well as maintenance to ensure uniform spread of the satellites per plane.

V. SUMMARY AND FUTURE WORK

This paper documents the preliminary results of Phase-A study for ADS-B constellations for Alaska, with the option of modifying it for other remote regions. Airplane populations and their daily, dynamic locations have been simulated using NASA ARC’s FACET tool. A Walker constellation with 16 satellites in 2 planes and a limb-to-limb sensor can cover more than 99% of Alaskan airspace continuously, and airplane states can be relayed to the space network in less than 6 minutes. Separate launches or propulsive drop-offs will be needed for

** Rocket Labs website :

<http://www.rocketlabusa.com/>

†† SFS website for secondary launch and Sherpa:

<http://www.spaceflightindustries.com/>

‡‡ Rocket Labs news release from July 2014:

http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11300831

§§ Spaceflight Now news article from March 2015:

<http://spaceflightnow.com/2015/03/23/debut-flight-of-rail-guided-space-launcher-slips-to-october/>

plane changes, and orbital spares will decrease the risk of performance drops in case of satellite failures. Ad-hoc constellations are a valuable alternative only if uniform spread can be achieved. In-track maintenance is essential to hold uniform spacing between satellites and ensure continuous coverage. Signal transmission reliability has been modelled statistically, and failure probability of air-to-space state transmission is found to be less than $1e-30$ for the simulated air traffic and less than 0.005 if the traffic were to increase 20-fold. With positive feedback and funding, and further development, we believe the presented concept holds great promise toward becoming a reality.

Future work includes the development of an ADS-B antenna with a larger FOV than GomSpace's current design. The new antenna design will help more detailed analysis of coverage in keeping with its gain pattern, range specifications and packet processing reliability along with the satellite's vertical radiation pattern. The air-sat communication community has voiced serious concerns about ADS-B's security, garbling and hack vulnerability. The presented study is directly applicable or easily modifiable for other protocols, such as ADS-C, as they become viable.

The presented study may also be extended to track and control unmanned air traffic in remote areas, especially those with challenging elevation maps such as Alaska. The results are deemed equally applicable to remote regions in the latitudes above the Arctic Circle. Global coverage can be achieved by adding 2 more planes of 8 satellites each, in addition to the 2 planes presented here. In other words, double the number of satellites used for Alaskan monitoring can provide world-wide air traffic tracking.

The design tool itself can be applied to applications beyond air traffic monitoring. By virtue of designing constellations for continuous coverage of a specific region, our constellation solutions will also be applicable to some Earth Science payloads such as a radiometer for sea-ice measurements in Alaska, whose temporal variation of albedo causes large uncertainties in the global radiation budget estimation. The tool can be additionally extended to include planning and scheduling design capabilities so that large numbers of airplanes, spacecraft and ground stations can interact with each other more seamlessly, much like the concept of an Internet of Things (IoT).

VI. ACKNOWLEDGMENTS

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