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CubeSat constellation design for air traffic monitoring

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ABSTRACT

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. It thereby 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 were driven by MATLAB and the satellites propagated and coverage calculated using AGI's Satellite Tool. While Ad-hoc and precession spread constellations have been quantitatively evaluated, Walker constellations show the best performance in simulation. Sixteen satellites in two perpendicular orbital planes are shown to provide more than 99% coverage over representative Alaskan airspace and the maximum time gap where *any* airplane in Alaska is *not* covered is six minutes, therefore meeting the standard set by the International Civil Aviation Organization to monitor every airplane at least once every fifteen minutes. In spite of the risk of signal collision when multiple packets arrive at the satellite receiver, the proposed constellation shows 99% cumulative probability of reception within four minutes when the airplanes are transmitting every minute, and at ~100% reception probability if transmitting every second. Data downlink can be performed using any of the three ground stations of NASA Earth Network in Alaska.

1. 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 systems [3]. 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. ADS-B surveillance service in the U.S. comprises of two systems: the 1090 Extended Squitter (1090ES) that operates on 1090 MHz and the Universal Access Transceiver (UAT) that operates on 978 MHz. While 1090ES is used commercially and worldwide, UAT is a regional system used extensively in the U.S. for aircraft operating below 18,000 ft.

The ADS-B signal is emitted from the aircraft's Mode-S, or sometimes Mode-C, transponder to provide surveillance data. The *surveillance* data includes aircraft position (latitude, longitude and altitude), velocity, 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-B [4] 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 (B or C) 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

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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 measurements, achievement of global coverage as well as continuous monitoring of specific regions [5,6]. This paper will use the tools and algorithms developed for distributed space mission design [7] to design and evaluate constellations for ADS-B or ADS-C signal relay from airplane to ground, given an airspace of interest.

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2. Problem and solution definition

2.1. 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 complimentarily with radio systems since the 1950s [8]. Due to large increase of air traffic (32% in the last decade [9]), radar systems are getting saturated and more sophisticated and advanced systems are being developed. Radar sensing is also noisy and prone to interference and garbling [10].

ADS-B and C systems saturate slower than radars because the transceivers can resolve two aircraft when they are at the same geographical position and can also discretely interrogate single aircraft transponders. They have very good line-of-sight propagation in the Earth's atmosphere and ionosphere, and provide increased efficiency, and enhanced position and speed information compared to radars. Signals deteriorate with range as characterized by the Friis equation, damped by signal interference due many applications sharing the same frequency [11] (see Section 2.3.2). If aircraft are also equipped with 'ADS-B In' capability, they can listen to the broadcast from all the airplanes in the airspace, know where the others are and use these data in their collision prevention systems. Additionally, the U.S. ADS-B system can also rebroadcast messages once received at ground stations (ADS Rebroadcast or ADS-R), to ensure aircraft receive position updates from other aircraft in the area that may be using a different transmission system (1090ES vs. UAT).

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 VHF [12]. However, it too suffers poor link quality due to deterioration with range.

2.2. Air traffic tracking using satellite communication

Satellite communication is indispensible for relaying aircraft signals in remote and oceanic areas. Current ADS-B systems have only been demonstrated as 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 demonstrator [13]. 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. The satellite operated normally for several months until the ADS-B payload stopped responding to queries in May 2014. The Canadian CanX-7 mission, primarily a drag sail mission [15] 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 experiment [16,17] that carried a receive-only ADS-B detector on a self-bursting stratospheric sounding balloon and spent 48 min 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 users [12]. 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 synchronize 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) [18], causing large uncertainty and delay in locating the aircraft after it stopped transmitting. While ADS-B (being automatic) and relaying ADS-B packets through a LEO constellation does not guarantee the prevention of the MH370 mishap, it does guarantee continuous tracking of airplanes which could reduce the probability of such an incident significantly or improve finding debris or remains faster.

2.3. Improving air-space communication

Faster and 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.

2.3.1. 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. The aircraft may use 978UAT up to 18,000 ft of altitude and 1090ES everywhere. 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 [4,19], 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 flights [20]. 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/year [20]. ADS-B has been demonstrated (in simulation) to aid collision avoidance planning using dynamic programming [21] 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 2018 [22]. The orbital ADS-B system will be hosted by Aireon LLC, which partners with NavCanada, Harris and Exelis, and promises a '100 percent global air traffic surveillance system' to Air Navigation Service Providers.[1] However, no public information is currently available about its cost or pricing model. Section 3 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.

2.3.2. *Better transponder algorithms*

The first vulnerability for ADS-B transmission is the risk of GPS failures and information integrity [23] 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 collide 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 [22] as well as data processing algorithms to retrieve ADS-B signal from noise [24] are currently being researched to mitigate these risks. They will be modeled statistically in this paper, with no claim to improve current methods.

Signal interference is more of a concern in the 1090 MHz data link (1090ES) because it shares the same frequency as downlink Air Traffic Control Radar Beacon System (ATCRBS) and Traffic Alert and Collision Avoidance System (TCAS). UAT at 978 MHz, being a regional system at low altitudes, has more data capacity and growth potential. In keeping with the Minimum Operational Performance Standards published in RTCA DO-181C and DO-260A, previous work [11] has extensively modeled probability of ADS-B 1090ES packet reception as a function of range and FRUIT (Friendly or False-Replies-Unsynchronized-In-Time) overlaps with up to one other TCAS Mode S packet and up to five other ATCRBS Mode A or Mode C packets. In comparison, our Poisson statistics model does not restrict the maximum allowable packet overlap and assumes that range-independence of constellation architectures, given the high transmit power of airplanes (200+W).

2.3.3. *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 [25]. 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 processing [9]. 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 [26]. 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.

We have used the message characteristics of ADS-B in this paper. However, the constellation design variables used in this paper are either the same between ADS-B and C or similar enough, that orbital coverage results are not expected to change. 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 modeled as they become available. Therefore, the data reception probability results can be updated appropriately.

3. 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 a CubeSat constellation with some parameters borrowed from PROBA-V [13] and the Thales Alenia design for Iridium NEXT [22]. 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 Fig. 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 Fig. 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

[1] Aireon (SM) Benefits and ANSPS Webpage: http://aireon.com/benefits/ansps/

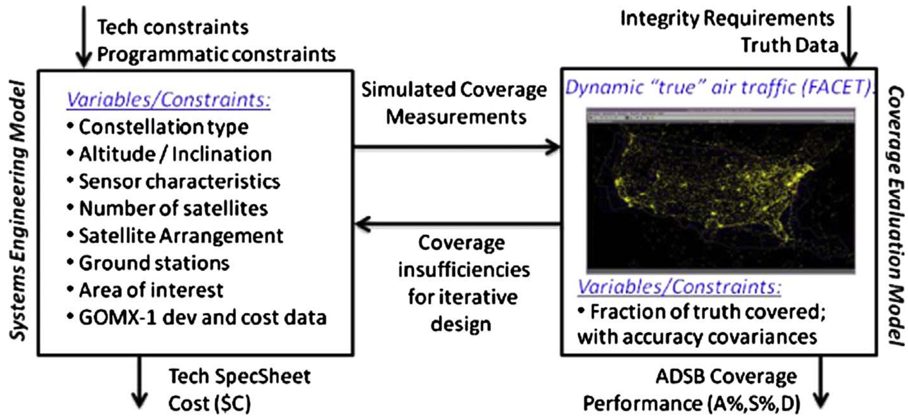

Fig. 1. Coupled constellation design (driven by Model Based Systems Engineering or MBSE) and evaluation (driven by science-inspired Observing System Simulation Experiments or OSSEs) tool for designing an air-traffic monitoring sensor network in space.

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 4.4.

Section 4 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 acquisition [13]. 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), with incomparable costs because NEXT's subscription model is not known. 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 Sciences [27]. Preliminary constellation design using such an approach has been demonstrated successfully for global Bi-Directional Reflectances [27] and albedo estimation and Earth radiation budget estimation [7].

3.1. Constellation types

Three types of constellations have been selected for the modeling 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 months [5] respectively.

Among the non-uniform constellations, ad-hoc constellations are those where satellites are launched as and when secondary launches become available. PlanetLabs Inc. [28], 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 [7]. Non-uniform constellations don't need to be maintained, except to avoid potential collisions.

3.2. Sensor characteristics

The ADS-B (1090ES) message is 112 bits, 120 μs long and characterized as an extended squitter message [24] (not interrogated). We have modeled only 1090ES in this paper, since it can be used by all aircraft, altitude notwithstanding, and is more prone to signal interference due to channel congestion, therefore more sensitive to constellation architecture. ADS-B may also contain 56 bit messages, which are used only for responding to interrogations by the ATCRBS. The message length and characteristics of UAT are also different, however our tool is modular enough that the message specifications can be changed easily if UAT were to be required in addition. The Half Power Beam Width (HPBW) of the GOMX-1 sensor [4] is 20° and provides a maximum gain of 10 dB. 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 dB [16]. 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.

ProbaV's antenna HPBW [13] 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 $2 \times 73°$, to be conservative) thus better than GOMX-1 in terms of coverage. Thales Alenia's simulations of the antenna being developed for Iridium NEXT [22] 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 simulations [29] show more than 60° off-nadir tilting for > 5 dBi gain, allowing for 120–130° FOV. All ADS-B receiver antenna designs [22,29] 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 Fig. 2) may be used and the coverage is not scalable. Antenna development is thus critical to the constellation's success. Future work will include 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, as part of the satellite constellation tradespace model. Individual models quantifying these dependences have been published [16,17,11] however never been included in a detailed constellation design optimization.

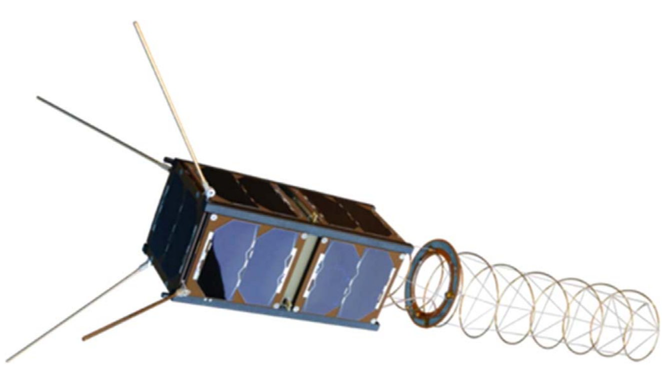

Fig. 2. GomSpace's GOMX-1 sensor [4].

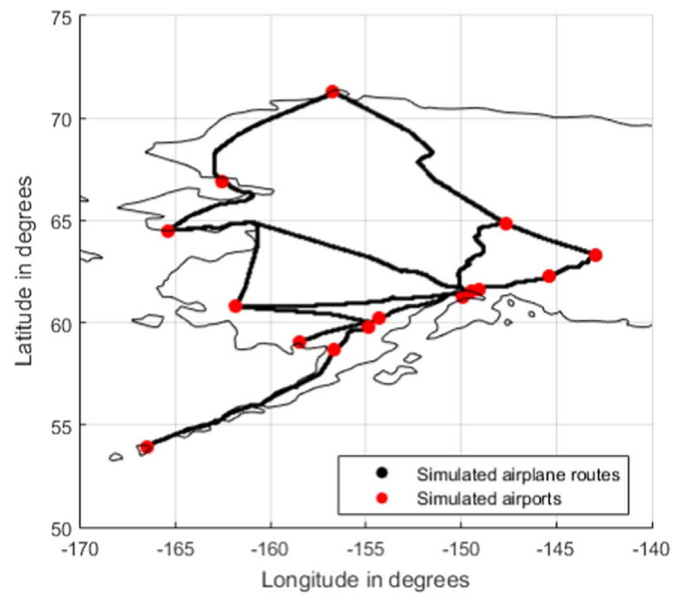

Fig. 3. The ground projection of 600 flights (22 flight paths, 30 flights per path) over one day in Alaska, received as the output of NASA's FACET simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3.3. Area of interest

For this study, airplane routes in Alaska over one day were generated in three steps.

First, sixteen airports in Alaska were identified to represent those with the busiest general aviation operations. They were also sufficiently spread over the state so that they cover the end points. The airports used are: ANC, PAL, WAS, FAI, SKW, GUL, TOK, POR, KIN, ILI, BET, DIL, UNA, NOM, KOT, BAR, as marked as red dots in Fig. 3. Twenty two edges or flight paths were hand drawn between the sixteen airports, representing reasonable routes that a general aviation (GA) pilot would take while following the existing and known mountain passes through Alaska's rugged terrain. Radar surveillance data in Alaska is mostly restricted to jet and cargo planes. GA pilots fly between altitudes 500 ft to 5000 ft, and radars are unable to cover such low altitudes due to the mountainous terrain. It is the lack of radar coverage that motivates this study of an alternate method of surveillance. Also, the pilots are not required to report their flight plans to any centralized authority and they are allowed to deviate from any reported plans during flight, therefore there is no standard, known database of plans.

Second, the 22 flight paths were input into the Future ATM Concepts Evaluation Tool[2] or FACET [30] to validate them. FACET has a physics based model of the US airspace and is capable of quickly generating and analyzing thousands of aircraft trajectories [31,32] based on real traffic data. FACET is extensively used in over 40 organizations and has more than 5000 users. A 24 h slice with 60,000 flights takes 15 min to simulate on a 3 GHz, 1 GB RAM computer [32]. The flights were validated using a Cessna-class airplane from the FACET database and the validated flight paths are shown in black in Fig. 3, corresponding to 7679 unique latitude–longitude points. The bends in the paths are due to the airplane flying through pre-assigned mountain passes and to stay over land, as much as possible, for safety reasons.

Third, the KML (Google Earth compatible) file outputs from the FACET simulation were used as waypoint inputs into a Java-based

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

tool, which propagated the trajectories of thirty flights per flight path over a day starting from June 6, 2015 at 13:00 UTC (Alaskan morning). The Java-based tool used the same equations as FACET but allowed for multiple and randomized generation of flights with different airplane start times, altitudes and speeds. Each flight was unique in time and altitude, but followed the FACET-validated waypoints so as to generate unpredictable but representative air traffic. The flights departed approximately every 30 min between 6 a.m. and 8:30 p.m. (Alaska Local Time). Alaskan terrain altitudes were generated using NASA World Wind SDK[3] and flights were simulated such that the airplane was always kept at least 500 ft above the ground. Airplane speeds for different flights are randomized around the Cessna-class typical speeds but are assumed constant throughout its flight.

The three-step process mentioned above produced a total of 660 flight trajectories (22 paths × 30 flights), with state information at every minute over one day, which we used as 'reference traffic'. The altitudes ranged from 1000 ft to 4600 ft. While these routes are not exhaustive because only large general aviation has been simulated, the airports and their connections serve as outer geographic bounds for expected Alaskan traffic. The addition of small aircraft, of which Alaska has many, and the inter-continental flights crossing Alaska to this traffic is expected to increase aircraft population and change overall routes. The performance numbers quoted in this paper are, therefore, representative of the full, true airspace. Expected change in performance due to increased traffic will be clearly pointed out in Section 4. More routes for smaller, shorter flights, which are expected to be more toward the interiors, may be added to increase fidelity.

The NASA Near Earth Network or NEN [33] 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 constraints [4]. 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.

3.4. 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 modeled using probability theory, as demonstrated by NASA Langley Research Center [34] and the CanX-7 team in Canada [35] 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 re-sent, 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 μs) and M_{att} is the number of messages attempted (1–3.1 per second [24,29] depending on 1090ES pr 978UAT protocols). A collision occurs if a message starts within the current or previous frame time. The throughput rate or reception rate is then given by Eq. (1), where exp^{-2G} is the probability of a single successful transmission (no collision in t = 2 frame times) 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.

$$M_{rx} = \frac{G * exp^{-2G}}{T} \tag{1}$$

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 Eq. (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:

$$P_x = \left[1 - M_{rx}/M_{att}\right]^x \tag{2}$$

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 data collision probability. Transmission power has not been modeled as a constellation architecture-differentiating design variable since large aircraft are mandated to transmit at at least 125W or 200W and at most 500W. In future studies, peak power available from airplanes as a function of range, signal interference from Mode A and C sources [11] and more detailed modeling of messages of different lengths [34] will be important parameters to include in the constellation optimization tool. When a realistic antenna model is available (Section 3.2), a trade space of multiple beams can also be explored.

4. 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.

4.1. 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) [36]. It has been extensively studied to provide global coverage, uniform revisits and specific latitudinal coverage [37]. 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

[3] NASA World Wind webpage with open source/open access: http://worldwind.arc.nasa.gov/java/.

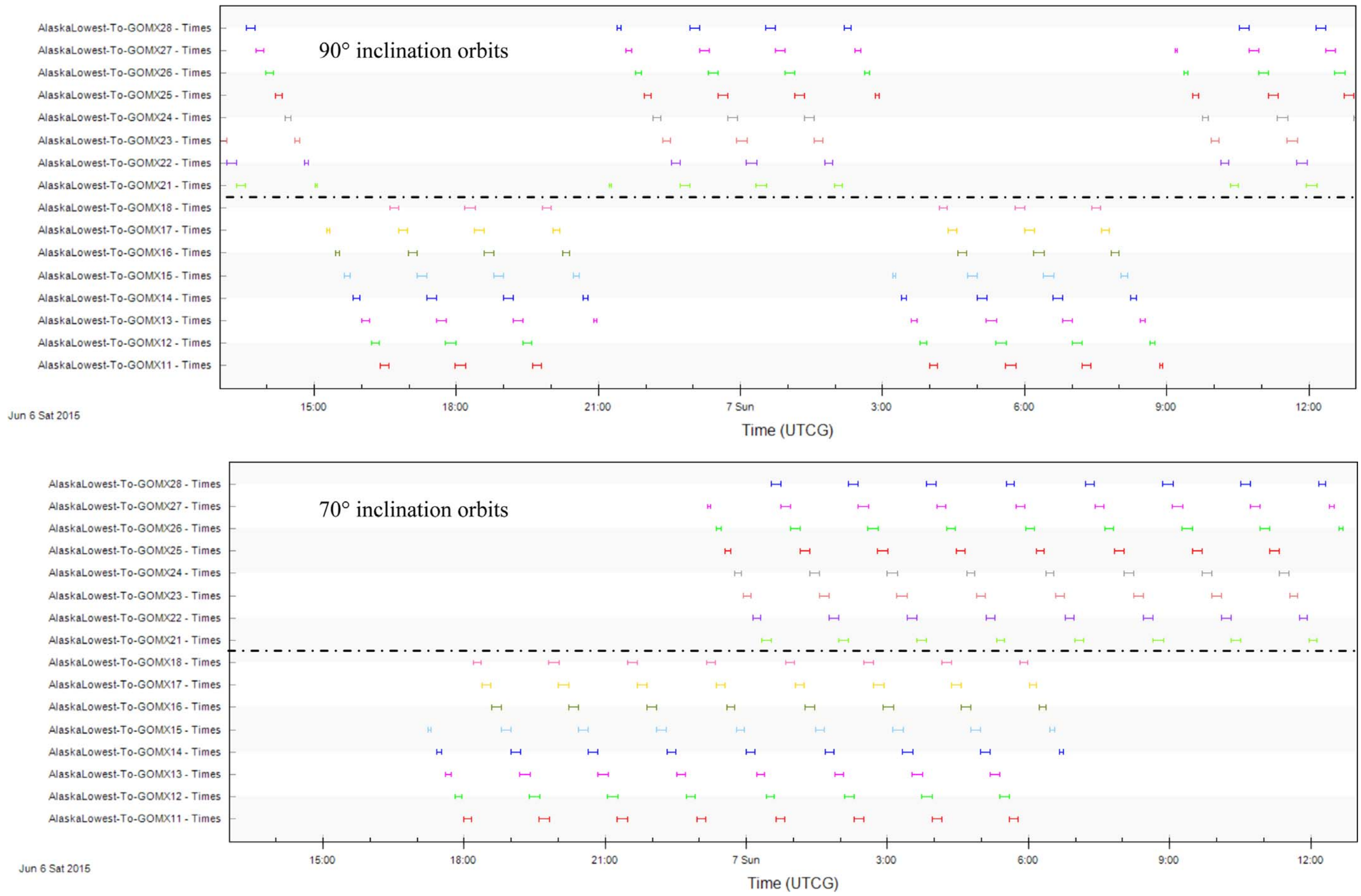

Fig. 4. Access duration for every satellite (rows) in a 16 satellite constellation arranged in two planes over a period of 24 h (*X*-axis) when the satellites are at a 90° [Top] and 70° [Bottom] inclination. Access is calculated for the point in Alaskan Airspace with lowest latitude, as obtained from FACET simulations. The lack of a colored horizontal bar across a vertical line drawn from a time step indicates that the Southern-most point of Alaska is not covered by any satellite at that time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 $360°/\lambda$ 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° and $\sim$44°, 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°. Typical sun-synchronous secondary orbits at around 97° may be used, however three orbital planes will be required for comparable coverage.

Access durations to the southern-most point in Alaskan airspace [53.89 – 166.54° 762.5 m], 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 Fig. 4. The orbital planes are 90° apart in RAAN. The exact RAAN values are assumed to be 0° and 90°, without loss of generality, because the initial RAAN will depend on launch epoch and location characteristics. 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 Southern-most point of Alaska is not covered by any satellite, because for 5 h it lies in the 90° RAAN gap between the two planes. The 90° constellation shows that the Southern-most point of Alaska is mostly covered by at least one sat at every instant and gaps are not visually noticeable. Therefore, orbital planes at 90° inclination are used in all proposed constellations and their performance more comprehensively quantified. The gaps seen in Fig. 4 are expected to repeat day after day, as long as the RAAN separation between the orbital planes is 90°. Since the orbits are circular at the same altitude and inclination, the differential gravity harmonics (J2, J3, J4) between them is minimal and the RAAN and perigee rotation is nearly equal. As a result, minimal maintenance will be required for inter-plane separation.

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 h 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 Fig. 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

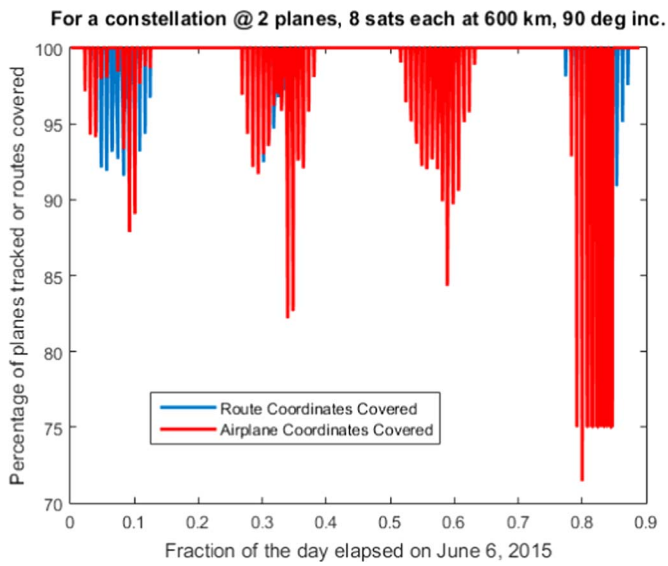

Fig. 5. Instantaneous percentage of airplanes (red) covered by a 16-sat Walker constellation, where the true airplane population over Alaskan routes are simulated by FACET over one day. Percentage of Alaskan airspace coordinates covered (blue) irrespective of having airplanes on them, has been shown as comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

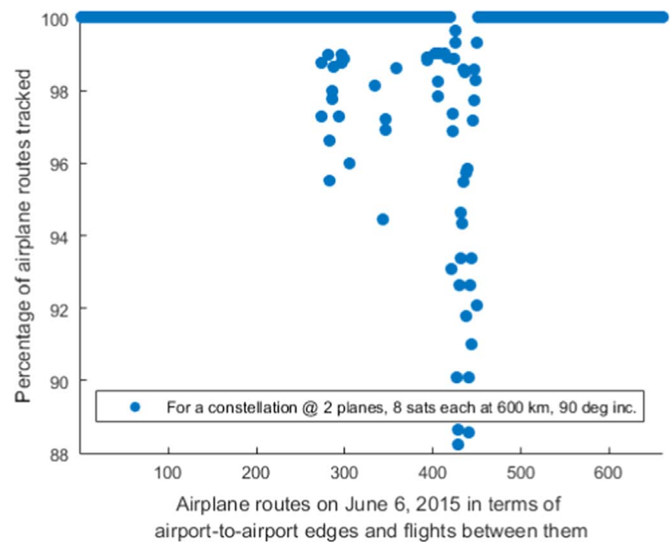

Fig. 7. Percentage of routes, among the total 660 populated by FACET over a day, covered by a 16-sat Walker constellation at 600 km.

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. Fig. 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.

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 Fig. 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 Fig. 6). The ratio is shown in Fig. 7 and is an average of 99.68% and median of 100% for the 600 km constellation. In

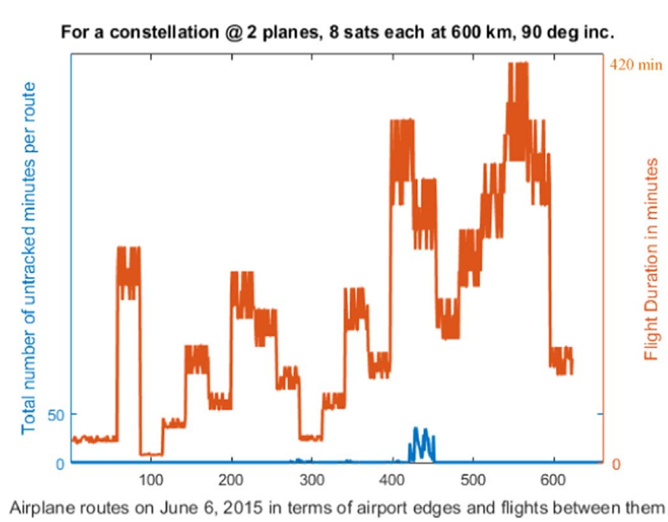

Fig. 6. Total time per route (blue), of 660 routes populated by FACET over a day, that an airplane is not covered by any satellite in a 16-sat Walker constellation. The time is the complement of percentages in Fig. 7 multiplied with the flight time for that route (orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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). The presented tool is very modular. It can be easily modified, if a more realistic antenna design becomes available or a different launch altitude is required, and the relative impact on the above performance metrics computed.

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 [38] the adoption of a new 15 min aircraft tracking Standard. In the context of this paper, the maximum delay (D) should be 15 min. For every airplane route, the tracking gap is plotted in Fig. 6. The average tracking gap (red) is well below 5 min 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 Fig. 8, the gap is 6 min for the 600 km design and 28 min 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 Fig. 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 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 (TDR satellite) 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.

If TDRSS is unavailable and spacecraft pointing constraints do not allow the 3 NEN stations in Alaska to be used, Fig. 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

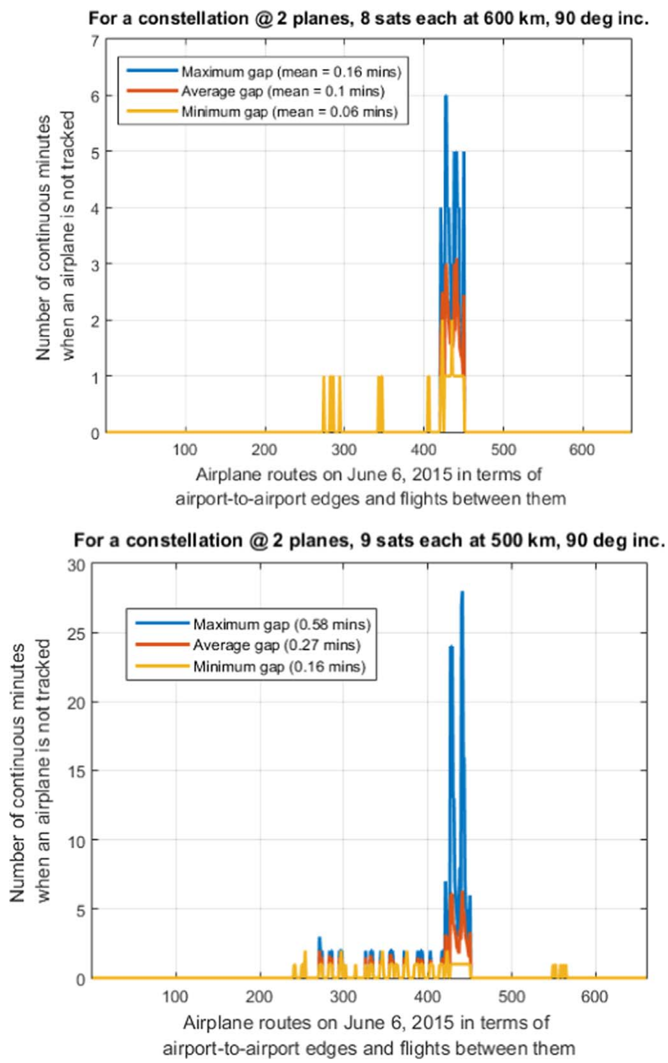

Fig. 8. Coverage gap time – maximum, minimum and average – per route, among the 660 populated by FACET over a day. A gap is a continuous stretch when an airplane is not covered by any satellite in a Walker Constellation at 600 km [Top] and 500 km [Bottom].

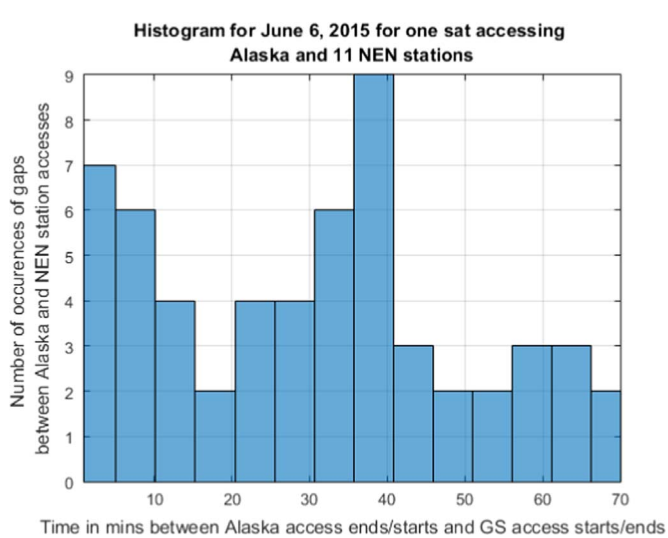

Fig. 9. Frequency of gaps between when a satellite covers the Alaskan Airspace and when it accesses the next closest ground station in the NEN network.

closest NEN GS. The simulation is run for 24 h, 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 min of coverage ops, as required to meet the ICAO 15-min standard after the 6-min air-to-sat delay. The mean sat-to-GS delay is 30 min. 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 omni-directional antenna, an appropriate non-amateur frequency allocation and a link budget that ensures reasonable data rates.

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 an orbital plane is subtracted from this design, i.e. 8 satellites in one plane are used, the mean instantaneous and route coverage is 74.7% and 67.8% respectively. Maximum delays in routes can be up to 5.5 h and minimum delays as high as 2.5 h, 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 4.5). 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 min 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. Fig. 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 drag [5]. Propulsive adapters such as Spaceflight Inc.'s Sherpa may also be used to provide the required ΔV.

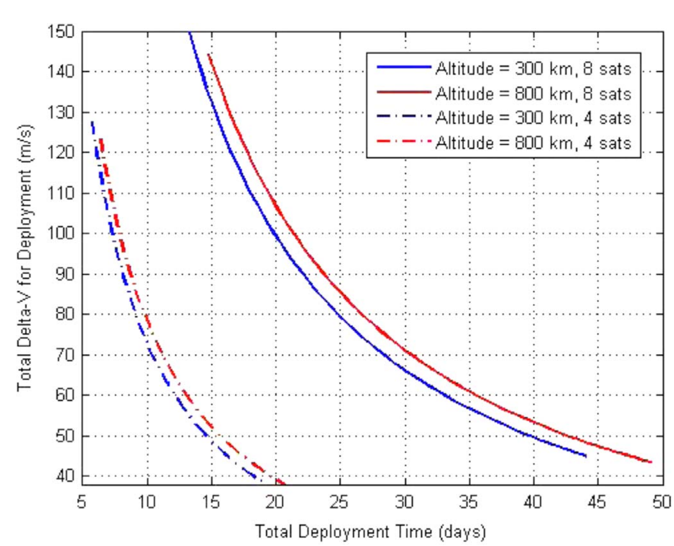

Fig. 10. Trade-off between total ΔV (proxy for required fuel) and deployment time required to propulsively deploy 4 or 8 uniformly spaced satellites in the same plane. Time is a function of the phasing orbit.

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 effects [7], causing in-plane changes. Maintenance ensures that the ground below any orbital plane is continuously covered by the theoretical number of satellites needed (360°/λ). 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) [7]. Adding more satellites than the theoretical value relaxes the coverage requirement, but periodic maintenance will still be needed to avoid collision.

4.2. Ad-Hoc constellations

Since Ad-Hoc constellations are formed by launching satellites as and when 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 rockets [28]. 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).

Since the Alaskan airspace ranges from 54° to 71° latitude (Fig. 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 RAAN and TA like a Walker constellation, coverage frequently drops to zero due to orbital gaps. Fig. 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.

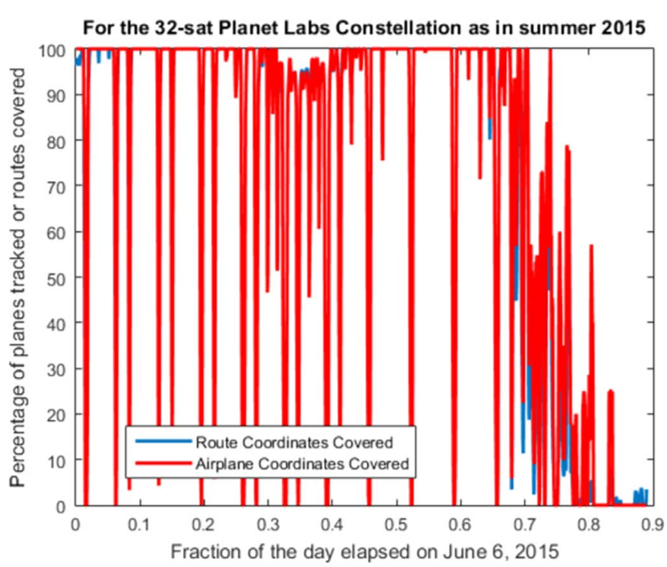

Fig. 11. Instantaneous percentage of airplanes (red) covered by the current set of 32 Planet Labs satellites. Compare to the percentage of Alaskan airspace coordinates covered (blue) irrespective of having airplanes on them. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

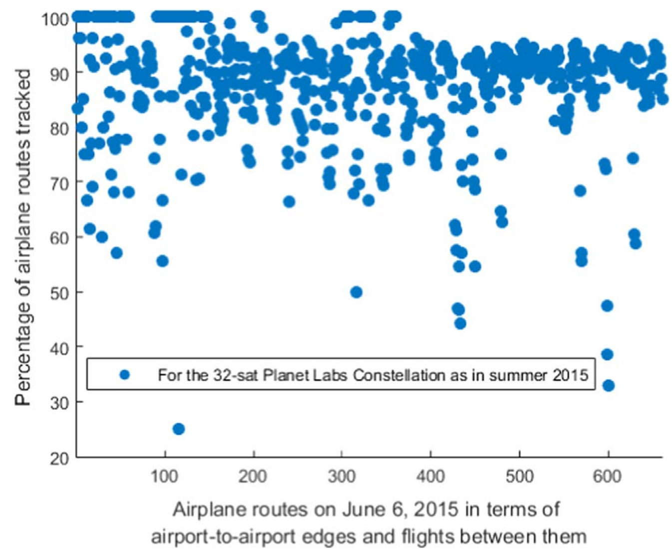

Fig. 12. Percentage of routes, among the total 660 populated by FACET over a day, covered by the current set of 32 Planet Labs satellites.

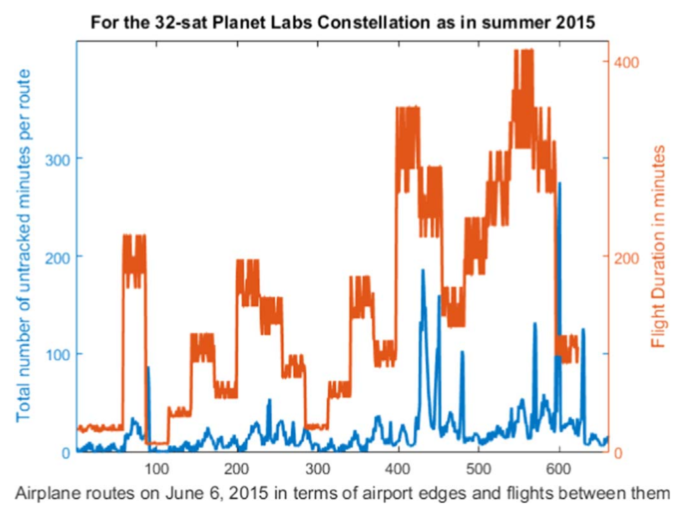

Fig. 13. Total time per route (blue), of 660 routes populated by FACET over a day, that an airplane is not covered by any current 32 Planet Labs satellite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The plot of route percentage coverage in Fig. 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 (Fig. 13). It is for the same reason, that the tracking gap time (D) is less than 15 min for 95% routes but peaks of up to 90 min are observed for a few routes – Fig. 14. The maximum, total, untracked time per route can be well over 3 h.

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.

4.3. Continuously precessing constellation

Unlike Walker and Ad-Hoc constellations which use different launches to achieve a RAAN spread, followed by launched

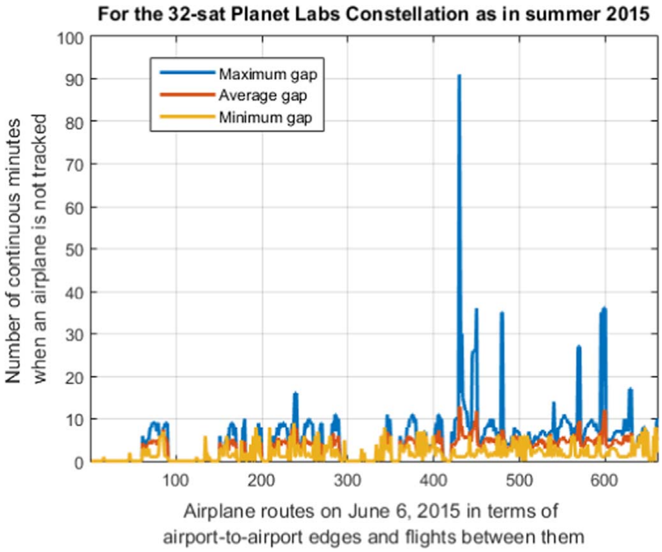

Fig. 14. Coverage gap time – maximum, minimum and average – per route, among the 660 populated by FACET over a day, caused by the current 32 Planet Labs satellite constellation.

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. Fig. 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 (Fig. 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 two successful Walker designs. Until then, performance is degraded due to nulls in coverage as seen in Fig. 4 [bottom] or Fig. 11.

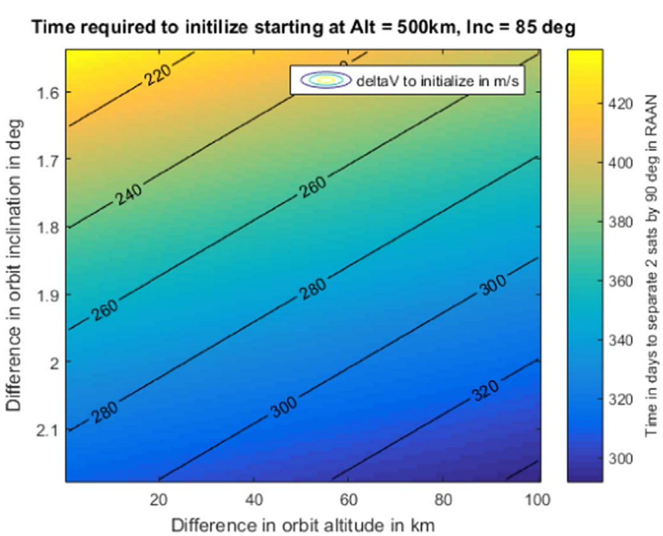

Fig. 15. Time-ΔV trade-off for moving 2 satellites from zero to 90° apart in RAAN as a function of differential altitude and inclination, using chemical propulsion. The colors indicate time in days and the contours are ΔV in m/s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

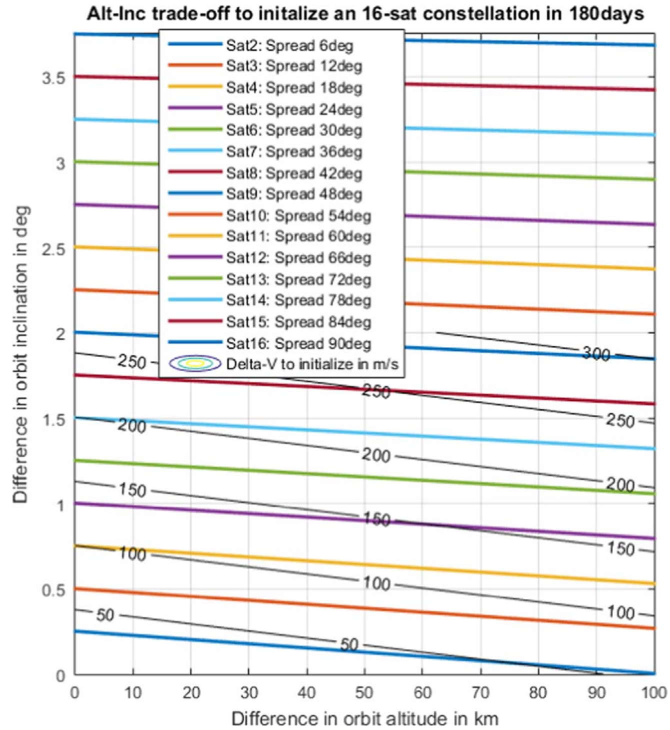

Fig. 16. Trade-off between differential altitude and inclination required for spreading 16 satellites uniformly between zero to 90° in RAAN within 180 days. Each color represents a different sat's trade-off. ΔV required for initializing the different alt/inc is shown as black contours within available Pegasus HAPS fuel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 Fig. 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 rocket [39] 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 Fig. 16 show the extent of Keplerian separation that fuel can get us – only half the required spread.

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 obit, 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 h 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.

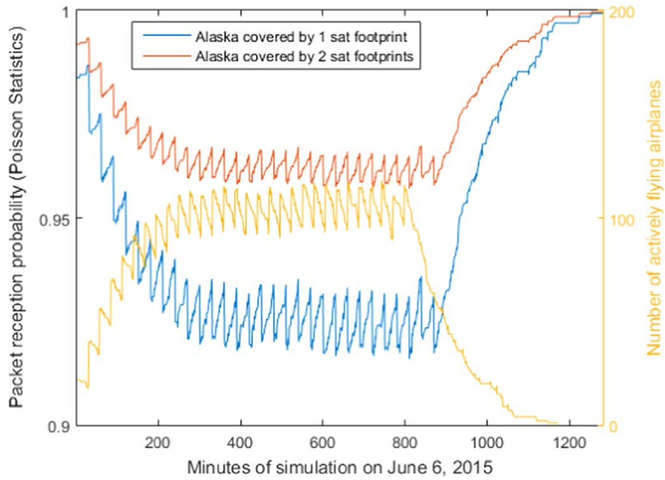

Fig. 17. Packet reception probability, or the probability of a satellite in the constellation successfully receiving a packet from transmitted from an airplane to a satellite, as a function of time of day, airplane population within the FOV and number of FOVs covering the space. ADS-B transmission is assumed every minute, a very conservative estimate because airplanes typically transmit 1–3 times per second. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

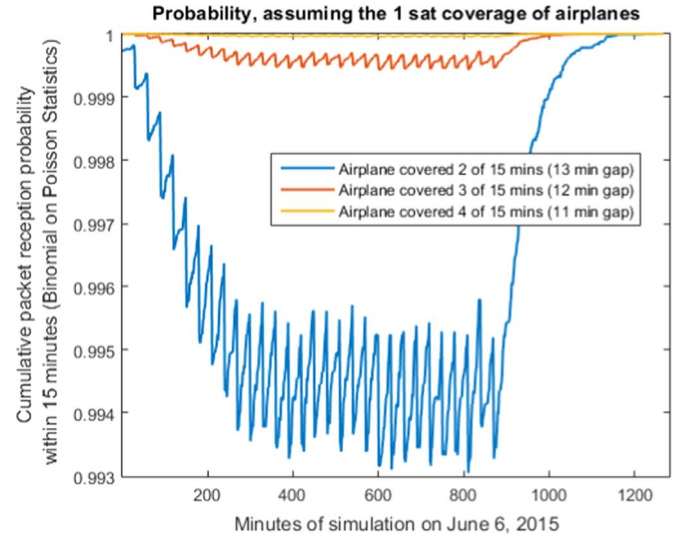

Fig. 18. Probability of successful packet transmission from airplane to any satellite in the constellation in spite of sending as low as *one packet a minute* and 11 to 13 min of gap in coverage. Not all transmitted packets are successfully received due to data collision of packets arriving at the same instant. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

4.4. 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 $\sim 25°$ 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. Fig. 17 shows the probability of packet collision, as calculated using Eq. (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 a.m., 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.

Since the ICAO recommends tracking of all airplane states every 15 min, the constellation must ensure that it successfully receives an ADS-B packet from an airplane in less than 15 min, in spite of nulls in coverage and data collision possibility. Eq. (2) is used to calculate the probability of successful packet transmission within 'x' time frames. Note that 'time frame' here means a time period of finite duration and is different from 'frame time', as described in relation with Eq. (1), which is the length of an ADS-B message or several multiples of its length. When transmission is considered every second, the probability of unsuccessful transmission for 30 s is between $1e-30$ and $10e-90$ while failure for a full 60 s is between $1e-70$ and $1e-190$. Therefore 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-min standard is well met. Since Fig. 17 assumes the worst case ADS-B transmission frequency of once per minute, the probability of successful transmission within $x=1$ min is shown by the blue curve at worst and red curve at best. When $x=2$ to 4 min, the results are shown by the curves in Fig. 18, for the worst case. Fig. 17 represents probability of successfully receiving individual packets while Fig. 18 is the probability of successfully receiving at least one packet in a given time frame. The probability increases very exponentially with time allowed for transmission, is ~ 1 if the airplane has at least 4 min 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 min, 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 min and possible 5 min gap to downlink to a ground station, allowing sufficient time for non-colliding transmission.

As mentioned in Section 3.3, the aircraft population will increase if more Alaskan airports, intercontinental flights and small general aviation are added to the currently simulated traffic. 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, data collision probability or successful transmission 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 Fig. 18), the probability of successful reception at the satellite, after an 11 min gap, would be only 55.55% at 20 times the air traffic, compared to the currently simulated 99.999%. Thus, decreased probability of packet reception due to increased air traffic load can be mitigated by more frequent packet transmission, at a rate within current ADS-B protocol.

Future work entails a detailed study of the ADS-B receive antenna and modeling its hardware-dependent success in processing received packets, in keeping with signal dilution due to space loss and atmospheric noise [29].

4.5. 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 model [40]. From a very high level estimate from GomSpace's sales team, it would cost \$350 k (USD) for one fully flight ready ADS-B satellite,

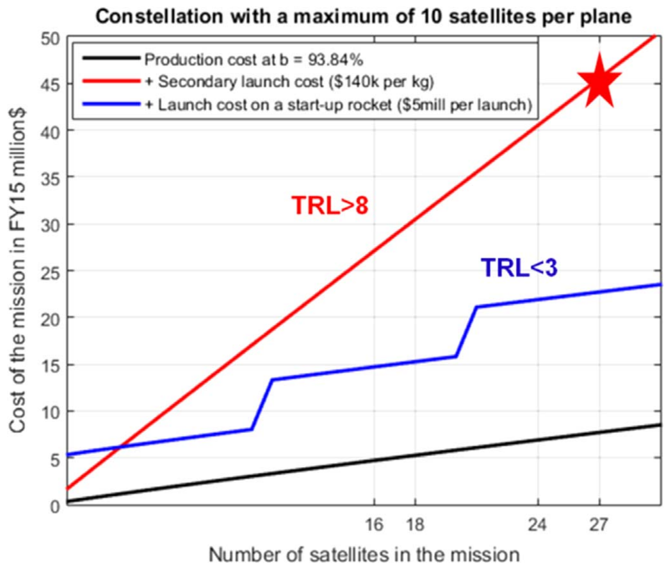

Fig. 19. Development and launch costs. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

reducing to $275 k as the number of satellites approach 50. We add an additional $100 k 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 data [40]. The percentage "*b*" represents the value at a doubled production quantity in relation to the previous quantity [41]. For example, with an learning curve of 85%, the value at unit two is 85% of the value of unit one and the value at unit four is 85% of the value at unit two. 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 Fig. 19.

Three launch options are considered for the constellations described in this paper – all satellites as a primary payload such as Orbital ATK's Pegasus [39] (Precessing 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[4] (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 Fig. 19. Secondary launches have been modeled at $140 k per kg – a rough upper-limit estimate inferred from conversations with Space Flight Services[5] 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[6] 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 Fig. 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.[7]

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.

5. Conclusions and future work

This paper documents the preliminary results of pre-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 min. Separate launches or propulsive drop-offs will be needed for 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 modeled 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).

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[4] Rocket Labs website: http://www.rocketlabusa.com/.

[5] SFS website for secondary launch and Sherpa: http://www.spaceflightindustries.com/.

[6] Rocket Labs news release from July 2014: http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11300831.

[7] Spaceflight Now news article from March 2015: http://spaceflightnow.com/2015/03/23/debut-flight-of-rail-guided-space-launcher-slips-to-october/.

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