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Low-Earth orbit satellite constellation for ADS-B based in-flight aircraft tracking

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Abstract. Automatic Dependent Surveillance Broadcast (ADS-B) is quickly being adopted by aviation safety authorities around the world as the standard for aircraft tracking. The technology provides the opportunity for live tracking of aircraft positions within range of an ADS-B receiver stations. Currently these receiver stations are bound by land and local infrastructural constraints. As such there is little to no coverage over oceans and poles, over which many commercial flights routinely travel. A low cost space based ADS-B receiving system is proposed as a constellation of small satellites. The possibility for a link between aircraft and satellite is dependent primarily on proximity. Calculating the likelihood of a link between two moving targets when considering with the non-periodic and non-uniform nature of actual aircraft flight-paths is non-trivial. This analysis of the link likelihood and the performance of the tracking ability of the satellite constellation has been carried out by a direct simulation of satellites and aircraft. Parameters defining the constellation (satellite numbers, orbit size and shape, orbit configuration) were varied between reasonable limits. The recent MH370 disappearance was simulated and potential tracking and coverage was analysed using an example constellation. The trend of more satellites at a higher altitude inclined at 60 degrees was found to be the optimal solution.

Keywords: low-earth orbit, satellite constellation, aircraft tracking, MH370

1. Introduction

Automatic Dependent Surveillance Broadcast (ADS-B) is an aircraft based transceiver system that has recently become the standard method for Air Traffic Control (ATC) Management in Europe, Australia and the United States. The currently available methods that provide ADS-B coverage to Air Navigation Service Providers (ANSPs) and ATC towers rely on terrestrial antennae which operate on line-of-sight. As a result aircraft cannot be tracked via ADS-B over

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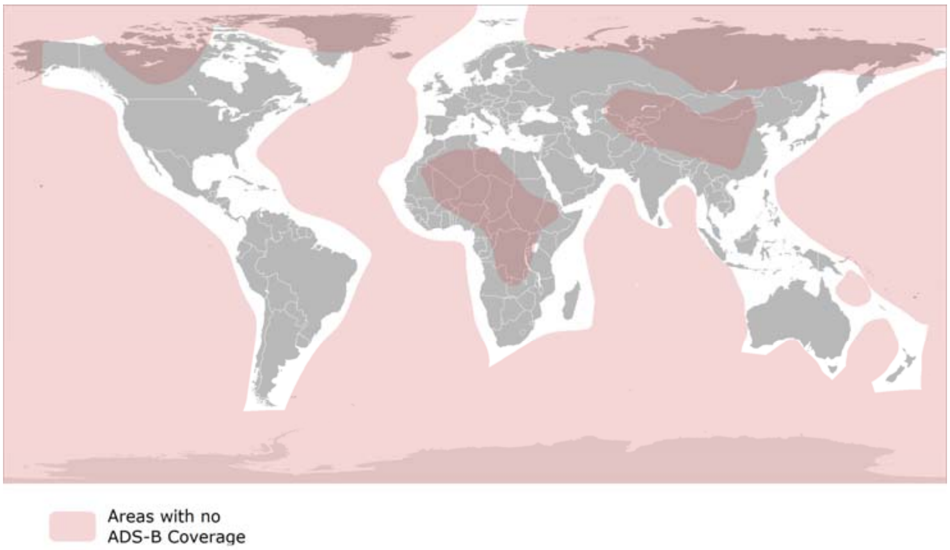

Fig. 1 Areas with no ADS-B coverage, as estimated by Aireon (2012)

oceanic and polar regions where installing ADS-B compatible ground stations is not possible. The recent development of the lost Malaysian Airlines flight MH370 on March 8th, 2014 highlights the detriment of not having constant, global, real-time coverage of commercial aircraft. These coverage gaps could be closed with the implementation of a space-based ADS-B receiver and re-transmitter system.

Tracking via ADS-B requires aircraft to be within the line-of-sight of a ground station (CASA 2012). ADS-B coverage areas vary with altitude and the existence of obstructing features in the terrain surrounding a ground station. Coverage is predictably sparse in remote and marine areas, as illustrated in Fig. 1, estimated by Aireon (2012). To address this gap, both Globalstar and Iridium NEXT propose global coverage via Low Earth Orbit (LEO) satellite constellations to be launched in 2015 at the earliest, as part of the ADS-B Link Augmentation System (ALAS) (Nelson *et al*. 2013, Aireon 2012) respectively.

This paper presents a parametric study into the design of a custom ADS-B Satellite constellation. The number of satellites, inclination and altitudes of each satellite were varied to examine their effect on coverage. The aim is to design an alternative low-cost satellite constellation providing equal or better ADS-B coverage than that provided by ground antennae. ALAS and Aireon represent existing solutions that require significant investment into infrastructure not necessarily geared toward ADS-B coverage (Aireon 2012, Nelson *et al*, 2013) The Proba V and GOM-X1 missions, run by the European Space Agency and GOM Space, prove that the technology is possible as a primary payload on small satellites (ESA 2014, GOMSpace 2014) This precipitated the possibility of developing a small satellite constellation and motivated research into the effect of constellation design parameters on ADS-B coverage performance.

The paper is organized as follows: Section 2 provides the details of the ADS-B constellation mission requirements, whereas parametric study is given in Section 3. The results and identified trends are given in Section 4 and a special case study on the MH370 flight is given in Section 5 with concluding remarks are given in Section 5.

2. Mission requirements

The fundamental 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, over the oceans and poles). Within this requirement are a number of variable mission parameters that affect the design, cost and effectiveness of resulting satellite systems.

- **Update Rate** - the timeliness with which aircraft data can be updated and disseminated terrestrially. With ADS-B, terrestrial ATC towers typically achieved at least 1 update per second, depending on airport capacity (Orlando 2001). For the purposes of live tracking and safety control, an update rate in the order of 1 second to 30 seconds is required (CASA 2012, DTFAA 2010, RTCA 2009, 2010, ICAO 2011)
- **Surveying Capacity** - ABS-B transmissions work on a Mode S Extended Squitter (Dawson 2013), which limits the number of aircraft surveyed by any one ADS-B receiver, reducing the effectiveness of ADS-B constellations in denser flight paths. For ADS-B reception via satellite, this limitation can be mitigated by scanning a populated area for a longer period, or 're-scanning' the area over multiple visits.

Full global coverage could be achieved by a series of polar or near polar orbits, similar to the Iridium Satellite constellation (ICAO 2007, Fossa *et al.* 1998). Achieving full coverage, however, would be the most costly solution, requiring the largest number of satellites and ground stations. As a minimum requirement, the ADS-B system should cover the North Atlantic, North Pacific and Indian Oceans and South East Asia in order to meet the fundamental system requirement. These areas have the highest amount of air traffic not covered by the terrestrial ADS-B systems. Monitoring these regions with specific orbits can reduce the number of spacecraft required in order to provide the coverage required by the system.

3. Parametric study

To evaluate the ability of a constellation of LEO satellites to provide ADS-B coverage in the absence of land-based ADS-B receivers, popular flights over the Atlantic and Pacific Oceans were simulated in Systems ToolKit (STK, Analytical Graphics Inc. Exton, PA USA). Different satellite constellations were simulated and the link-budget data for each test case was analysed. The efficacy of a constellation was determined by comparing the aggregated access times and link budgets for the ADS-B links between a given trans-oceanic flight and the overhead satellites. The input values used to create the simulation were based on ADS-B signal characteristics from AGI (2013), Garmin (2007), Avidyne Corporation (2011), Trig Avionics (2013), BendixKing (2013), RTCA (2013), while plane performance statistics were acquired from Boeing (2014), Frawley (2013). The full set of STK simulation files is available in (Nguyen 2014).

3.1 Flight path selection

The advantages of space-based ADS-B coverage would mainly come from areas where ground-coverage is not possible. As such, to evaluate the performance of a given satellite constellation, flight paths passing over oceans were selected, mostly between the United States, Europe and Asia. Data for these flights were accessed from OpenFlights (OpenFlights 2014), and is shown in Fig. 2.

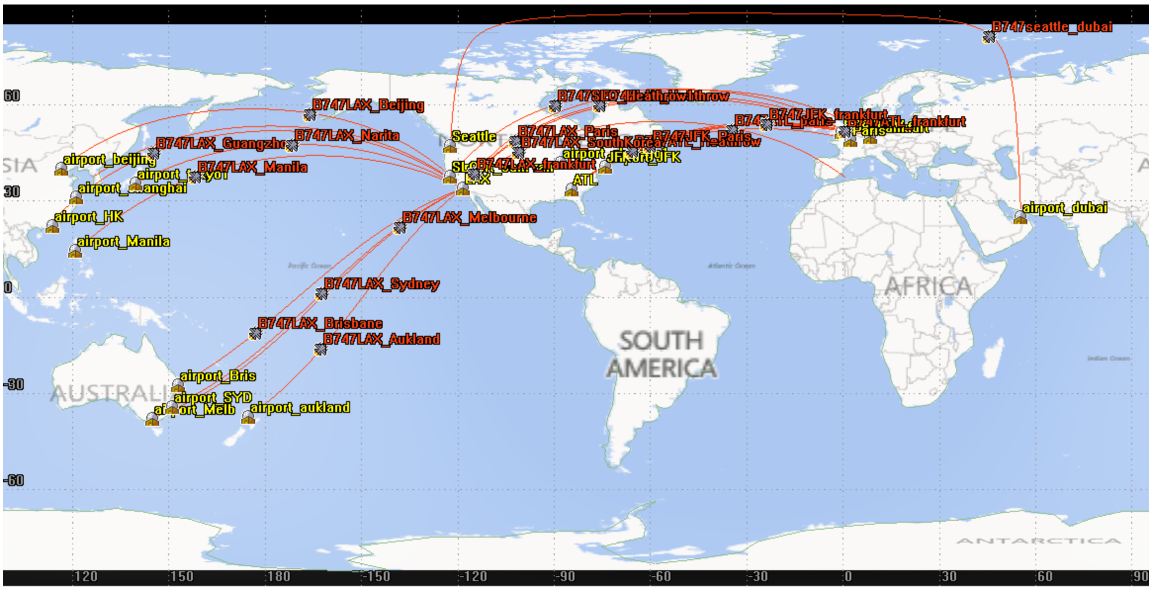

Fig. 2 Trans-oceanic flight paths selected for analysis

For the purpose of parametric analysis, three flight path generalisations were defined and one flight from each generalisation was used for modelling:

- North America to Asia - The path between Los Angeles International Airport (LAX) and Narita airport (NRT)
- North America to Europe - The path between LAX and London Heathrow (LHR).
- North America to Australia - The path between LAX and Sydney (SYD) International Airport.

3.2 Output parameters

ADS-B coverage for each satellite constellation was analysed on a flight-by-flight basis. For a given constellation, the communication link was analysed separately for a sample of trans-oceanic test flights. Each link was characterised by four parameters:

- **Access Times** - the periods of time during which a flight had line-of-sight to at least one overhead satellite and therefore could theoretically establish an ADS-B link. A longer access time is more desirable. This was available as primary data from STK.
- **Coverage Gap Times** - the periods of time during which a flight has line-of-sight access to no satellites in the constellation. Smaller gap coverage times would be more desirable. This was calculated by processing raw data from STK.
- **Received Isotropic Power** - the power of the ADS-B signal after it has been propagated from a flight to an overhead satellite. A higher received power would be more desirable, allowing for a more robust link. This was available as primary data from STK.
- **Cost of Operation and Launch** - A larger number of satellites or a more complex constellation would present an increased launch and operations cost. The total cost of operation was important when performing the trade-off analysis for different constellation parameters. Here lower would be better to reduce the overall cost of a system.

From these data, four values were computed and used as performance metrics to evaluate the efficacy of a constellation:

1. Total coverage gap fraction - the fraction of time a simulated flight spends without being able to transmit ADS-B signals to a satellite. This would be representative of the time the flight would expect to spend out of communication for a given period of time. This was calculated by:

2. Maximum gap time - the maximum amount of time a flight spends without a communication link to a satellite. This represents the worst case scenario for the amount of time a flight would spend out of communication.[1]

$$\text{Gap Fraction} = \frac{\text{total time with no access to a satellite}}{\text{total analysis time}}$$

3. Average Gap Time and Average Access Time - the mean of access times and coverage gap times identified during the analysis period. This gives an indication of the periodicity of the ‘access-no access’ cycles that a flight would experience.[1]

4. Minimum Received Isotropic Power - the minimum power of an ADS-B signal as it is received by a satellite. This can be later used to determine the link budgets and perform system definition for a given satellite in the constellation. [1]

5. Total Number of Satellites - the number of satellites required by a particular constellation as an indication of launch and operations cost. It was assumed that each satellite was identical and therefore the relative cost of launch was well represented by the number of satellites

For this study, surveying capacity was not directly considered due to the lack of appropriate resources available for an accurate link-budget analysis. A reasonable estimation of surveying capacity would require more realistic antenna modelling, discussed later in this report. Instead received isotropic power was considered a rough indicator of relative performance.

3.3 Test cases

A reference constellation was chosen with key orbital parameters varied in order to generate the suite of test constellations. The reference case was constellation of 12 satellites distributed in three circular orbits, each with four equidistant satellites, inclined at 60 degrees and at an altitude of 700km (semi-major axis 7078.14km). The three orbital planes were separated by 120 degrees of longitude with Right Ascension of Ascending Nodes (RAAN) starting from 0 degrees for the first plane. The four satellites within each plane were separated by true anomalies of 90 degrees. The ground track of the configuration is shown in Fig. 3 and the 3D representation is given in Fig. 4. From this reference, altitude, inclination and satellite number were varied to determine an optimal solution.

4. Results and discussion

4.1 Altitude variation

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[1] These values were calculated after parsing all discrete accesses into a database. The data were calculated using MATLAB scripts, available in (Nguyen 2014).

This series of tests involved evaluating the effect of uniformly changing the altitudes of each satellite from the reference case on the performance metrics outlined in Section 3.2. All altitudes tested were restricted to LEO.

The effect of altitude variations against coverage gap and minimum received signal power was as expected. Received power decreased roughly linearly with altitude, with consistent values across all fights. Similarly, the coverage gap ratio decreased linearly with altitude, with each test flight reporting the same rate of decay.

The difference in orbital period between the extremes of altitude (1 hour and 32.5 minutes at 800km against 1 hour and 42.9 minutes at 400 km) was less than 10% and had minimal effect on the periodicity of access times. The net effect was an observed increase in coverage time and decrease of coverage gaps for any given flight path.

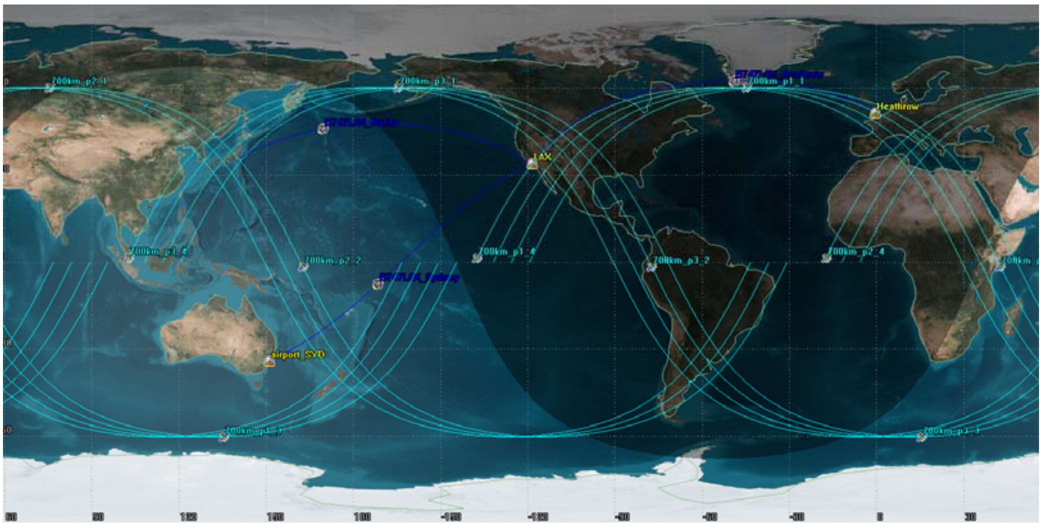


Fig. 3 Reference constellation ground rrack

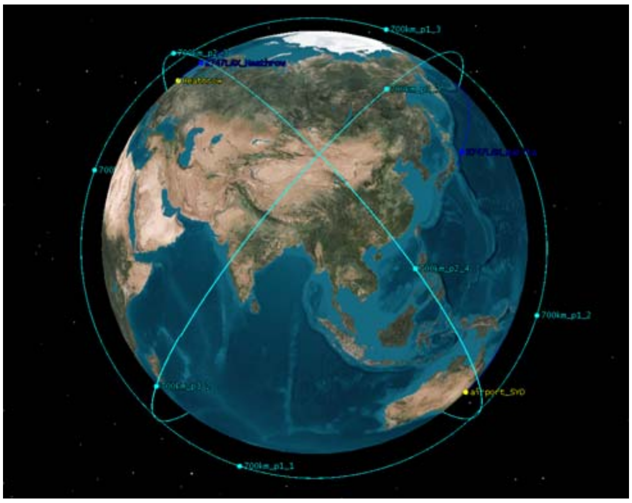


Fig. 4 3D Reference constellation visualization

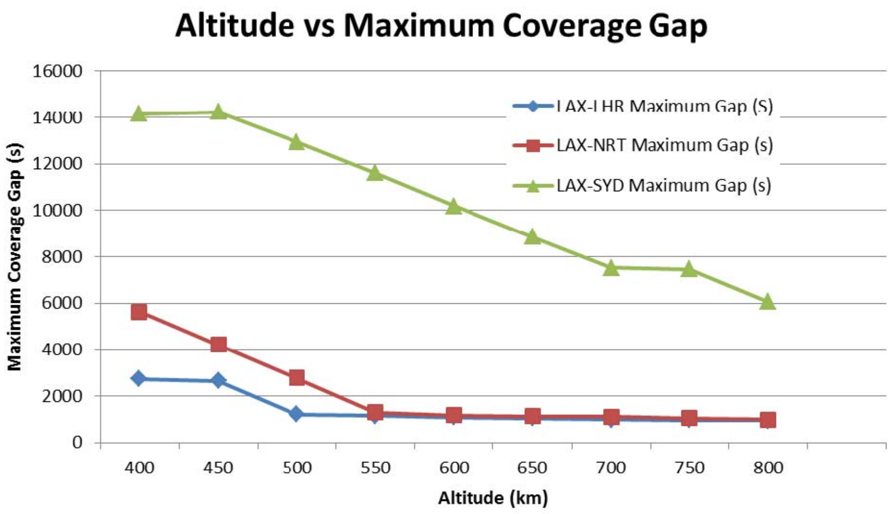


Fig. 5 Altitude against maximum coverage gap

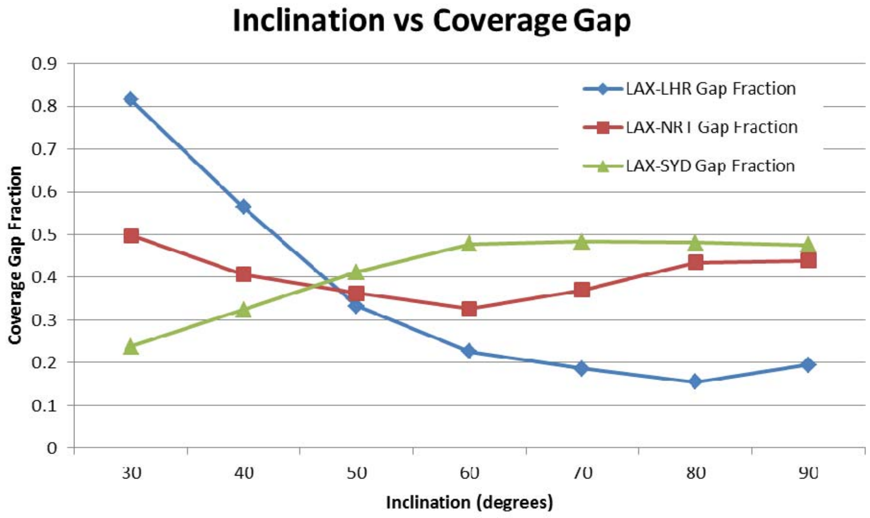


Fig. 6 Inclination against coverage gap fraction

While LAX-LHR and LAX-NRT displayed similar trends, the maximum coverage gaps for LAX-SYD were worse by one order of magnitude of time, as is shown in Fig. 5. This is due to the ground tracks of the 60 degree inclination of the satellites being almost coincident with the flight paths between LAX and NRT or LHR. The geometry of the ground tracks was not optimized for the flight path between LAX and SYD, resulting in a less desirable maximum coverage gap.

Despite the increased access time at higher altitudes a significant drop in received signal strength is observed between 400km and 800km altitude. The minimum received isotropic power is optimized at 400km, with a measurement of -137.8 dBW and is the least optimized at 800km with a measurement of -140.5 dBW. This is a difference of 2.7 dB, meaning that from 400km to

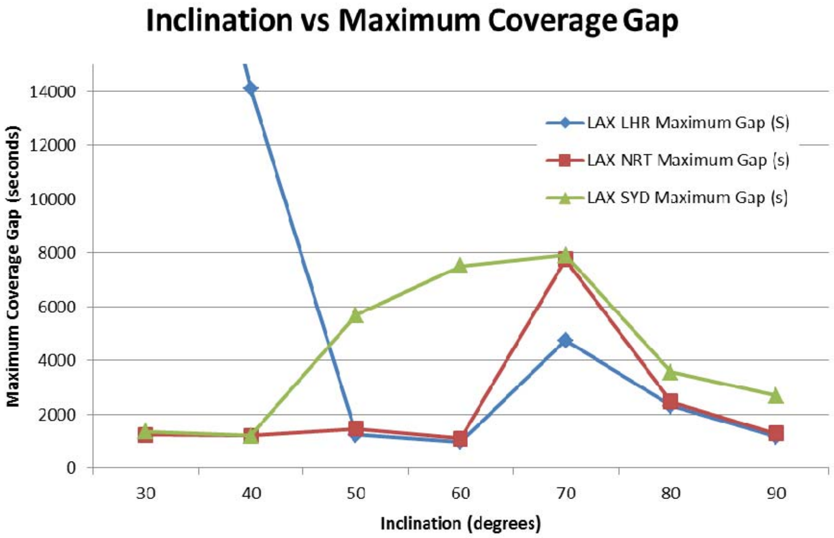


Fig. 7 Inclination against maximum coverage gap

800km altitude, the raw signal power has been reduced by a factor of 1.86. This will affect ADS-B signal reception as weaker signals will be harder to detect and process. The minimum trigger threshold level for an ADS-B receiver class R3 (Extended) as specified by the RTCA is set at -84 dBm (RTCA 2009) or equivalently -114 dBW. This is already well above that reported possible with the standard STK transmitter-receiver model at 400 km altitude.

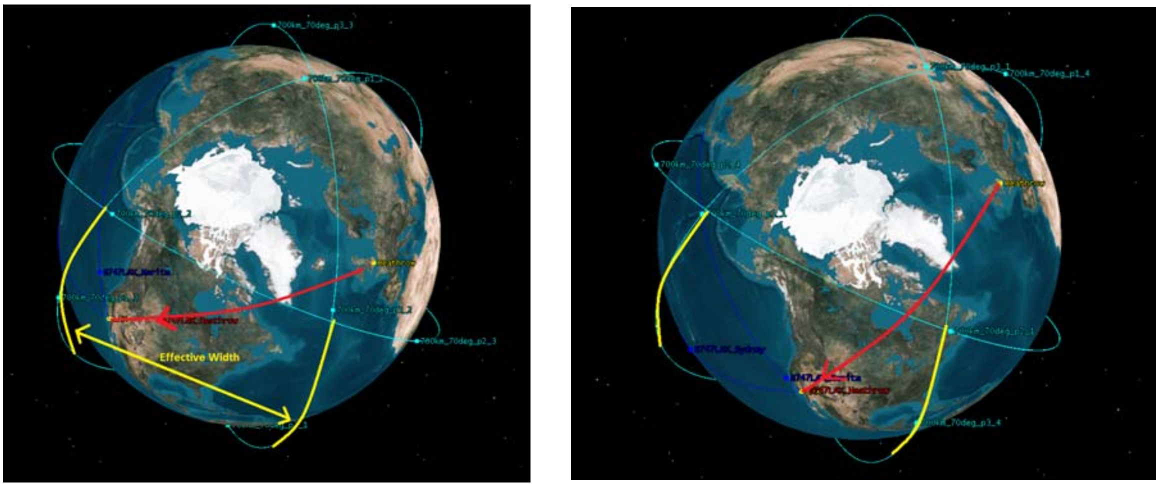
4.2 Inclination variation

This series of tests involved evaluating the effect of uniformly changing the inclination of each satellite from the reference case on the performance metrics outlined in Section 3.2.

The results for inclination variations against the resulting coverage gap fractions and maximum gap period are shown in Figs. 6 and 7 respectively.

As can be observed from Figs. 6 and 7, at lower inclinations, the ground tracks of the satellite have a significant degree of coincidence with the LAX-SYD flight path. This results in the LAX-SYD flight path having an optimized maximum coverage time and coverage fraction at 30 degrees inclination. Increasing inclinations resulted in a higher coverage gap ratio, before settling at 60 degrees and remaining constant through to 90 degrees due to the geometric nature of the ground tracks.

The relatively high inclination of the LAX-LHR flight path resulted in poor coverage by the low inclination constellations. At low inclinations there were few opportunities for line of sight to be established between the LAX-LHR flight, with access periods only occurring when satellites reached high latitudes at the same time as the flight was at a low latitude. The resulting maximum gap is approximately 8 hours and 18 minutes - more than half the duration of the flight. The aggregate result also yielded a poor coverage gap fraction performance below 50 degrees (Fig. 6). The effect sharply decreased with higher inclinations, with coverage gaps lowering to an acceptable level after 50 degrees.



(a) Flight initially in the 'dead zone' of no ADS-B Access between planes

(b) Rotation of the Earth eastward keeps the flight in the dead zone for an extended period of time

Fig. 8 Flight in dead zone between satellite planes, inclined at 70 degrees. View from North Pole

As can be observed from Fig. 7, all flight paths observe a sudden step increase in maximum coverage gap time with satellites inclined at 70 degrees. This occurs due to the geometry of the constellation and the effect of the Earth's rotation under the constellation. Fig. 8(a) shows that the effective width between the two orbital planes is quite high, creating an effective radio dead zone in which the flight cannot access a satellite. Although the satellite continues to travel out of the dead zone, the rotation of the Earth underneath the constellation moves the position of the plane back into the dead zone, as shown in Fig. 8(b). At inclinations of 80 degrees and 90 degrees this effect is mediated by the changing geometry and intersections between satellite ground tracks and flight paths, resulting in more acceptable coverage gaps.

There is relatively little change in the minimum received isotropic powers, with values ranging between -139.9 dBW and -140.02 dBW, the difference resulting from a trigonometric change in effective signal path as the satellite rotates.

4.3 Satellite number variation

This series of tests involved evaluating the effect of changing the number of satellites in the constellation on the performance metrics outlined in Section 3.2.1. The same three-plane orbital configuration was kept from the reference case whilst the number of satellites per-plane wase varied between 1 and 6.

As would be expected, increasing the number of satellites increased the coverage times available for each flight path. A higher number of satellites results in smaller coverage gaps. A higher number of satellites per plane increases the probability that a given flight is able to see at least one satellite, and also increases the revisit time for a given area on Earth. The number of satellites in the constellation does not affect the minimum received RF power.

Despite the net beneficial effect on the ADS-B system, the number of satellites needs to be weighed against the increased launch and maintenance cost, especially when considering the need to distribute the satellites evenly per plane and potential replacement at end of life.

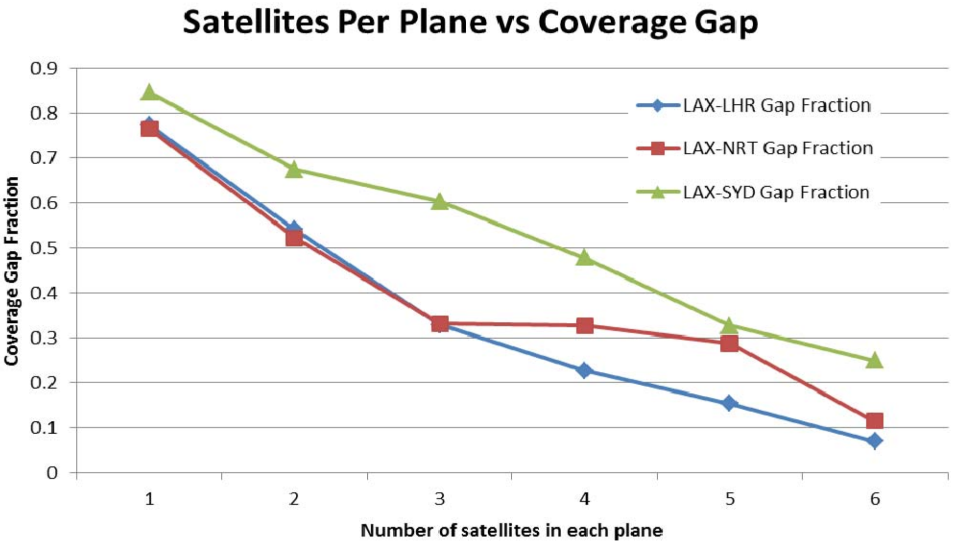


Fig. 9 Number of satellites against coverage gap fraction

Fig. 10 Simulated MH370 flight path with 18 satellite constellation

5. MH370 case study

The Malaysia Airlines Flight MH370 disappeared on the evening of March the 7th, after losing contact with air traffic control at approximately 5:20pm GMT (Rahman 2014).There is no publicly available data of the flight after 5:21pm GMT, at which point the flight was approximately 6.92°N and 101.70°E (FlightRadar24 2014). Military radar information suggests that the flight visited a series of known way points west of the planned flight path before being completely lost (Koswanage and Gobvindasamy 2014). Data from satellite pings and international search efforts suggested that the aircraft may have crashed in the Indian Ocean (Colgan 2014, Pandey and Ruwitch 2014). As of April 16th 2014, there is an ongoing international effort to attempt to locate the possible crash site and location of the debris from the MH370.

Table 1 Results from MH370 simulation using 18 satellites

Parameter	Value
Coverage Gap Fraction	0.10%
Discrete Accesses	20.00
Maximum Gap	309.72 seconds
Minimum RX Power	-139.95 dBW

In this section MH370 is used as a case study to assess and demonstrate the efficacy of space based tracking of aircraft. The best performing constellation found during the study, 18 satellites at 700km altitude, was tested against an estimated flight path for the MH370 alongside its standard path. This estimated path assumed that the flight terminated over the Indian Ocean, as shown in Fig. 10. For the sake of coverage analysis it was assumed that the ADS-B transponder remained operational for the duration of the flight.

The coverage results are summarized in Table 1. As can be seen, results show that the 18 satellite constellation would have allowed for near constant coverage, with the flight only being out of sight for 10% of the flight duration. The high number of discrete accesses for the one flight would have also allowed for deviations in the flight path to be detected early and accurately mapped with many sample points.

The results from this simulation show that the 18 satellite constellation would have provided coverage to almost continually track the MH370 during its flight. If the ADS-B transponder remained operational during the flight, the probable crash and debris locations could be much smaller providing for a much more feasible search area.

The exact status of the ADS-B transponder during the flight is currently unknown. No ADS-B data exists beyond of that reported by FlightRadar24 (2014). Ground based ADS-B receivers in the vicinity of this disappearance suggest that the ADS-B transponder was inoperable after this period. In this case the constellation would have not been able to track the entirety of the deviated flight path. However, the high effective ADS-B sample rate of the 18 satellite constellation would have provided a more accurate estimation as to the exact time and location when the ADS-B signal would have been lost. This could have aided in search efforts and generated potential flight paths with greater confidence.

5. Conclusions

In this paper a space based ADS-B receiving system, consisting of constellation of small satellites is proposed for tracking aircraft in-flight over oceans and poles where ground based ADS-B receivers are not available. The parametric study suggests that a higher number of satellites at a higher altitude provide more reliable ADS-B coverage for the trans-oceanic flights of interest. Geometrically, a 60 degree inclination was the most co-incident with the flight paths of interest and provided the most optimal coverage of the inclinations tested.

A further tradeoff analysis and systems study needs to be undertaken into the link-budget and economic requirements of the proposed satellite constellation. The ADS-B link models used in this work were quite simplified and did not yield raw link-budget data which would be representative of that possible with currently available technologies. Furthermore, an economic analysis needs to be carried out in order to determine the full cost-benefit of launching more or less satellites into the proposed constellation.

Acknowledgments

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EC

Nomenclature

ADS-B	Automatic Dependent Surveilance Broadcast
ALAS	ADS-B Link Augmentation System
ANSP	Air Navigation Service Providers
ATC	Air Traffic Control
ATM	Air Traffic Management
CASA	Civil Aviation Safety Authority
ESA	European Space Agency
LAX	Los Angeles International Airport
LEO	Low Earth Orbit
LHR	London Heathrow Airport

NRT	Narita Airport
PSTN	Public Switched Telephone Network
RAAN	Right Angle of Ascending Node
RTCA	Radio Technical Commission for Aeronautics
STK	Systems Tool Kit
UAT	Universal Access Transceiver Standard
US	United States (of America)