Tracking Aircraft via a Low-Earth-Orbit CubeSat Constellation

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Automatic Dependant Surveillance-Broadcast (ADS-B) is quickly becoming the primary method that Air Navigation Service Providers (ANSPs) and Air Traffic Control (ATC) systems use to track aircraft during flight. ADS-B coverage can be supplemented by space based receiving stations in order to track aircraft over regions where ground-based stations cannot be installed, for example, over oceans and poles. Commercial interest for ADS-B coverage from space is strong and two low risk but high-cost solutions have been proposed as secondary payloads on the Globalstar and Iridium NEXT constellations of commercial telecommunication satellites. Hosting the service in a constellation of low-cost CubeSats will provide a more economical solution, with lower production and launch costs. The key challenge in the design of the system is balancing coverage area, revisit times and link-budgets against cost and CubeSat technological limitations.

Nomenclature

ADS-B	Automatic Dependant Surveillance-Broadcast
AIS	Automatic Identification System
ALAS	ADS-B Link Augmentation System
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
DLR	German Aerospace Centre
ESA	European Space Agency
LEO	Low Earth Orbit
PolyCal	California Polytechnic University
PSTN	Public Switched Telephone Network
RAAN	Right Angle of Ascending Node
SAPID	Space-Based ADS-B In-Orbit Demonstration Payload Develpoment for Air Traffic Surveillance Project
SNOC	Satellite Network Operations Center
SSR	Secondary Surveillance Radar
TCAS	Traffic Collision Avoidance System

I. Introduction

Automatic Dependant Surveillance Broadcast (ADS-B) is an aircraft tracking system based upon digital aircraft-to-ground and aircraft-to-aircraft transmissions. It is intended to support and eventually replace the existing Air Traffic Control Radar Beacon System (ATCRBS) which uses a radar call-and-response protocol in order to track aircraft within range of ATC stations. ADS-B is now being adopted as a primary Air Traffic Control (ATC) management system in the United States of America,[1] the European Union and Australia.[2]

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ADS-B specifies that aircraft continuously broadcast data packets containing their identification, position and aircraft health using information generated by on-board avionics. Data packets are transmitted with an average update rate of once per second with broadcast periods ranging between 0.5 seconds and 5 seconds.[3,4] Transmissions occur over the L-band 1090 MHz Mode S Extended Squitter frequency shared by Aircraft Secondary Surveillance Radar (SSR) and Traffic Collision Avoidance System (TCAS). ADS-B is broadcast on a random access basis with paticular aircraft identified by information in their data packets.[4]

Tracking via ADS-B requires aircraft to be within the line-of-sight of a ground station. ADS-B coverage areas vary with altitude and the existence of obstructing features in the terrain surrounding a ground station. Out of the range of these ground stations, aircraft tracking via ADS-B is not possible. Although comprehensive coverage is already in place in Australia,[2] the Asia-Pacific region[5] and much of North America,[1] there still exists areas, particularly over oceanic and polar regions where the service is not available. These areas are illustrated in Figure 1. Some solutions exist for ADS-B coverage in remote and marine areas. Ground stations installed on oil platforms currently provide coverage over the Gulf of Mexico[1] - a solution which could be extended to other bodies of water. However, relying on terrestrial systems to provide global ADS-B coverage is not cost effective.

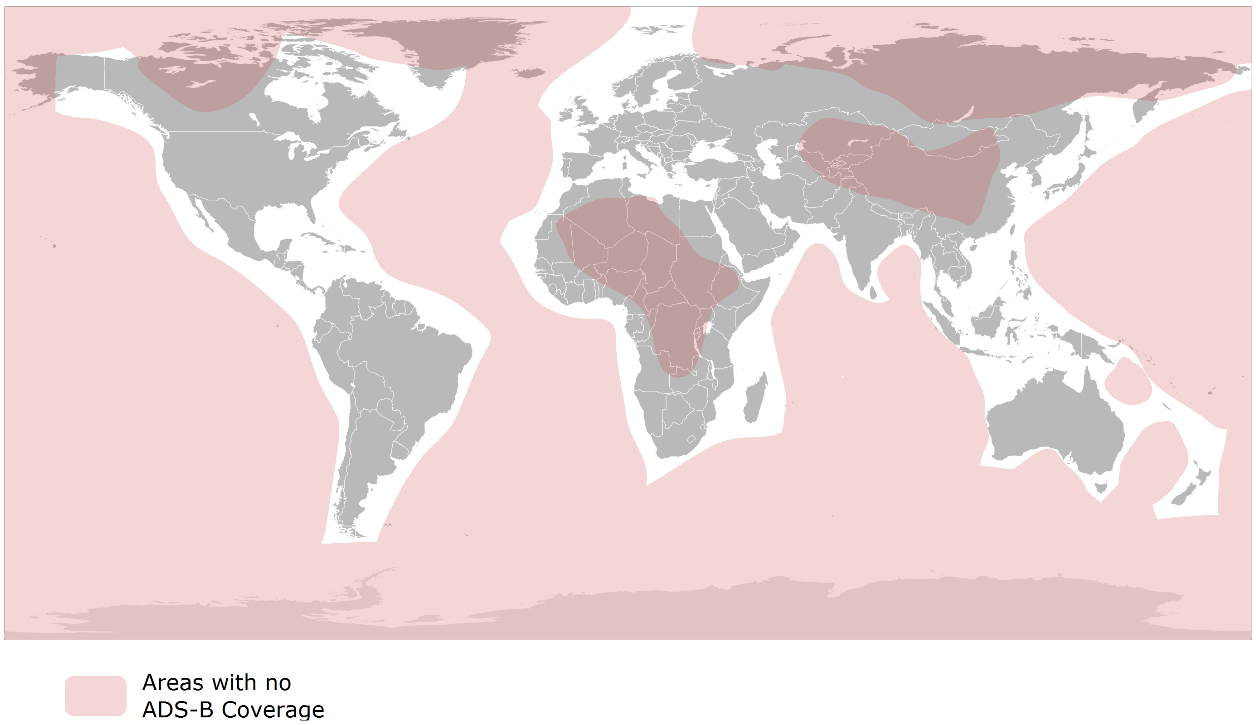


Figure 1. Approximate areas with a lack of adequate terrestrial ADS-B coverage.

This paper presents a background study on satellite constellations and space ADS-B technology. Design concepts from existing communications satellite constellations and space ADS-B receiving technologies will be used in order to determine the mission parameters of the required space-based ADS-B tracking system. This will lay down the foundation for future work in the development of a constellation of CubeSats which can be used to augment terrestrial ATC systems.

Strong interest is being shown by American, European and Australian Aviation authorities in implementing a satellite-based ADS-B system in order to address this coverage gap. The European Space Agency has commissioned a series of studies into the feasibility of receiving ADS-B from Low Earth Orbit (LEO).[4] The German Aerospace Agency (DLR),[6] and private companies such as Aireon[7] and ADS-B Technologies[8] have already invested heavily into implementing space-based ADS-B.

II. Mission Overview

The root requirement of a satellite-based ADS-B system is the provision of ADS-B coverage over regions where terrestrial systems do not currently provide coverage (in particular, oceans and poles). Within this requirement are a number of variable mission parameters that effect the design and economic cost of resulting satellite systems. Varying the parameters and analysing the performance of resulting designs will allow for more effective mission trade-off analysis.

A. System Users

A spaced based ADS-B system would have two key user groups

- Air Navigation Service Providers
- Airlines and air transportation service providers

Although Australia, America and Europe are able to implement terrestrial ADS-B stations, rolling out terrestrial stations to cover all interest areas is not necessarily cost effective. This is particularly true in regions such as South East Asia. In such regions, the technology and economic base does not exist to make terrestrial deployment viable.[4] In these situations a satellite-based system can more effectively augment existing ADS-B coverage for use by ANSPs.

Another key user would be airlines and other air transportation services. Greater position and telemetry coverage of aircraft over oceanic and polar regions allows for more optimal flight path co-ordination. ADS-B assisted flight routing will allow for narrower longitudinal and latitudinal track separation, allowing for more flights to travel on desired fuel-saving paths. A flight simulation analysis presented by Aireon suggests that increased density of planes in jet streams can result in fuel savings of up to 450 litres per oceanic flight.[9]

B. System Update Rate

The update rate of a space-based ADS-B system defines timeliness with which aircraft data can be updated and disseminated terrestrially. Having a high-effective update rate is crucial in range of Airports with ATC towers having to co-ordinate a large density of aircraft traffic. With ADS-B, terrestrial ATC towers typically achieve an update rate of less than 10 seconds depending on airport capacity.[10,11] For the purposes of live tracking and safety control, an update rate in the order of 10 to 30 seconds will be required [11, B.5.2]. An update rate in the order of 5 to 10 minutes would enable satisfactory tracking by airlines and air transport services at less cost. A lowest cost system with an update rate of 1-2 hours could be useful for occasional tracking of aircraft making oceanic flights. This, however, would be inadequate for safety applications or any short-range terrestrial flights.

In order to determine the update rate, all communication delays must be considered, encompassing all communication links between the aircraft and end users. The desired update rate will define the down-link requirements for the system. This will then affect the communication architecture of the resulting satellite system. Higher downlink requirements will necessitate that the space-segment have more downlink opportunities. This will require either a higher number of ground stations or inter-satellite data-linking.

C. Revisit Time

Due to the random access nature of Mode S Extended Squitter, the number of aircraft surveyed by an ADS-B receiver is limited. With current technology, a terrestrial omni-directional Mode S antenna with a 100 nautical mile operational range can cover a maximum of 120 aircraft with a 99.5 % detect probability over 5 seconds.[10] Regulations for civil aviation equipment in Europe specify a detect probability of at least 95% over an update interval of 10 seconds [11, B.5.2]. Scanning for a shorter period, or scanning an area with more aircraft will result in more ADS-B collisions and a drastically reduced detect rate. 'Missing' aircraft in this manner is unacceptable from a safety perspective. Suggested solutions for high density areas include more sophisticated antenna design with spot beams,[4] or variable-periodicity of ADS-B signals.[10]

For ADS-B reception via satellite, a populated area can be either scanned for a longer period, or 're-scanned' over multiple revisits. This would mediate the need for a larger or more sophisticated and costly antenna array. A longer scanning period can be achieved slowing the ground-track of the space segment over key areas. Such behaviour can be achieved using Molniya orbits. Slowing the ground-track will require a higher-altitude, which then requires a higher gain antennae to effectively service. This is particularly a problem on CubeSats where technology implementation is limited. The revisit time will therefore be defined by limitations of the antennae array and on-board processing technology for ADS-B signal reception. Satellite ADS-B receivers are currently being tested by the German Aerospace Centre (DLR) in conjunction with the European Space Agency (ESA)[6] and Thales Alenia Space.[4]

D. Geographical Coverage

Full global coverage would be achieved by a series of polar or near polar orbits, such as the Iridium Satellite constellation.[12,13] Achieving full coverage would be the most costly solution, requiring the largest number of satellites and ground stations. At the very least, the ADS-B system should cover the poles, the North Atlantic, North Pacific and Indian Oceans and South East Asia in order to meet the root system requirement. These areas have the highest amount of air traffic not covered by terrestrial ADS-B systems. Monitoring these regions with specific orbits can reduce the number of spacecraft required in order to provide the coverage gap required by the system.

E. Mission Parameter Summary

- The ADS-B system should at least provide coverage gaps over the North and South Poles, The North Atlantic, North Pacific and Indian Oceans and South East Asia.
- The system will be used to service both ANSPs and commercial Airlines
- The system should have an update rate of less than 30 seconds for safety tracking applications,[11] 5-10 minutes for low-fidelity tracking applications[9] and 1 to 2 hours for basic flight path studying.
- Revisit times will be affected by the effectiveness of antenna technology available for ADS-B reception on a CubeSat scale
- Constellation configurations, including satellite orbits and ground station placement will then affect revisit times and system update rates.

III. Space Based ADS-B

A number of existing technologies are being investigated to evaluate the effectiveness space-based ADS-B technology. At the moment, none of these systems would comply with with the size and power-requirements of a CubeSat systems. However the general design principles can be adopted for development of a CubeSat ready implementation.

A. ADS-B Link Augmentation System (ALAS)

ADS-B Technologies have developed the ALAS as a space-based ADS-B coverage solution. The ALAS will be flown as hosted payloads on the Globalstar's second generation constellation of satellites. The system is expected to provide global coverage with a one-second update rate.[14,8] The system is intended to operate by relaying ADS-B data received L band transmissions to ground based gateways through the C band. These gateways then relate that data to Air Traffic Management (ATM) systems as necessary. The system is full duplex and is designed to transparently augment the existing ADS-B ground coverage network.

The system will require both ANSPs and Aircraft to purchase additional L and S band transceivers to communicate with the space segment. ALAS will not be compatible with standard ADS-B hardware implementation.

The second Globalstar constellation will have limited coverage due to its orbit configuration and communication infrastructure. The inclination of the Globalstar orbits will not provide ADS-B coverage over the poles, and reliance on a permanent link with ground stations restricts the predicted coverage to continental areas. The predicted ADS-B coverage is much the same as the first constellation, shown in Figure 2,[14] missing key oceanic and polar areas.

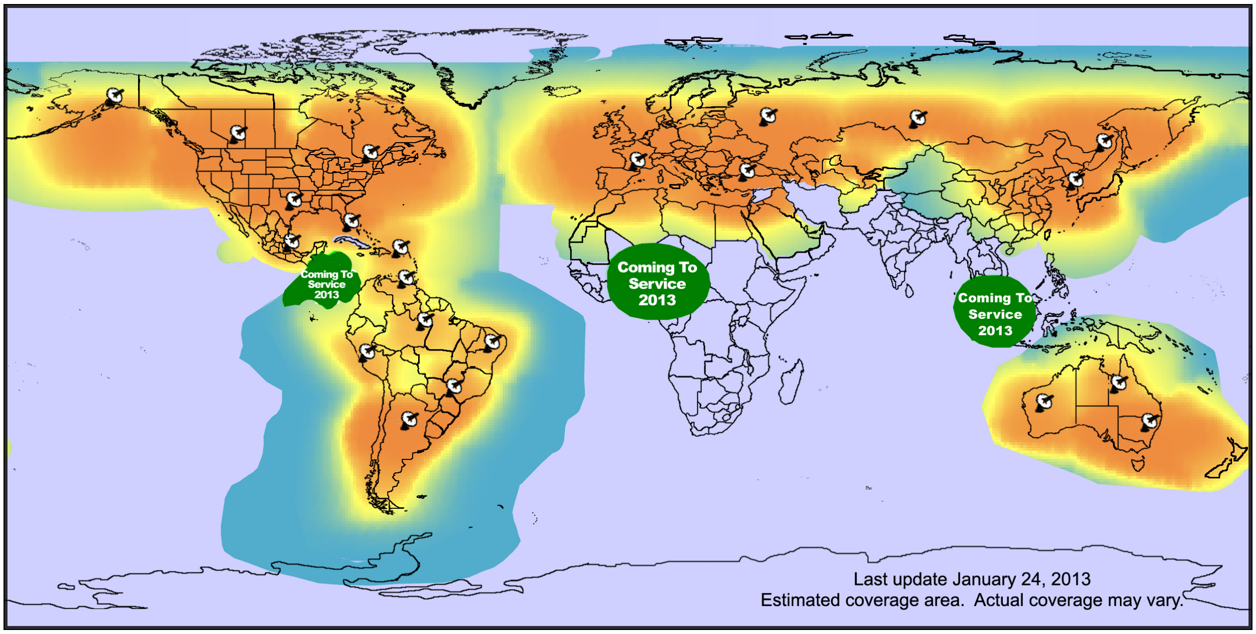


Figure 2. Globalstar System Coverage, from[15]

B. Aireon

Aireon LLC are currently developing an space-based, ADS-B reliant 'global aviation surveillance system'[7] to be flown on the Iridium NEXT constellation of Low-Earth Orbit satellites. The constellation is expected to provide complete global coverage, including over polar regions.[16]

This system is presented as flight path solutions for both ANSPs and Aircraft Carriers. Marketing material claims that intelligent flight path planning will save Airlines money in fuel with more optimised routes.[16] The Aireon Payload and Iridium NEXT satellites are being developed by Thales Alenia Space. The service is expected to be available by 2017.

The concept presented for the system suggest that unlike the Globalstar hosted ALAS, Aireon will use the standard Mode S Extended Squitter carrier signal in order to receive ADS-B signals.[9] This has a distinct advantage in that no additional hardware is required in order to implement the system.

Space-Based ADS-B In-Orbit Demonstration (SAPID)

Thales Alenia Space has been involved in the development of the Space-Based ADS-B In-Orbit Demonstration Payload Development for Air Traffic Surveillance Project (SAPID) transceiver. The involvement of Thales suggests that similar technology will be used for the Aireon system. The SAPID attempts to address key issue of signal collision on the 1090Mhz RF link over an area densely populated by aircraft. The proposed solutions focuses the receiving system into multiple spot beams to increase the 'hit rate' of aircraft detection.[4]

C. Proba V

In early 2013, the European Space Agency (ESA) launched their fifth experimental Proba satellite, Proba V, with a guest ADS-B Payload. Like SAPID, the ADS-B payload is designed to receive signals via the native Mode S 1090Mhz carrier. The receiver, designed by the German Aerospace Center (DLR) is designed to receive ADS-B from LEO in Proba V's 820km orbit.[6,17,18] Proba V is travelling in a Sun-Synchronus polar orbit at an altitude of 820km.[17]

The satellite is currently tracking Aircraft over Northern Europe.[6] Tests to determine how sensitive the receiver is to problems caused by signal density (as put forward by[4]) are ongoing. No results beyond the initial proof of concept have been published.

IV. Satellite Constellation Survey

A number of LEO satellite constellations with similar coverage requirements were studied and their performance requirements compared against those needed by an ADS-B satellite constellation

A. Iridium

The Iridium Satellite Constellation is a network of 66 LEO satellites which provide mobile communication services over a truly global coverage network. The system provides voice and data coverage for subscribers equipped with Iridium hardware, including mobile handsets and data modems. The intention is that the system will work in remote areas of the Earth where reliable mobile and wireless data over conventional means (i.e. 3G and emerging 4G technologies) is not available.

1. Communication

The Iridium network relies inter-satellite and satellite-to-ground communication in order to complete data and voice links between Iridium subscribers and other service providers. User end-devices, such as mobile handsets, data receivers and in-vehicle radio units link with satellites using L-band transmissions. A connection with a data source or other L-Band transceiver is routed between satellites and ground based gateways over K-Band transmissions.[12,19] A second K band 'control' link is used by ground operators to monitor the space segment through the Iridium Satellite Network Operations Center (SNOC).

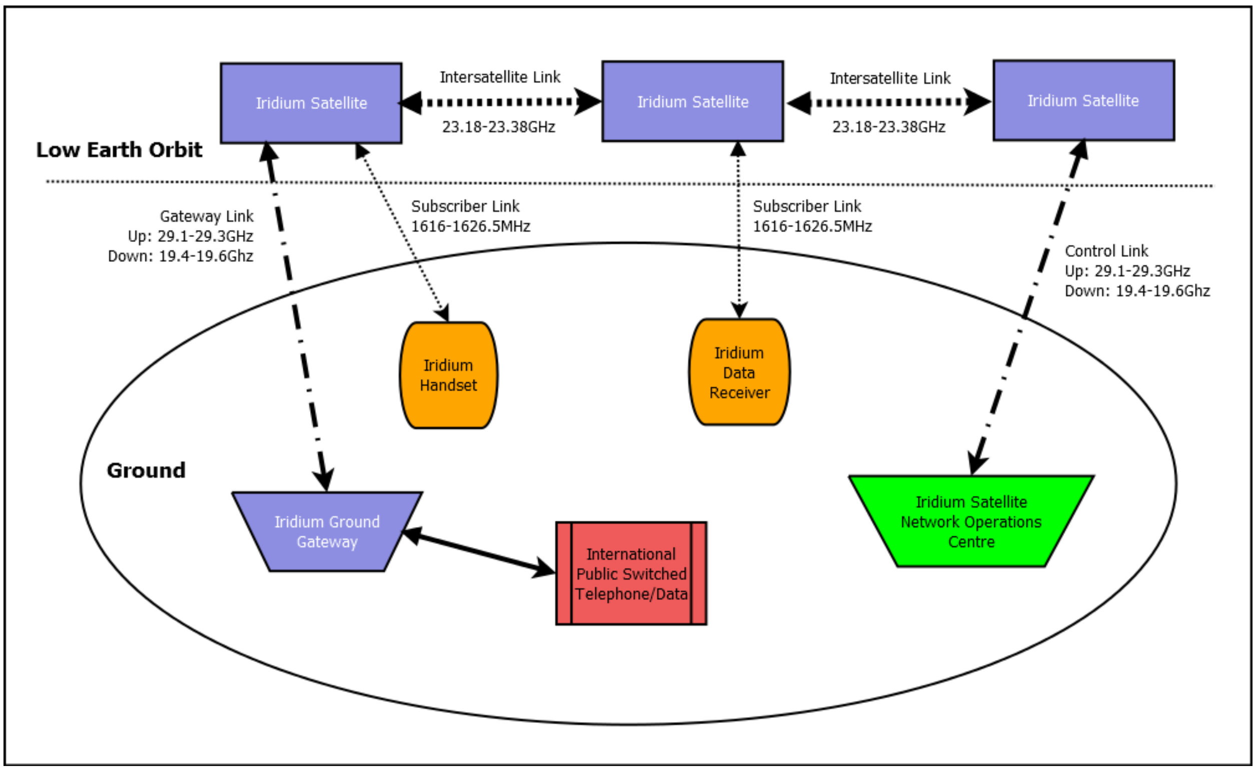
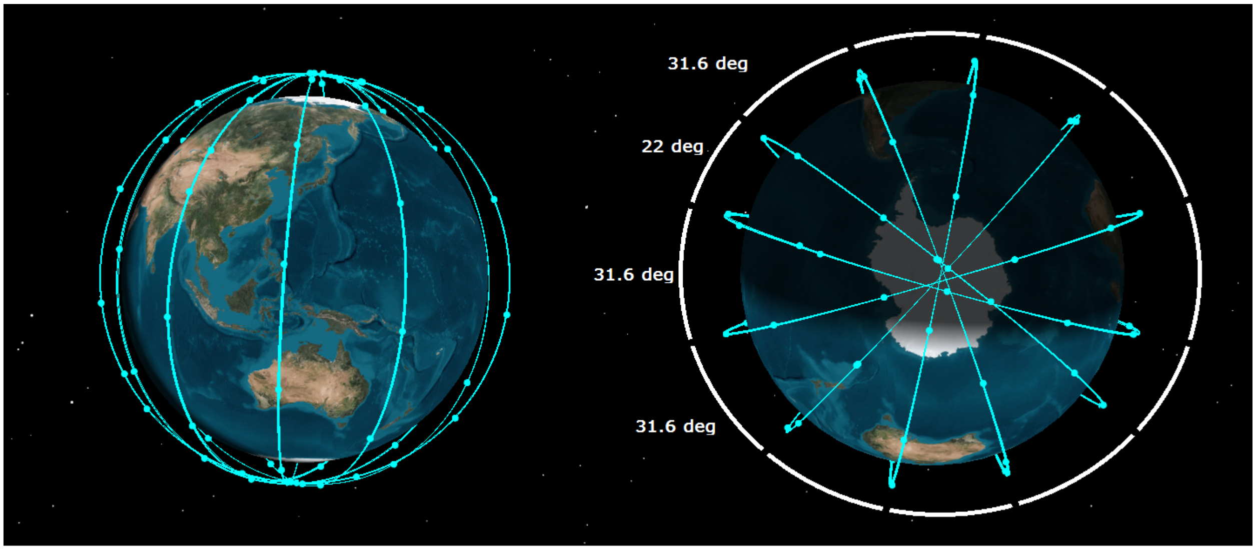


Figure 3. Overview of the Iridium Satellite Network, after[12,20,13]

An ADS-B system would benefit from employing a similar communications architecture. Employing inter-satellite communication links would increase the system-update rate and potential coverage without increasing the number of satellites or ground stations required. Alternatively, the Iridium payload data link itself could be employed to relay information from an ADS-B constellation to the ground.

2. *Space Segment*

The space segment of the system consists of 66 satellites in Low Earth Orbit at an altitude of approximately 780km. The satellites are evenly distributed amongst six polar co-rotating planes each spaced 31.6° apart in longitude, with the first and sixth planes counter-rotating and spaced 22 degrees apart.[12,13] The planes have a near circular orbit[21] Each orbital plane has 11 satellites evenly distributed across the orbit. This configuration is shown in Figure 4. High inclination polar orbits such as this would be ideal for providing coverage over the north and south poles.



a) b)

Figure 4. Iridium Satellite constellation showing a) a view over Australia and South East Asia and b) the view from above the south pole. Data taken from STK

B. Globalstar

The Globalstar Constellation consists of 48 LEO satellites that provide mobile communication services that, as far as end-users are concerned, are much the same as those offered by Iridium. Globalstar Inc. provide voice and data coverage over service areas where traditional PSTN data links are not availble. Unlike Iridium, Globalstar does not provide 100% global coverage, with swaths only cover areas between 70° north and south latitudes.[22]

1. *Communication and Coverage*

The Globalstar provides a simple 'bent-pipe' architecture for completion of communication links. Globalstar user terminals (for example, handsets or modems) connect directly with an overhead satellite via L and S band radios. The voice or data path is then routed through a ground gateway to international Public Switch Telephone Networks (PSTNs)[22,23] The ability for a satellite to complete this link relies on the satellite being within the line of site of a ground-gateway. Globalstar provides no inter-satellite linking and as such the system coverage is limited by gateway locations. This limitation can be seen in Figure 2.

The restriction of coverage to terrestrial areas does not provide an ideal solution for space-based ADS-B coverage. A space ADS-B system would be in operation to address coverage issues over areas where terrestrial systems cannot be installed. A Globalstar like system would not provide an ideal solution to this problem.

2. *Space Segment*

The space segment of the Globalstar system consists of 48 satellites equally distributed in eight orbital planes. Each orbital plane contains 6 satellites has a 52° inclination.[23,22] Data from STK indicates that the orbits have equally spaced right ascensions of ascending node (RAANs) between 0° and 360°, offset 45° from each other. Each satellite is in a roughly circular orbit, with an altitude of 1414 kilometres[23] and a period of approximately 115 minutes. Although this configuration does not provide coverage over polar regions, satellites and launch operate at lower cost - a potential mission trade-off for ADS-B.

C. Automatic Identification System (AIS)

The Automatic Identification System (AIS) is the maritime analogue to ADS-B. The system consists of VHF transponders which relay ship telemetry (identity, heading, destination etc.) between ships and between ships and shore stations. The viability of augmenting AIS with a LEO space-segment has been in investigation since 2003.[24] The primary goal of the proposed Satellite AIS systems is to provide route monitoring, allowing for longer update periods and data-lag.

The key challenge with Satellite-based AIS, is the detection of signals in high density areas where signal collision is prominent. Like ADS-B, AIS operates on a random-access basis on a single RF channel. Low density areas with less than 2000 ships will yield a detection rate of 99% from conventional AIS receivers.[24,25] This number drops off significantly as more ships enter the antenna footprint, dropping as low as 50% with 2500 ships for an observation time of 15 minutes.[24]

The performance parameters for each of the Satellite AIS systems investigated[26,24,27] do not meet the immediacy requirements of ADS-B. The proposed AIS constellation designs can be mimicked in order to provide basic route monitoring for aircraft, but not live tracking data. However, the technologies investigated and basic system design provide a good base model from which a more immediate system can be designed. In particular, having more satellites and implementing inter-satellite links as per Iridium can drastically improve the update time performance of the proposed system.

V. CubeSat Capabilities

The CubeSat picosatellite standard maintained by California Polytechnic University (PolyCal) has eased space access for non-military and non-commercial space interest groups, including Academic and Hobbyist groups. The launch interface design is such that multiple CubeSats can be launched on the same vehicle at reduced cost.[28] The proliferation of open-source CubeSat designs has allowed the academic and hobbyist community to collaborate and refine CubeSat design concepts. The resulting reduction in design and launch makes developing space-bound payloads more accessible with less design risk. CubeSats come in a range of sizes, from the 1 Unit (1U) 10cm×10cm×10cm cube to the 3-unit (3U) 30cm×10cm×10cm square prism.

Launching a constellation of CubeSats to provide a global ADS-B service could potentially be more cost effective than launching large telecommunications satellites for the same purpose. However, due to size and the lack of maturity for key CubeSat technologies, the capability for CubeSats to carry out long term or large scale missions is severely limited. In particular propulsion, attitude control and power systems limit the capability of CubeSat payloads.

A. Propulsion

In LEO, satellites are subject to an atmospheric drag, resulting in orbital decay. LEO orbits are maintained using on-board propulsion systems which perform station keeping manoeuvres to correct the effects of atmospheric drag.

Research conducted in[29] shows that some Electric Propulsion Systems may be suitable for attitude control and station keeping on a 2U or 3U CubeSat. The Ionic Liquid Field Emission Electric Propulsion (IL-FEEP) thruster presented in[30] and the Hydrazine Propulsion module presented in[31] are promising candidates for long-term station keeping. However both require a significant portion of the mass, volume and power budget available on a CubeSat, and neither have had extensive flight heritage.

The lack of a clear thruster system complicates the design of the proposed ADS-B CubeSat Constellation. The inability to perform station keeping manoeuvres could significantly limit the lifespan of a CubeSat, without the ability to manage orbital perturbations and orbital decay.

B. Attitude Control

Attitude determination and control on CubeSats is an area of on-going study. The pointing accuracy possible on CubeSat missions will affect telecommunications-like payloads, such as an ADS-B receiver. [32, Chapter 3.1.2] summarises the determination and control capability reported by on-going CubeSat missions and claimed by commercial off-the-shelf CubeSat Part suppliers.

The CubeSat Kit offers an attitude determination and control system that has 1° pointing accuracy. The system uses 3-axis reaction wheels, torque coils and magnetometers and sun-sensors in order to determine and control attitude. The system's mass and volume is non-trivial, taking up 1 whole unit of a CubeSat.[33]

Research summarised in [32, Chapter 3.1.2] suggests that pointing accuracies of less than 5° be reliably achieved with existing, flight proven systems. Improvements to pointing systems seem to chiefly rely in the software and control space, without any significant changes to available hardware. This existing capability will be taken into account during the CubeSat mission design.

Attitude control will be important in order to maintain a desired coverage area and for inter-satellite communication. To address signal density issues, the on-board ADS-B receiver must have a limited Earth-footprint. Maintaining accurate knowledge and control of this footprint will be necessary in order to achieve the desired coverage from the satellite.

C. Electrical Power

The small size and limited bus capability of CubeSats restrict the areas on which solar-panels can be mounted. This restricts the power budget for a CubeSat mission, which then have design ramifications for the design of on-board electrical systems, such as sensors, communication arrays and electric thrusters.

A survey conducted in[32] yielded that theoretically, 1U CubeSats can only generate less than 2W, given the limited surface areaand available solar panel technologies. 3U CubeSats identified by the study claim between 5.5W and 6W in peak power generation capabilities.

D. Typical Mission Life

CubeSat mission life varies and is typically limited by catastrophic systems failures. One of the first CubeSats launched, the Japanese CUTE I operated for 4 years between launch in 2003 and 2007.[34] Other than CubeSats who have failed during launch, the lifespan of CubeSats range between 2 months (CUTE II) to 3 years (QuakeSat, XI-V and others). The majority of these failures have occurred due to unexpected component or systems failures during satellite operation. In some cases failures occurred well beyond the design life of the mission.[35]

VI. Summary and Future Work

The work conducted so far has identified the key user group for a satellite-based ADS-B system. Varying mission parameters, particularly revisit times and system update rates will have significant effects on the design and cost of the subsequent system. There are some technologies in development that are able to track Aircraft from space using ADS-B. However, these have not been implemented to the scale and performance required for true global ADS-B integration. Implementing a CubeSat constellation in either a global coverage or oceanic and polar coverage configuration will require the balance of system requirements of similar constellations (seen in Iridium and Globalstar) with the technological limitations of CubeSats.

The following work needs to be carried out in future.

- Simulation of different system configurations with varying mission parameters.
- Performance of each simulation will be evaluated against functional requirements and cost (both launch and maintenance).
- In order to address CubeSat limitations, simulations will be run with 'ideal' cases where technology is not limited by CubeSats. The configurations will then be scaled down to what is achievable by CubeSats and re-evaluated.

The final result of the above work will result in another study quantitatively comparing the performance of all the above configurations.

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