Part II

Experimental Method

In general terms we were interested in the ability for a given constellation of LEO satellites to provide ADS-B coverage in the absence of land-based ADS-B receivers. To evaluate this, popular flights over the Atlantic and Pacific Oceans were simulated in STK. The simulation was extended to include communication links to LEO satellites. Different satellite constellations were simulated and the link-budget data for each test case was collected. 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.

1 Experimental Parameters

1.1 Performance Metrics

ADS-B coverage for a 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 three 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. 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. This was calculated after evaluating 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. This was available as primary data from STK.

From this 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 the formula

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

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.
3. **Average Gap Time** and **Average Access Time** - the mean of access times and coverage gap times identified during the analysis period. This would give an indication of the periodicity of the 'access-no access' cycles that a flight would experience.

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

These performance metrics will be compared in section **??**

1.2 Flight Selection

OpenFlights [1] has statistics on all flight paths currently being serviced by major airlines, illustrated in Figure 1.1.

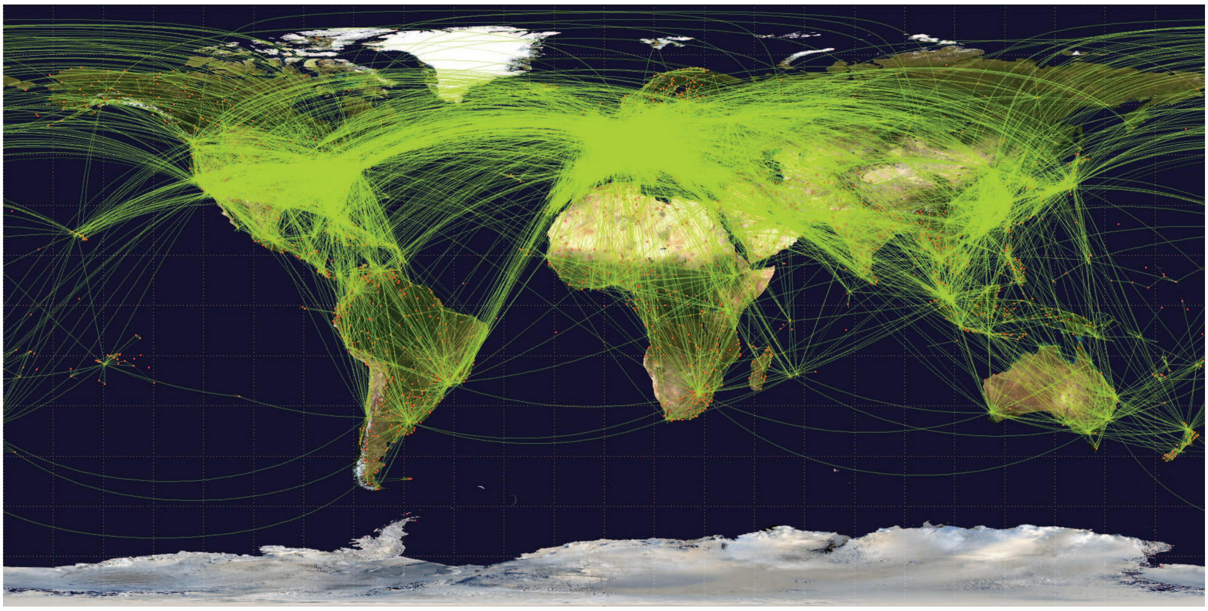

Figure 1.1: Popular flight routes, from [1]

The advantages of space-based ADS-B coverage would mainly come from areas where ground-coverage is not possible. For this reason, flight paths that were primarily over land-masses were not considered for analysis. This eliminated the majority of flights originating in the EU and ending in any of Africa, Asia and Australia. Analysis then focussed on flights passing over the Atlantic and Pacific Oceans. These flights were mostly between the United States and Europe, Asia and Australia, as shown in Figure 1.2.

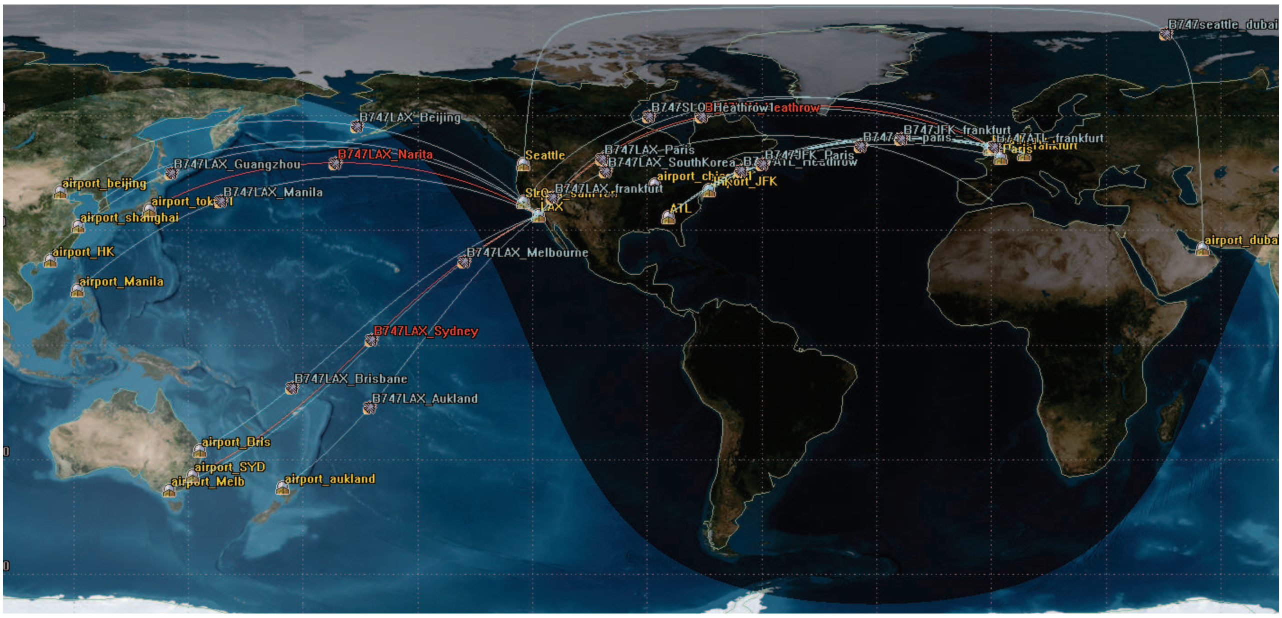

Figure 1.2: Trans-Oceanic Flight paths, as modelled in STK. The three red flights were chosen for analysis

Of these flights, three generalisations were defined and one flight from each generalisation was used for modelling -

1. **North America to Asia** - The path between Los Angeles International Airport (LAX) and Narita airport (NRT) in Tokyo Japan

2. **North America to Europe** - The path between LAX and Heathrow (LHR).

3. **North America to Australia** - The path between LAX and Sydney (SYD) International Airport.

These generalisations are highlighted in red on Figure 1.2.

The performance of a given constellation was determined by examining the ADS-B coverage available for each flight by the parameters outlined in Section 1.1. The flights were simulated as going continuously back and forth between their two destination airports. The effect of this periodicity is expanded upon in Section 1.5.

1.3 Input Variables

The performance metrics presented in Section 1.1 were evaluated against different constellation configurations. Initial tests, discussed later in BLAH and BLAH, ruled out Molniya, geostationary and medium to high earth orbits as practical solutions. The parametric study was then restricted to Low-Earth Orbits, varying orbital parameters from a 'reference case'.

1.3.1 Reference Case

The reference case was chosen to be a constellation of 12 satellites distributed in three circular orbital planes, each with four equispaced satellites. Each orbital plane was inclined at 60 degrees and were at an altitude of 700km above the Earth (a semi-major axis of 7078.14km). The three planes were separated by 120 degrees of Right Angle of Ascending Node (RAAN), starting from 0 degrees for plane one. The four satellites within each plane were separated by true anomalies of 90 degrees. These parameters are summarised in Table 1.1. The ground track of the configuration is shown in Figure 1.3 and the 3D representation is given in Figure 1.4

Table 1.1: 'Reference' constellation configuration

Parameter	Value
Total number of satellites	12
Orbital planes	3
Satellites per plane	4
Separation between planes	120 deg RAAN
Spacing within a plane	90 deg true anomaly
Orbit type	Circular, LEO
Semi-major axis	7078.14km
	(700km altitude)

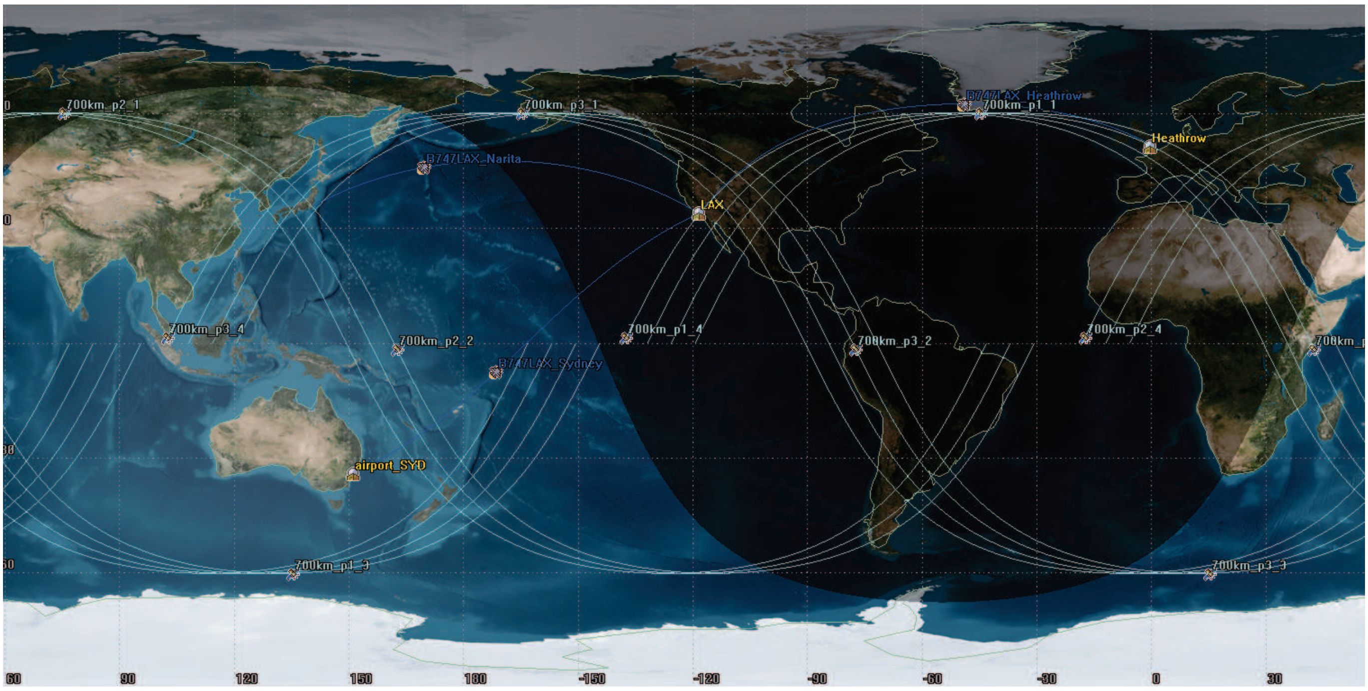

Figure 1.3: Ground track of the 12 satellite reference configuration in STK

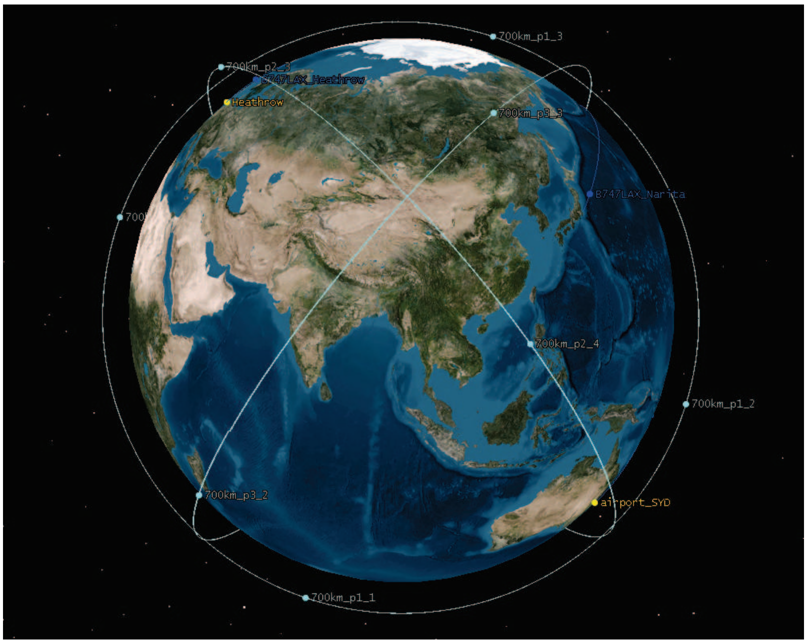

Figure 1.4: 3D model of the 12 satellite reference configuration in STK

It was expected that change in inclination, altitude and number of satellites will effect the performance of a given constellation. An increase in altitude would result in an increase in orbital period, but would also increase the receiver footprint of a given satellite with a greater field of view. The change in inclination would vary the maximum and average coverage gap times as the ground traces intersect with the flight paths in different ways. The change in the number of satellites would change the average and maximum ADS-B coverage gaps, but provide a trade-off with the number of satellites requiring production, maintenance and replacement.

1.4 Test Cases

From the reference case, inclination, altitude and number of satellites per-plane were varied according to the values presented in Table 1.2. Data was obtained from each step and is presented and discussed in section BLAH. The full table of cases evaluated is given in Appendix A.

Table 1.2: Varying input parameters used for data and analysis

Input Parameter	Minimum	Maximum	Step Size
Altitude	400km	800km	50km
Satellites per plane	1	6	1
Inclination	30°	90°	10°

1.5 Analysis Period

In selecting a period of time over which to carry out the analysis, synchronisation and periodicity were taken into account. The discrepancy between air speed of planes (in the order of 250m/s) and the orbital velocity of LEO satellites (in the order of 8km/s) resulted in asynchronous behaviour. This meant that analysis of one period was not a sufficient representation of performance of a given constellation over its lifetime. The analysis period was therefore chosen to be long enough to such that -

- The effective ground track for one satellite would form a continuous swath between the latitudes of inclination. The length of period was chosen so that the ground track would repeat over the same global co-ordinates at least once.

- The aggregate results of analysis would accurately take into account all cases where the lack of synchronisation between orbital period and flight time would produce abnormal results. That is, sufficiently many orbital and flight periods are repeated in order to observe an accurate aggregate effect and also identify each of the worst-case scenarios.

After initial tests it was found that an analysis period of approximately six days was appropriate. In STK the scenario was analysed between 12:00AM on December 6th, 2013 to 12:00AM December 9th, 2013, $\pm$ 24 hours to allow for varying flight times.

2 Analysis Tools

Analysis occurred using computer simulations. The work carried out used a combination of STK, Matlab and Microsoft Excel in order to simulate, process and display the relevant data. Observations and analysis was carried out based upon the outputs from each of the three steps in the experimental process.

2.1 STK

STK version 10.0.2 was used in order to simulate flights, satellite orbits and communication links over the relevant analysis period. The flight paths of interest were chosen according to the process outlined in Section 1.2 and the characteristics (defined in Section 3.3) were programmed into STK in order to create the plane and flight models. Each satellite constellation was modelled as a collection of standard satellites, with orbital parameters as specified in Section 1.4. The STK Communications Toolkit was then used to simulate the ADS-B links between the modelled flights and satellites, outputting data about access times and link budget. The simulation was run continuously for the duration of the analysis period discussed in 1.5. The raw data generated by this model is described in Table 2.1.

Table 2.1: Raw data generated by STK

Data	Description
Access Times	The start and stop times of periods where a particular flight can access a particular satellite. This is output as `.csv` files per test of all accesses for the flight and the satellites in the orbit of interest during the test.
Link Budget	Characteristics of the communication link established during each flight-to-satellite access. Of particular interest is the received isotropic power at the satellite. This is output as `.csv` files per test of all accesses for the flight and the satellites in the orbit of interest during the test.

2.2 Matlab

Matlab was used in order to concatenate and sort the data generated by the STK simulation and output the performance data specified in Section 1.1. The access times `.csv` files were sorted and concatenated in order to extract the 'gap' times where a flight has no access to any satellite. Periods of 'access' and 'gap' were averaged and the minima and maxima were extracted for further analysis and display. Similarly the link budget `.csv` files were analysed in Matlab to extract the minimum received isotropic power for each flight.

2.3 Excel

Finally, the data outputted from Matlab was imported into Microsoft Excel in order to easily display the data for further analysis.

3 Model Input Data and Assumptions

3.1 Link Type

In order to utilise the STK Communications Toolkit, a series of simplifying assumptions were made about the characteristics of the ADS-B links being analysed. The parameters used in the STK link model are summarised in Table 3.1.

Table 3.1: Link Parameters used in STK

Parameter	Value	Description	Source
Transmitter Model	‘Simple Transmitter Model’	The transmitter model type used by STK to propagate and analyse link budgets	[2]
Equivalent Isotropically Radiated Power (EIRP)	240W	Power transmitted through an ADS-B antenna assuming zero losses between transponder and antenna	[3–6]
Bit Error Rate (BER)	10^{-6}	Minimum bit error rate of a link	[7]
Modulation Type	‘Pulsed Signal’	Type of modulation used in the link	
Bandwidth	8MHz	The bandwidth of an ADS-B Signal	[7]
Frequency	1090MHz	The carrier frequency of ADS-B and Mode S signals	[2]
Receiver Model	‘Simple Receiver Model’	The receiver model type used by STK to analyse links from transmitters	[2]

Transmission power was generalised based upon a survey of commercially available transponders [3–6] to 240W, transmitted with the assumption that there were insignificant signal losses between the transmitter and antenna. The minimum bit-error rate (BER) was set to 10^6 bits per second based on the ADS-B transimission specification released by the RTCA [7]. A 'pulsed signal' was used in order to model the radar-like behaviour of ADS-B, as suggested by [2] and no filter was applied to the output. The signal bandwidth was set to 8MHz (+/- 4MHz) as specified by [7].

These parameters were input to a 'Simple Transmitter Model' was used in STK, as the suggested model to use during the system engineering process [2]. Modelling a more complex transmitter model, defining antenna and propagation type were considered outside the scope of this thesis.

Each of the satellites in the space segment was given a 'Simple Receiver Model'. The receiver gain divided by system noise temperature G/T was left unchanged from the default $20K$. Other link parameters would be automatically completed upon analysis of a link with a specified transmitter [2].

3.2 Flight Characteristics

Analysis focussed primarily on the performance of ADS-B coverage for a plane during the transoceanic portion of the flight path of interest. Planes within range of an airport would already be serviced by the airport's ground ADS-B receivers. Flights were therefore modelled as planes travelling at a constant cruise speed and altitude between the source and destination airports, ignoring landing and take-off procedure.

Typical cruise altitudes for commercial airliners range between 30 000 and 40 000 feet. For the sake of worst-case analysis, 30 000 feet was chosen as the cruising altitude. The lower bound was chosen in order to maximise the distance travelled by an ADS-B transmission, producing a worst case scenario for signal loss.

The Boeing 747 was chosen as a 'typical' commercial transoceanic aircraft, with a cruising speed of 913 km/h. The 747 was chosen after examining a cross section of the typical cruising speeds of popular 'long haul' commercial aircraft, given in Table 3.2.

Table 3.2: Cruising speeds of typical commercial aircraft

Manufacturer	Model	Speed (km/h)	Speed(km/s)	Source
Boeing	747-400	913	0.25361	[8]
Boeing	777-200	1029	0.28584	[9]
Boeing	757-200	980	0.27222	[10]
Airbus	A380	945	0.2625	[11]

A summary of the aircraft parameters used in STK is given in Table 3.3

Table 3.3: STK Parameters used for each flight model

Parameter	Value
Altitude	9.144 km (30,000 feet)
Speed	0.2536 km/sec (913 km/h)

The global co-ordinates for the 4 airports of interest were taken from [1], presented in Table 3.4.

Table 3.4: Airport global co-ordinates, from [1].

Airport Name	City	Code	Longitude	Latitude
Los Angeles International Airport	Los Angeles	LAX	33.9425°N	118.4081 °W
London Heathrow Airport	London	LHR	51.4775°N	0.4614 °W
Narita International Airport	Tokyo	NRT	35.7653°N	149,3856 °E
Sydney Airport	Sydney	SYD	33.9461°S	151,1772 °E

3.3 Satellite Characteristics

The standard STK satellite model was used to model each satellite in the test constellations. It was assumed that there would be attitude control aligning the antenna element with the nadir and no active station keeping systems. The STK `J4Pertubation` orbit propagator was used in order to account for the oblateness of the Earth.

Part III

Results and Analysis