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Design concept of cost effective LEO satellite system for Automatic Dependent Surveillance-Broadcast (ADS-B)

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Abstract

The air traffic surveillance has been performed by radar over the past few decades. In recent days, it is gradually being replaced by technologically advanced Automatic Dependent Surveillance–Broadcast (ADS-B). ADS-B offers numerous advantages in terms of superior accuracy and range and low power consumption, etc. The coverage of terrestrial radar and ADS-B is confined to continental parts of the globe, leaving oceans and poles uncovered by instantaneous surveillance measures. Meanwhile available airspace has become congested due to rapidly growing air traffic. The paper presents the mission design of a satellite based ADS-B system for air traffic surveillance over intercontinental trans-oceanic flight routes. Performance assessment of the designed constellation is based on the analysis of various parameters such as regional and global coverage and satellite availability. LEO satellite handover mechanism and link budget for the ADS-B system are also discussed. The results of parametric analysis indicate that the constellation provides adequate coverage in the simulated global and regional areas. The constellation is a feasible and cost effective solution for global air surveillance which can supplement/replace the terrestrial ADS-B and radar systems.

Keywords: Radar; ADS-B; Air traffic; Surveillance, Simulation, Link budget

1. Introduction

Air surveillance is a fundamental requirement of civil and military aviation industries. In past few decades, the tracking is based on numerous technologies, i.e. Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR) and Automatic Dependent Surveillance-Broadcast (ADS-B). ADS-B

Figure 1 Global ADS-B coverage, adopted from (Maps of World, World air routes, 2022)

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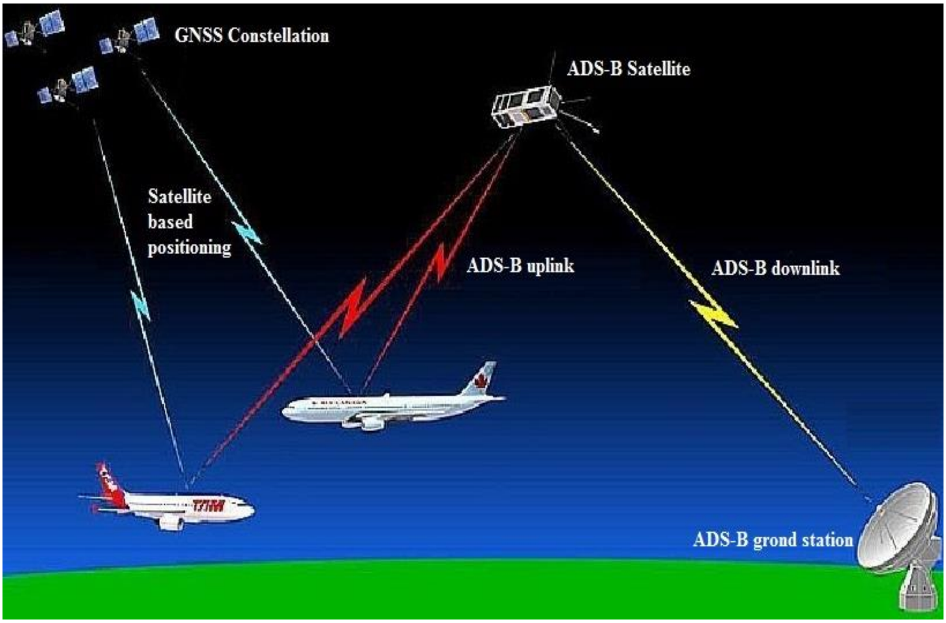

Figure 2 Illustration of the concept of space-based ADS-B system, adopted from (Space based ADS-B, 2018).

is comparatively a new technology which is quickly being adopted as an aviation standard around the globe past few years. The technology has several benefits over radar, such as cost effective and simple ground architecture, less data latency and data update rate of 1sec (Strohmeier, Schäfer, Lenders, & Martinovic, 2014) (Blomenhofer, Pawlitzki, Rosenthal, & Escudero, 2012). ADS-B equipped aircrafts drive their geo-coordinates and velocity via an on-board GNSS receiver. The geo-location information is combined with other parameters such as, aircraft identification, intent uncertainty level etc. The entire set of parameters is then transmitted over an Extended Squitter (ES) 1090 MHz SSR-Mode-S downlink signal, which is called ADS-B out. The ADS-B signal is received by neighbour air traffic for collision avoidance and by the ground station network (Ali, 2016), (Werner, Bredemeyer, & Delovski, 2014).

At this time, a terrestrial infrastructure provides ADS-B services to Air Traffic Control (ATC) authorities. This ground based infrastructure is dependent on the constraint of "line of sight" of aircrafts within a defined range of the ground station (Nguyen & Dixon1d, 2015). Typically, a terrestrial ADS-B system is effective within 80 nautical miles which means that oceanic coverage is just confined to the coastal areas. This is due to the fact that installation of ground station in remote areas like poles and oceans is either technically or economically not viable. Consequently, air traffic cannot be monitored over these remote regions. Moreover, it is also costly to cover large land areas using poor infrastructure (Alminde, Christiansen, Kaas, Midtgaard, Bisgard, Jensen, Gosvig, Birklykke, Koch, & Le Moullec 2012). In case of an air crash in non-radar or ADS-B airspace, the rescue operation has to be performed without valid information about the crash site location. This makes the situation even more complex. A similar situation was witnessed during the incidents of Air France's flight 447 in 2009 and Malaysian MH370 in 2014. The accurate locations of these accidents were unknown and it took several days to figure out possible crash locations. The ground based global ADS-B coverage area is presented in Figure 1, which shows significant gaps over the oceans which act as basic routes for inter-continental flights.

As a consequence of the terrestrial ADS-B constraints, the gap regions over the oceans can be covered with a space based ADS-B. The whole idea is to place a highly sensitive receiver on a satellite, capable of receiving ADS-B signals in space. Afterwards, the data would be relayed to ADS-B ground receiving stations. The whole concept of space based ADS-B is illustrated in Figure 2. The subject has already gained interest of the key stakeholders of the aviation industry and numerous projects have been initiated. Proba V, a mission of the European Space Agency, is a classical example of ongoing advancements in space based air traffic surveillance. It is primarily an Earth observation satellite with an added secondary experimental payload of ADS-B receiver. The satellite was launched in 2013 and is successfully receiving ADS-B signals without any moderation in the existing ADS-B infrastructure of the aircrafts. This mission has proved that the technology is feasible as a primary payload on small satellites (Delovski, Bredemeyer & Werner, 2016).

Based on orbital altitude, satellite-based communication networks can be classified into three main classes, Geostationary Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO) satellite systems. GEO satellites have an altitude of nearly 36000 km above the equatorial plane, where the satellite's orbital motion is synchronized with the Earth's rotation. At GEO altitude a few satellites are required for global coverage. However, GEO satellites exhibit some major drawbacks for communication networks. The user terminals and the space segment are not power efficient, and the propagation delay is comparatively high in these systems. LEO systems, on the other hand, have prominent advantages, like efficient bandwidth utilization, low propagation delay, and are more power efficient as compared to GEO systems (Henderson & Katz 2000).

The aim of this study is to design a low cost LEO constellation that can provide competitive global ADS-B surveillance by utilizing the least number of satellites. Typically, LEO constellations are deployed within 400-2000 Km altitude with circular orbits. However, the orbital geometry and altitude of the constellation design varies greatly according to the space mission requirements. LEO constellations are widely used in the communication sector. There are various space missions that have been planned for numerous applications, e.g. LeoSat, Samsung and Telesat LEO etc. The total number of satellites of these planned missions may range between 70 and 4700. Iridium is also launching NEXT generation constellation of 66 satellites for global internet communication and it would also be used as ADS-B Link Augmentation System (ALAS) (Noschese, Porfili, & Di Girolamo, 2011), (Gupta, 2011).

2. Constellation Geometry

Satellite constellation is defined as a group of satellites, operating to achieve a common goal. The orbital geometry is calculated with a set of six keplerian orbital elements, including Inclination angle (i), Semi-major axis (a), Right Ascension of Ascending Node (RAAN), True anomaly, Eccentricity (e), and Argument of Perigee (ω) (Cakaj, 2014). The design parameters are thoroughly investigated as follows:

2.1. Constellation Altitude Selection

The orbital altitude is one of the key design parameters of a constellation. The RF communication a requirements and satellite coverage have direct relationship with the orbital altitude. If the orbital altitude is low, it would be less demanding in terms of the Equivalent Isotropic Radiated Power (EIRP) requirement of the system. Moreover, signal propagation losses would also be low but a higher number of satellites would be required for coverage. This setting would certainly

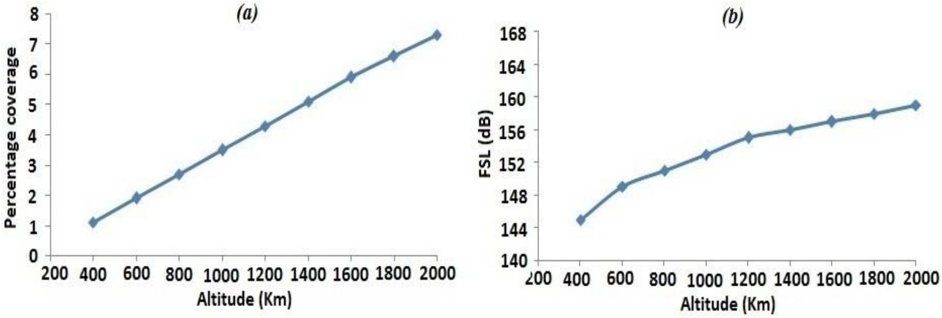

Figure 3 Variation in percentage coverage and FSL of LEO constellation with altitude (a) Variation in LEO satellite percentage coverage of the globe, (b) Variation of the FSL with the distance, considering f = 1090 MHz

escalate the entire space mission design cost. The selection process of the system's orbital altitude generally requires a balance between space mission deployment cost and quality of service (QoS) (Long, 2014). During the altitude finalization process, one must consider the fact that the EIRP requirement is satisfied, which means that the spacecraft has an adequate signal to noise ratio (SNR) and therefore it can be detected in space. The relationship between LEO satellite orbital altitude with the percentage coverage area and free space loss (FSL) is shown in Figure 3. Additionally, some space weather constraints (Earth's atmospheric drift and Van Allen belts) should also be taken into consideration in the altitude selection algorithm (Horne, Thorne, Shprits, Meredith, Glauert, Smith, Kanekal, Baker, Engebretson, Posch, 2005).

2.2. Constellation Orbital Geometry Selection

To determine optimum orbital geometry, the total number of orbital planes and satellites necessary for ADS-B coverage needs to be determined. The relative satellite-observer geometry is determined by two angles, i.e. elevation and azimuth angles. Azimuth is the angular direction of the satellite which is calculated on the horizontal plane in the clockwise direction from the geographic north. Its range is 0˚ to 360˚. The elevation is defined as the angle between the observer's horizontal plane and the line joining to satellite in a vertical plane. Its range is 0˚ to 90˚. The coverage of the satellite is generally represented by a circle on a surface of the globe and generally refers as footprint. We can communicate with the satellite within its footprint at a predefined minimum elevation angle. This minimum value of elevation angle is a dependent on system constraints. Ideally, big footprint is accomplished at minimum elevation. But, practically we may not be able to communicate with a spacecraft at too low elevations due to natural or man-made barriers. To overcome these barriers, the minimum elevation angle constraint for the LEO system ranges between 5˚-10˚ (Cakaj, Kamo, Lala, & Rakipi 2014). For satellite view geometry calculation, it is assumed the worst scenario in which the minimum elevation is considered 10˚.

The cross-sectional coverage area of a LEO satellite at the equatorial plane is depicted in Figure 4 (a). We have selected the equatorial circle because it is a great circle that has the maximum radius, shown in Figure 4 (b). All of the other latitudinal circles (parallels) of the sphere are small circles whose radius is lesser as compared to that of the equator. This implies that higher LEO planes and satellites are required to cover the equatorial plane. We can obtain the longitudinal range of a LEO satellite footprint by calculating the Earth's central angle (ϕ). Total LEO planes and satellites required for full ADS-B coverage of the equatorial plane can then be

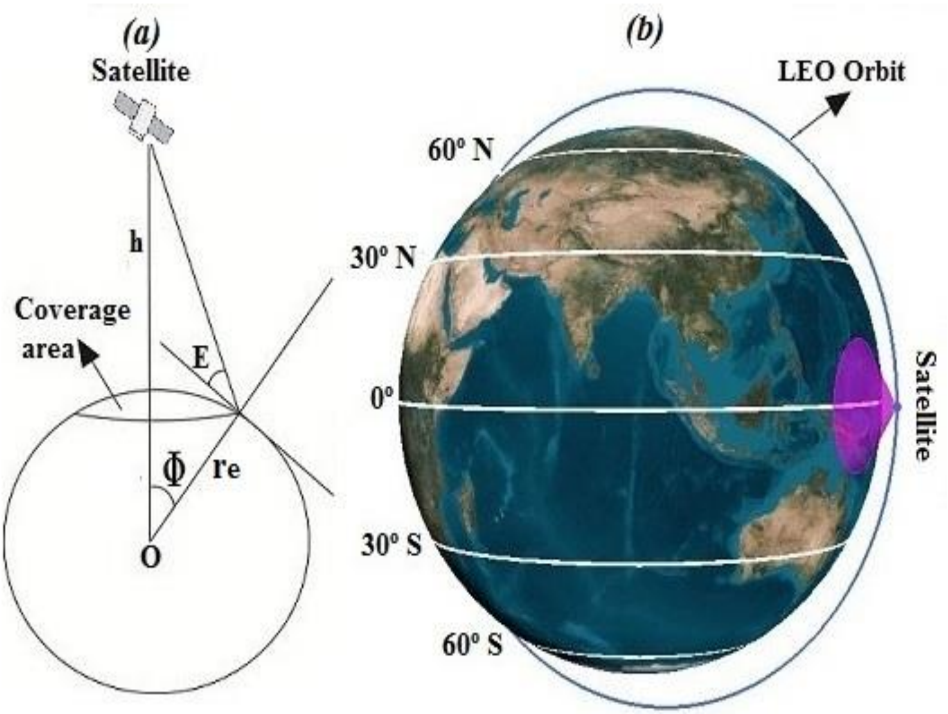

Figure 4 Illustration of the concepts of satellite view geometry: (a) LEO satellite cross-sectional coverage area of the equatorial plane, (b) 3-D visualization of LEO satellite foot print.

calculated. ϕ is obtained by the following equation:

$$\phi = [\cos^{-1}[\frac{\text{re}\cos E}{Re+h}]] - E \qquad (1)$$

In the above equation, r_e represents Earth's radius, *h* is the spacecraft's altitude and *E* is the elevation angle. By incorporating the values of *Re*, *h* and *E* in equation (1), ϕ comes out to be 19.90°. From Figure 4 (a), one LEO satellite covers 2ϕ or 39.8° of longitude of the equator, the quantity of orbital planes for global coverage is calculated as:

$$\text{Total number orbital planes} = 360°/4\phi = 5 \qquad (2)$$

As we have not covered the polar region due to the absence of major air traffic activity, so one orbital plane is reduced and a LEO constellation with four orbital planes is designed which is adequate to cover the airspace with dense traffic (59° N to 58° S).The total in-orbit satellites per plane can be found with the following equation:

$$\text{Satellites per plane} = 360°/2\phi = 9 \qquad (3)$$

Overall, a delta walker constellation of 36 equidistant satellites, separated by 40° of true anomalies in 4 orbital planes at 60° inclination is required for full coverage of the globe within the latitudinal range of 59°N - 58°S. A walker constellation has several orbits at the same inclination that are rotated about the poles, i.e. have different RAAN. The surface coverage area of LEO satellite can also be calculated using the Earth's central angle as follows:

$$\text{Percentage Coverage} = \frac{\text{Surface coverage area of satellite}}{\text{Surface area of the Earth}} \times 100 \qquad (4)$$

$$\text{Percentage Coverage} = \frac{2\pi \text{Re}^2\,(1-\cos\phi)}{4\pi \text{Re}^2} \times 100 \qquad (5)$$

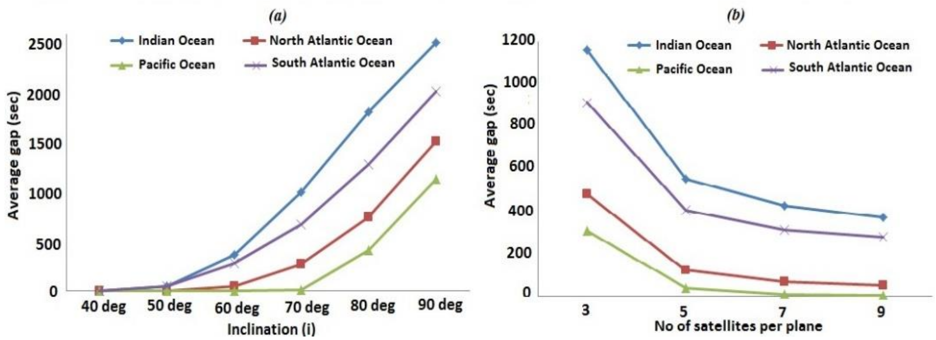

Figure 5 Geometry optimization results (a) Variation in average gap duration of oceanic regions with inclination angle considering satellites per plane = 9, (b) variation in average gap duration of oceanic regions with satellites per plane considering i=60˚.

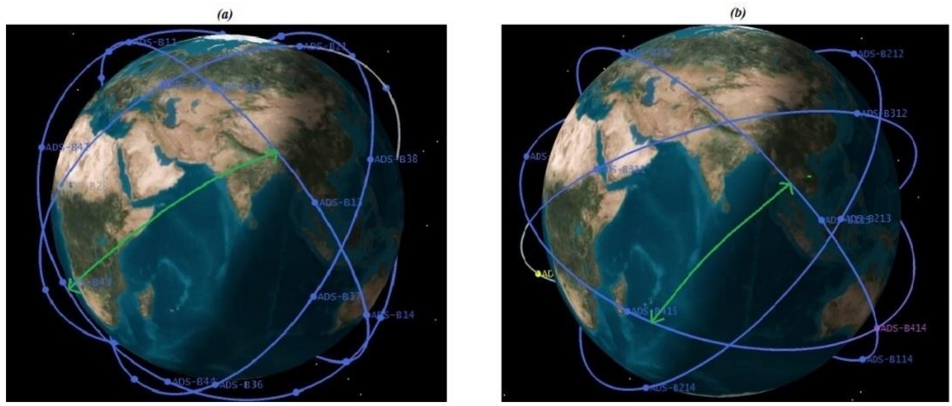

Figure 6 3-D visualization of constellation models, (a) Theoretical delta walker constellation of 36 satellites, (b) Proposed constellation of 20 satellites.

The footprint a LEO satellite orbiting the Earth at 850 Km altitude is computed as 15261970Km^2 with 2206 Km of coverage radius. Incorporating this value in equation (5), the percentage surface area covered by one LEO satellite is calculated as 2.98% of the entire globe.

Regardless of the overall advantageous effect of this LEO tracking system, launching 36 satellites for global air traffic surveillance would be costly, particularly when considering the maintenance and replacement of satellites at the end of life. The total number of satellites must be balanced against the overall cost of the space mission. As a fundamental requirement, space based ADS-B system should ensure surveillance over the North Atlantic, South Atlantic, Pacific and Indian Oceans. These oceanic regions have the highest amount of un-tracked air traffic by the terrestrial systems (Radar or ADS-B). Tracking these regions with satellites in specific orbits can greatly diminish the constellation deployment cost. Thus, in order to lower the manufacture and launch cost of the ADS-B mission constellation size is systematically condensed using an optimization approach. A series of tests is conducted in which the geometric parameters of the constellation are optimized to analyze the effect on coverage of the trans-oceanic flight route regions. The geographical spread and significance of the simulated oceanic regions is discussed in detail in the section 3.

According to the fundamentals of orbital mechanics, the keplerian elements that influence the coverage include semi-major axis, inclination and eccentricity. As LEO orbits are circular, their eccentricity

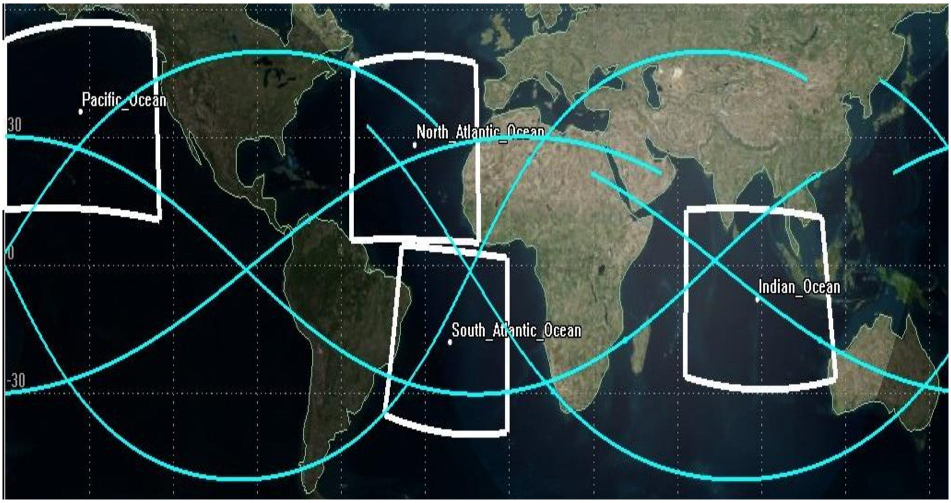

Figure7 ADS-B constellation ground tracks and study areas.

is very close to zero so the orbital eccentricity is fixed. There is a direct relation between semi-major and orbital altitude and therefore it is already being fixed based on ADS-B link requirements as explained in Section 2. The true anomaly does not directly affect the coverage of the LEO system when satellites are evenly spread in each of the orbital planes. Therefore, the orbital inclination and number of spacecrafts per plane are optimized to find the most suitable combination of these parameters. The results of the optimization process are shown in Figure 5, which shows the variation in average gap duration in selected oceanic regions against inclination and spacecrafts per plane.

The inclination optimization demonstrates that the average gap duration of all the oceanic regions is below 500 sec and increases with the inclination, e.g. from 0˚ to 90˚. The gap duration escalates as the inclination rises above 50˚. Similarly, the number of satellites per plane also has a major impact on the gap duration. The duration of a gap for each of the oceanic regions is less than 600 sec and sharply fluctuates by decreasing the satellites per plane to 3. These results suggest that the constellation with $i \leq 60^\circ$ and 5 satellites per plane is an optimum choice to achieve maximum surveillance and reduced gap duration over the trans-oceanic flight route regions. Once a, e, i, and the number of satellites per plane are

Table 1 Orbital configuration of ADS-B constellation.

Orbital parameter	Unit	Orbit 1	Orbit 2	Orbit 3	Orbit 4
Orbit type	NA	Prograde	Retrograde	Prograde	Retrograde
Inclination (deg)	Deg	50	-50	30	-30
Altitude (Km)	Km	850	850	850	850
Eccentricity (e)	N/A	0	0	0	0
Argument of Perigee (deg)	Deg	Undefined	Undefined	Undefined	Undefined
RAAN (deg)	Deg	0	0	90	90
No of Satellites	NA	5	5	5	5

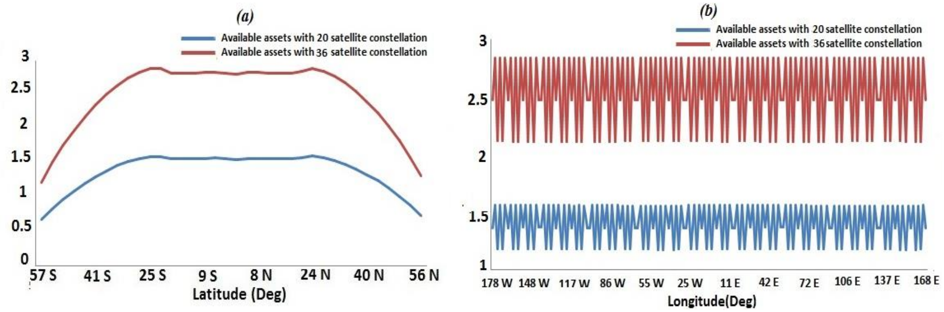

Figure 8 Spatial variation in asset availability of ADS-B constellation at 5˚ mask angle for the entire globe, (a) Latitudinal variation, (b) Longitudinal variation.

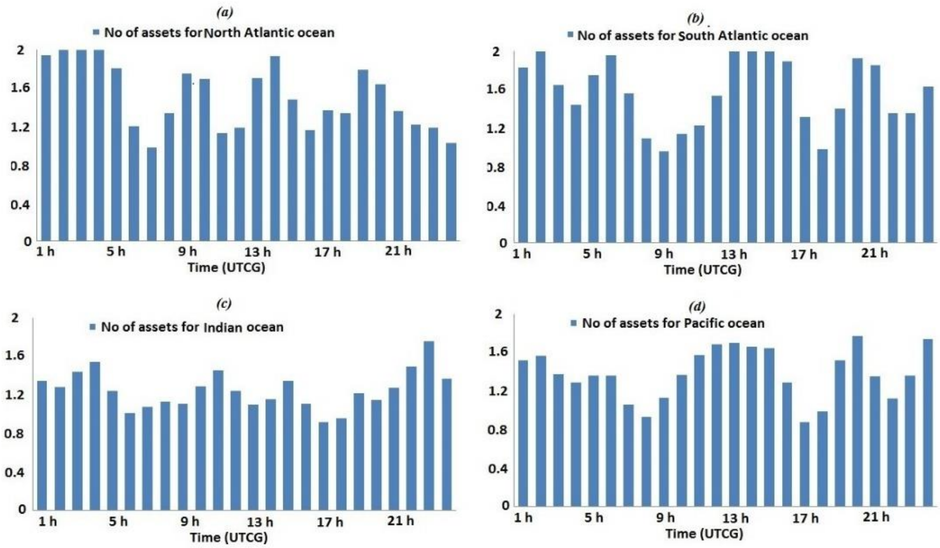

Figure 9 Temporal variation in assets availability for simulated oceanic regions, (a) North Atlantic Ocean, (b) South Atlantic Ocean, (c) Indian Ocean, (d) Pacific Ocean.

finalized, we can select the final geometry of the constellation.

The proposed constellation for global ADS-B surveillance is an inclined constellation of 20 satellites in two prograde (50º and 30º) and two retrograde (-50º and -30º) orbits at 850 Km altitude. Each orbital plane is equipped with five equally spaced satellites with true anomaly separation of 72º from each other. The orbital plane separation (RAAN) is 90°, starting from 0º for the first plane. The orbital velocity of the satellites at 850 km altitude is 7.42 km/s with a moment period of 102 min. The geometric arrangements of the theoretical delta walker constellation and the proposed constellation are given in Figure 6. As can be seen, the inter-planar spacing of the proposed constellation is small as compared to that of the delta walker constellation. This results in lowering the design and launch cost without compromising the space mission performance. The geometric arrangement of the proposed constellation is depicted in Table 1.

3. Simulation Analysis

ADS-B based in-flight tracking ability of the proposed system is evaluated in real-time dynamic simulator (AGI, Engineering Tools, 2022). The simulation parameters include altitude, orbital elements of the designed LEO system of

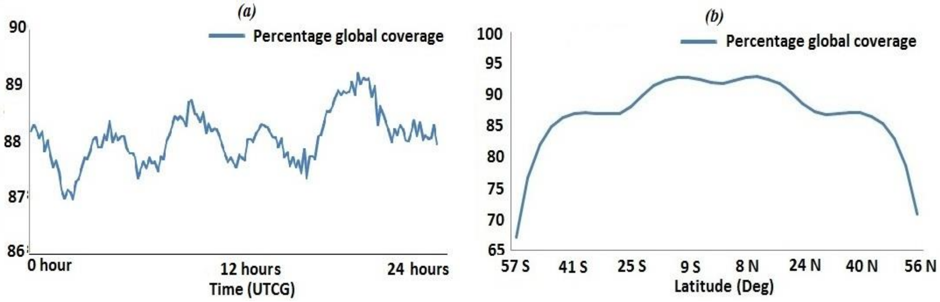

Figure 10 Temporal and spatial variation in percentage coverage area of the globe within latitudinal range of 59˚ N to 58˚ S.

20 satellites and regional and global coverage regions. Numerous testing parameters, such as coverage, satellite visibility, access time and time average gap are analyzed in a constrained setting. ADS-B link is analyzed separately using a test case trans-oceanic flight. The theoretical delta walker constellation is also simulated for a comparative analysis of the performance evaluation parameters.

The surveillance ability of the constellation is analyzed on the global and regional scales. Global surveillance of the constellation is assessed on a latitude bound global coverage definition between 59°N – 58°S. On the other hand, regional surveillance is assessed by simulating intercontinental flight route regions over the Atlantic, Indian and Pacific Oceans, shown in Figure 7. These oceanic regions are deprived of ground based radar or ADS-B surveillance and connect all major cities of Stockholm, Kuwait, Karachi, San Francisco, Los Angeles, New York, Stockholm, Zurich, Paris, London, Copenhagen, Vienna, Sydney, Tokyo, Nagoya and Osaka (Maps of World, World air routes, 2002). The analysis time of the simulation is one day (24 h), and the start time is 00:00:00 UTC, October 1, 2022. The parametric calculations are performed on 3° lat/long grid for both global and regional simulation analysis.

3.1. Constellation Visibility Analysis

To analyze ADS-B constellation visibility, the total number of available assets in various parts of the globe has been computed. The satellite visibility of the designed constellation is also compared with that of the theoretical constellation of 36 satellites to see if the visibility constraint is satisfied and to analyse the difference between the two scenarios. Firstly, to determine constellation visibility on global scale, we have computed system visibility for the simulated latitude bound region between 59°N - 58°S. The statistical results are shown in Figure 8, which suggest that 1-2 satellites are visible in the area of interest. A moderate variation can be observed in asset availability against the latitude. Satellite availability is slightly higher at low latitudes because of the optimum geometry of the constellation that allows better asset availability in dense air traffic regions, e.g. the equatorial, subtropical and mid latitude regions.

Secondly, satellite availability for the simulated oceanic regions has been computed which is graphically represented in Figure 9.The graphs are plotted by selecting 5˚ mask angle visibility constraint and data sampling interval of one hour. It can clearly be seen that at least one satellite is overhead for all the oceanic regions, which fulfills the basic space mission requirement of efficient air surveillance over trans-oceanic flight regions. Furthermore, different scenarios are simulated to evaluate the outcome of varying numbers of satellites in the constellation. The orbital geometry is preserved while spacecraft number is varied between 6 and 9 per plane. As estimated, a higher number of satellites per plane increases the coverage and reduces

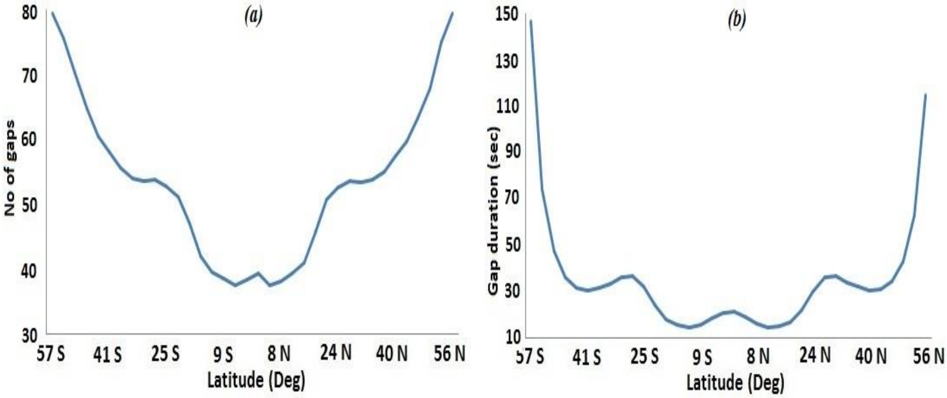

Figure 11 Spatial variation in coverage gaps throughout the simulation time of 24 hours, (a) Total number of gaps, (b) Gap duration.

gaps in the trans-oceanic flight regions. More satellites per orbit also increase the probability of one satellite accessibility for a particular region and decreases the revisit time.

3.2. Constellation Coverage Analysis

As specified previously, the constellation is designed to primarily cover the trans-oceanic intercontinental flight routes; therefore, a coverage analysis is carried out to determine the constellation's total coverage area on the entire globe. In simulations, the satellite footprint is expressed as a fraction (percentage) of the Earth's area. We also analyzed the spatial and temporal variation in the percentage coverage. Percentage coverage is mathematically expressed by the following equation:

$$\text{Percentage Coverage} = \frac{\text{Total access time to a satellite}}{\text{Total analysis time}} \times 100 \qquad (6)$$

The simulation results of the coverage analysis are shown in Figure 10. The constellation of 20 satellites efficiently covers up to 88 % region of the Earth between 59° N - 58° S in overall simulation time with a moderate temporal variation in percentage coverage. This temporal variation is caused by the combined effect of Earth's rotation and orbital motion of the constellation. Likewise, there is a considerable latitudinal variation in the percentage coverage area, illustrated in Figure 10 (b). The coverage in the low latitude regions is higher as compared to the high latitude regions. This is due to higher satellite availability in the equatorial, tropical and mid latitude regions that provide a consistent ADS-B coverage in the busiest air traffic routes.

3.3. Constellation Gap Analysis

Theoretically, a walker constellation of 36 satellites is required for 100% ADS-B coverage within the latitudinal range of 59°N - 58°S. As such, to minimize space mission cost, number of spacecrafts per orbit is reduced, which has resulted in coverage gaps. A gap is a duration in which no satellite is accessible to a particular region on the Earth meaning e.g. that the aircrafts cannot establish a communication link with a satellite during this interval. The coverage analysis of the constellation suggests that 12 % of the total airspace remains uncovered from real time surveillance measures. To inspect the geographical distribution of the gap regions, the total number of gaps and time average gap has been computed. The results of the coverage gap analysis are presented in Figure 11.

The total number of gaps lies between 40 and 80 for different regions of the globe in a simulation time of 24 hours. The duration of each gap greatly depends on

Table 2 ADS-B link budget analysis

Link Budget Parameter	**Symbol**	**Value**	**Unit**
Carrier frequency	f_c	1090	MHz
Transmitter power	P_t	26.98	dBW
Transmitter gain	G_t	1	dB
Line loss	L_t	-2	dB
Maximum geometric distance (E = 0˚)	d_{max}	3291	Km
Minimum geometric distance (E = 90˚)	d_{min}	850	Km
Free space loss at d_{max}	FSL_{max}	-163.5	dB
Free space loss at d_{min}	FSL_{min}	-151.8	dB
Receiver antenna gain	G_r	11.2	dB
Atmospheric loss	L_{atm}	-2.5	dB
Polarization loss	L_{pol}	-6	dB
Minimum received power at d_{max}	$P_{r\ (min)}$	-134.8	dBW
Minimum received power at d_{min}	$P_{r\ (max)}$	-123.12	dBW
System noise temperature	T_{eq}	290	K
Carrier-to-Noise Spectral Power Density Ratio at d_{max} and d_{min}	C/N_0	69.1, 80.8	dB.Hz

the geographic location of the gap region. The gap duration is higher in sub polar regions and decreases towards the equator. The time average gap is less than 50 sec in mid latitude, tropical and equatorial parts of the globe. This is mainly due to the higher percentage of coverage provided by the constellation at low latitudes. The results of the coverage gap analysis indicate a consistent surveillance in dense air traffic routes over the oceans as a result of small gap intervals.

4. Communication Analysis

The ADS-B 1090 MHz ES signal is 120 µs long, comprising of 8 µs preamble and 112 µs data block. The signal is transmitted frequently within 0.4 to 0.6 seconds. The main purpose of this periodic randomization is to prevent the aircraft from obscuring each other's communication. As we know in a communication system, the signal is transmitted from the transmitter travels through the medium and is received by the receiver. Link budget is the quantitative representation of all the gains and losses of the signal propagation (Francis, Vincent, Noël, Tremblay, Desjardins, Cushley, & Wallace, 2011). The link has to be examined to evaluate the power of the transmitted ADS-B signal at a distance of several hundred kilometers. We must consider the fact that the detection and processing of weak signals at an altitude of about 850 Km cannot be compared with that of the terrestrial ADS-B system due to limited link margins. Thus, the link budget is calculated based on an assumption that the transmitter has a high gain antenna and the on-board receiver is of higher sensitivity as compared to the terrestrial receiver.

Table 3 Results of performance evaluation parameters of flight 447

Parameter	**Unit**	**Value**
Total simulation time	sec	43680.12
Coverage time	sec	35023.7
Total coverage	%	81.1
Average available assets		1.3
Total accesses		87
Average access duration	sec	669.4
No of gaps		31
Time average gap	sec	62.5
Approximate maximum slant range between Flight 447 and satellite	Km	3290
Minimum received power at d_{max}	dBW	-135
Carrier to noise spectral power density at d_{max}	dB.Hz	84.9

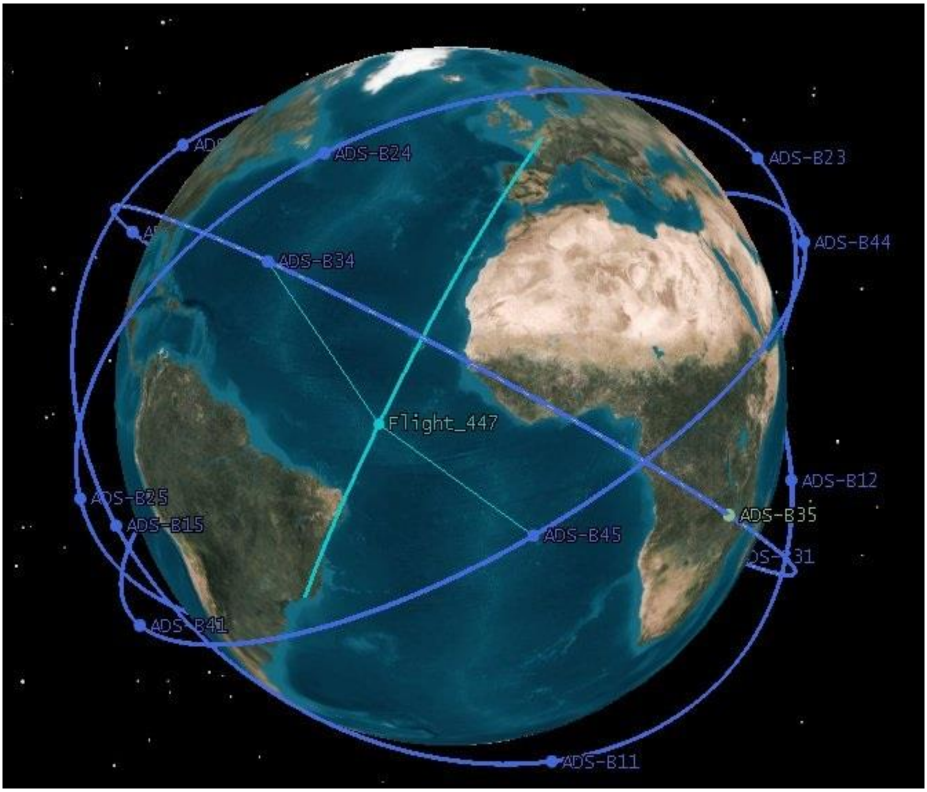

Figure 12 Access between Air France flight 447 and the satellites at the last known position.

The aviation standards for ADS-B allow aircraft to transmit signal at a transmitting power of 75W to 500 W, depending upon the aircraft type. Such a variation in transmitter power greatly affects the Minimum Detectable Signal (MDS) for a given ADS-B receiver (Betz, 2015). For the purpose of link analysis, we considered 1090 ES ADS-B omni-directional transmitter with board ADS-B receiver is considered the same as of Proba V. It is a planer and right hand polarized

antenna having 11.2 dBi gain. This link budget analysis is based on the reference

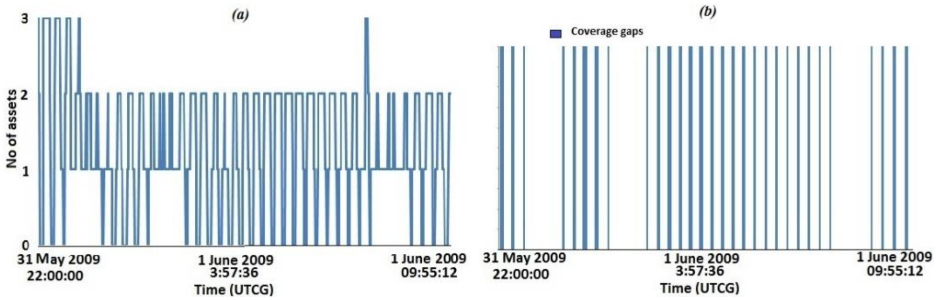

Figure 13 (a)Total number of available assets for flight 447 in overall simulation time, (b) Total number of coverage gaps for flight 447 in overall simulation time.

data and can be adjusted in the design process. The link budget is presented in the Table 2 (Betz, 2015), (Zhang, Wu, Cheng, & Zhu 2018).

5. Case Study

On 1 June 2009, Air France flight 447 crashed in the middle of the South Atlantic Ocean while going from Brazil to France. At 22:29:00 UTC on 31 May 2009, the flight took off from Rio de Janeiro-Galena airport. It had to arrive at Paris-Charles de Gaulle airport at 10:03:00 UTC but it was not that case. The known last communication of Brazilian ATC with flight 447 was made 3 hours and 6 minutes after. At 01:49 UTC, the airliner left Brazilian Atlantic radar surveillance and went through the airspace with no radar surveillance. It was expected to reach the Senegalese airspace at about 02:20 UTC, but got disappeared within the airspace of no radar surveillance. It was a modern airliner and was equipped with Aircraft Communication Addressing and Reporting System (ACARS).This system has the capability to transmit data messages by means of Very High Frequency (VHF) after every 10 minutes (Stone, Keller, Kratzke, & Strumpfer, 2011). Its final known geographical coordinates of the aircraft were 2°59′N lat 30°35′W long at about 02:10:34 UTC.

In this section, Air France flight 447 is used as a case study to demonstrate the tracking efficacy of this novel low cost space mission. The flight is simulated in a simulator to analyze the coverage, total gaps, gap duration and available assets to the aircraft. The simulation time is exactly the time of flight 447 from 30 May 2009 22:20 UTC to 1 June 2009 10:10UTC. The simulation results of coverage analysis parameters of flight 447 are illustrated in Table III. The ADS-B constellation of 20 satellites provides 80.1% coverage to the aircraft in overall simulation time with 87 accesses and 31 gaps. The average access time for flight 447 is 669.4 sec and the time average gap is 62 sec. The total number of available assets and gaps for the aircraft throughout the flight path is graphically presented in Figure 13. The aircraft entered the region of no radar coverage at 01:49 UTC and its last known position was reported at 02:10 UTC. We examined aircraft accesses in non-radar airspace, particularly at the last known position (2°59′N 30°35′W). The results from the simulation confirm that 2 satellites are in access with the aircraft at the last known position at the time when the simulation analysis of flight 447 reveals that the model LEO constellation of 20 satellites would have provided consistent coverage to flight 447 and the possible crash site location could precisely be Figured out with the space based ADS-B system provided the transponder of the aircraft remained operational.

6. Conclusion

In this paper, a low cost and technically feasible LEO tracking system has been proposed for global air traffic surveillance over the intercontinental trans-oceanic flight regions. The LEO system is designed according to the purpose and its performance is evaluated by analyzing percentage global and regional coverage, satellite visibility and coverage gaps using dynamic simulations. The results of the parametric study recommend that the designed ADS-B satellite system provides up to 88% coverage in the simulated oceanic regions. We also analyzed the spatial and temporal variation in the performance evaluation parameters which has given some valuable results. The satellite visibility and coverage in lower latitude regions is higher due to the optimum constellation geometry selected by the optimization process.

The communication analysis was also carried out which involves ADS-B link design and analysis of the LEO satellite antenna handoff mechanism. The simulation analysis verifies the theoretical calculations of the link budget and suggests that the MDS of on-board ADS-B receiver should be greater than 104.8 dBm to receive and interpret weak ADS-B signals.

Although, Iridium has planned to launch a walker system of 66 LEO satellites which will assure global coverage without any gap region. But, the designed constellation with 20 satellites provides a consistent ADS-B coverage over intercontinental air traffic routes over the Atlantic, Pacific and Indian Oceans. This proves the proposed ADS-B system to be a cost effective alternative as compared to the Iridium Next. The primary payload of the constellation is the on-board ADS-B receiver, but it can be used for oceanic disaster management and ship navigation as well.

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8. Conflict of Interest

The authors declare no conflict of interest.

9. References

AGI, Engineering Tools. (2023). https://www.agi.com/products/engineering-tools.

Ali, B. S. (2016). System specifications for developing an Automatic Dependent Surveillance-Broadcast (ADS-B) monitoring system. *International Journal of Critical Infrastructure Protection*, *15*, 40–46.

Alminde, L., Christiansen, J., Kaas Laursen, K., Midtgaard, A., Bisgard, M., Jensen, M., Gosvig, B., Birklykke, A., Koch, P., & Le Moullec, Y. (2012). *Gomx-1: A nano-satellite mission to demonstrate improved situational awareness for air traffic control*.

Betz, J. W. (2015). *Engineering satellite-based navigation and timing: global navigation satellite systems, signals, and receivers*. John Wiley & Sons.

Blomenhofer, H., Pawlitzki, A., Rosenthal, P., & Escudero, L. (2012). Space-based automatic dependent surveillance broadcast (ads-b) payload for in-orbit demonstration. *Advanced Satellite Multimedia Systems Conference (ASMS) and 12th Signal Processing for Space Communications Workshop (SPSC), 2012 6th*, 160–165.

Cakaj, S., Kamo, B., Lala, A., & Rakipi, A. (2014). The coverage analysis for low earth orbiting satellites at low elevation. *Int. J. Adv. Comput. Sci. Appl.(Ijacsa)*, *5*(6).

Delovski, T., Bredemeyer, J., & Werner, K. (2016). *ADS-B over Satellite Coherent detection of weak Mode-S signals from Low Earth Orbit*.

Estimated current global ADS-B coverage. (2023). http://www.aero-news.net/images/content/general/2012/Aireon-Coverage-0612b.jpg.

Francis, R., Vincent, R., Noël, J.-M., Tremblay, P., Desjardins, D., Cushley, A., & Wallace, M. (2011). The flying laboratory for the observation of ADS-B signals. *International Journal of Navigation and Observation, 2011*.

Gupta, O. P. (2011). Global augmentation of ADS-B using Iridium NEXT hosted payloads. *Integrated Communications, Navigation and Surveilance Conference (ICNS), 2011*, 1–15.

Henderson, T., & Katz, R. (2000). Network simulation for LEO satellite networks. *18th International Communications Satellite Systems Conference and Exhibit*, 1237.

Horne, R. B., Thorne, R. M., Shprits, Y. Y., Meredith, N. P., Glauert, S. A., Smith, A. J., Kanekal, S. G., Baker, D. N., Engebretson, M. J., Posch, J. L., & others. (2005). Wave acceleration of electrons in the Van Allen radiation belts. *Nature*, *437*(7056), 227–230.

Long, F. (2014). *Satellite network robust QoS-aware routing*. Springer.

Maps of World, World air routes. (2022). http://www.mapsofworld.com/world-airroutes-map.htm.

Nguyen, T. H., & Dixon1d, T. F. (2015). Low-Earth orbit satellite constellation for ADS-B based in-flight aircraft tracking. *Advances in Aircraft and Spacecraft Science*, *2*(1), 95–108.

Noschese, P., Porfili, S., & Di Girolamo, S. (2011). Ads-b via iridium next satellites. *Digital Communications-Enhanced Surveillance of Aircraft and Vehicles (TIWDC/ESAV), 2011 Tyrrhenian International Workshop On*, 213–218.

Parkinson, A. (2011). Space-based ADS-B: A small step for technology a giant leap for ATM? *Digital Communications-Enhanced Surveillance of Aircraft and Vehicles (TIWDC/ESAV), 2011 Tyrrhenian International Workshop On*, 159–164.

Space-based ADS-B. (2018). http://i2.wp.com/idstch. com/home5/ wpcontent/uploads/2015/10/CanX7_Auto2.jpeg?fit=875%2C491.

Stone, L. D., Keller, C. M., Kratzke, T. M., & Strumpfer, J. P. (2011). Search analysis for the underwater wreckage of Air France Flight 447. *14th International Conference on Information Fusion*, 1–8.

Strohmeier, M., Schäfer, M., Lenders, V., & Martinovic, I. (2014). Realities and challenges of nextgen air traffic management: the case of ADS-B. *IEEE Communications Magazine*, *52*(5), 111–118.

Werner, K., Bredemeyer, J., & Delovski, T. (2014). ADS-B over satellite: Global air traffic surveillance from space. *Digital Communications-Enhanced Surveillance of Aircraft and Vehicles (TIWDC/ESAV), 2014 Tyrrhenian International Workshop On*, 47–52.

Zhang, X., Zhang, J., Wu, S., Cheng, Q., & Zhu, R. (2018). Aircraft monitoring by the fusion of satellite and ground ADS-B data. *Acta Astronautica*, *143*, 398–405.