ENVIRONMENTAL BENEFITS of *Space-based ADS-B*

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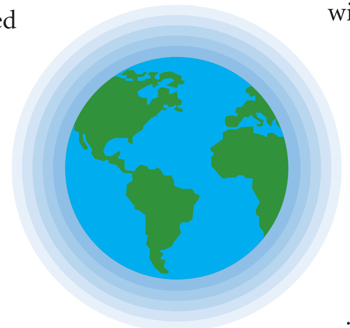
Executive Summary. Commercial aviation worldwide contributes about 2% of global manmade CO_2 emissions annually [ICAO, 2016a]. Efforts are proceeding along many fronts to reduce aviation's environmental impact. This year, the UN's International Civil Aviation Organization (ICAO) recommended the first-ever CO_2 certification standard for commercial aircraft. The Air Transport Action Group (ATAG), an international coalition of aerospace manufacturers, airlines, airports and air navigation service providers, is committed to improving overall fuel efficiency by 1.5% annually through 2020. Advances in sustainable alternative jet fuel research and development could turn commercially viable, low-carbon fuels from fantasy to reality in the not-too-distant future. But, among all of these efforts, only operational efficiency improvements—reducing the amount of fuel or time it takes an aircraft to go from point A to point B—bring immediate CO_2 reductions. Efforts to improve one area of operational efficiency—Air Traffic Management—have centered mostly on areas where aircraft are under constant radar control.



Examples of operational efficiency improvements include single-engine taxi procedures, continuous/idle power descents, and optimized profile descents and approaches during which aircraft fly shorter approach patterns at lower power settings [Marais et al., 2013]. One area for significant operational and procedural improvement remains underexploited: remote and oceanic airspace. In contrast to air traffic control over land, where controllers use real time radar returns to monitor and separate aircraft, air traffic control over the Atlantic Ocean and other remote regions must be performed without radar data. As a result, aircraft are separated "procedurally". Procedural control, while very safe, is inefficient because it relies on large spacing between aircraft (on average 50 nm laterally, and 10 minutes, or 80 nm, longitudinally), meaning that aircraft often cannot fly the most efficient routes. Scheduled for worldwide deployment in 2018, Space-based ADS-B is a new surveillance technology, mounted on 66 low earth orbit satellites, that will enable controllers to monitor and separate aircraft over oceans much like they do today over land using legacy radar systems. The surveillance capabilities of space-based ADS-B will allow oceanic controllers to monitor aircraft progress in near real time. This level of monitoring will enable aircraft to be spaced more closely (15 nm laterally and longitudinally) without sacrificing safety. As a result, more aircraft will be able to fly at the most fuel efficient altitudes on the most favorable routes. These enhanced separation capabilities can significantly improve operational efficiency over oceanic and remote airspace, reduce fuel burn, and, in turn, decrease CO_2 emissions. Almost all new airliners come equipped with ADS-B and the percentage of equipped aircraft is growing steadily. By virtue of an FAA mandate, all aircraft operating in U.S. controlled airspace must be equipped with ADS-B equipment by 2020. Therefore, by 2020, any U.S. aircraft equipped to fly in oceanic airspace will be equipped to use space-based ADS-B without further modification or additional equipment.

There is an emerging consensus among all members of the commercial aviation community that reducing aviation's environmental impact is an imperative, not a choice. This Fall, the International Civil Aviation Organization (ICAO) struck the world's first agreement to curb CO_2 emissions by a single industry. The Carbon Offset and Reduction Scheme for International Aviation (CORSIA) is designed to complement mitigation measures industry groups like ATAG are already pursuing to reduce CO_2 emissions from international aviation. The use of space-based ADS-B to reduce separation in oceanic and remote airspace can positively impact these efforts through operational efficiencies that bring signifi cant, near-term fuel burn reductions.

The North Atlantic is the busiest oceanic airspace in the world and offers significant potential for fuel efficiency improvements and hence reductions in CO_2 emissions. Space-based ADS-B will reduce lateral and longitudinal separation, increase access to preferred altitudes, and allow fuel-saving speed changes for the majority of aircraft crossing the Atlantic. While benefits will vary by flight, space-based ADS-B can help airlines save, on average, at least 2% fuel in currently unsurveilled oceanic and remote airspace. These savings translate to an average reduction in CO_2 emissions of about 1200 kg per flight (or the equivalent of taking one car off the road for a year). Each year, US passenger airlines crossing the North Atlantic burn approximately 2 billion gallons of fuel [MIT Airline Data Project, 2016]. FAA and industry analyses have found that reducing separation to 15/15 nm for 86% of the fleet can, by 2020, save on average between 30 and 40 kg fuel per flight in New York Oceanic airspace. Allowing the remaining 14% to reduce spacing to 60/25 nm, and allowing all aircraft to straighten their routes and vary their speed, results in total average savings per flight of 446 kg, or 1.6% [ISA, 2016]. In the world of aircraft operations where every percent matters, these savings are signifi cant. B y 2020, those fuel savings could add up to 111 million kg of fuel annually, and by 2025, 129 million kg.

The Pacific and Arctic Airspace offers similar proportional benefi ts, and, since the distances covered are larger, approximately twice the absolute reduction. By 2020, absolute savings could add up to 330 million kg of fuel per year, and, by 2025, 351 million kg [ISA, 2016].

Taking these two airspaces together, implementing space-based ADS-B offers benefits equivalent to taking approximately 292 822 cars off the road by 2020, or 318 718 cars by 2025.

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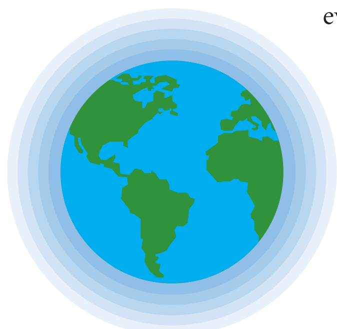
ENVIRONMENTAL BENEFITS

of Space-based ADS-B

1. Introduction

Global commercial air transportation allows people, organizations and governments to connect in ways that were impossible a century ago. It directly provides 8.5 million jobs, contributes over $2.4 trillion to global annual Gross Domestic Product, and carries more than 2.9 billion passengers and $5.3 trillion worth of cargo every year [ICAO, 2016a]. But this enterprise has a darker side too—emissions of harmful pollutants. Gases like nitrous and sulphur oxides have a complex effect on climate, ultimately contributing to warming. Carbon dioxide, while not as potent in the short term, lasts a long time (on the order of hundreds of years) and, therefore, scientists and policy makers around the world have agreed on the importance of limiting its emissions. Recognizing the importance of CO_2, the United States has set a target to reduce total CO_2 emissions from all sources by 26–28% below 2005 levels by 2025 [White House, 2015].



According to 2015 estimates, commercial aviation worldwide contributes about 2% of global manmade CO_2 emissions annually [ICAO, 2016a]. As we travel more and more, this number will increase, and along with it, aviation's contribution to climate change. Aircraft manufacturers, airlines, regulators, air navigation service providers, and international bodies are very sensitive to this problem and are setting ambitious goals for impact reduction. In 2010, aviation became the first industrial sector to agree on global goals for environmental sustainability [ICAO, 2016a]. In February 2016, the International Civil Aviation Organization (ICAO) finalized a performance standard for new aircraft that will mandate an average 4% reduction in new aircraft cruise fuel burn. This Fall, the International Civil Aviation Organization (ICAO) agreed on the Carbon Offset and Reduction Scheme for International Aviation (CORSIA), which is designed to complement mitigation measures industry groups like ATAG are already pursuing to reduce CO_2 emissions from international aviation.

Efforts are proceeding along many fronts to meet these goals to reduce aviation's environmental impact. Not counting an overall reduction or suspension of flying, there are three ways to reduce aviation's carbon footprint: (1) design and build engines and aircraft that use less fuel than today's aircraft to carry a given payload a given distance, (2) develop sustainable alternative fuels that reduce net carbon emissions, and (3) fly aircraft more efficiently from point A to point B.

While all three options offer significant long term benefits, only the third option can bring immediate results. Many operational improvements are underway. For example, aircraft now routinely taxi using just one engine, and significant progress has been made on using continuous descent approaches to land more quickly and using less fuel [Marais et al., 2016]. One area for significant operational and procedural improvement remains underexploited: remote and oceanic airspace.

Many laypeople may not know this, but aircraft are not actively monitored with radar over most of the oceans—they are not observed and must instead report their arrival at predetermined waypoints, as well as when they expect to arrive at the next waypoint. While many position reports are now made digitally via satellite link, a significant proportion are still made via long-range high-frequency radio, much as the earliest aviators did. So, to ensure aircraft maintain a safe separation, oceanic air navigation service providers (ANSPs) around the world and the civil aviation authorities that regulate them have developed a set of cooperative procedural rules that keep aircraft far apart from one another.

In radar-controlled airspace, where aircraft positions are refreshed on a controller's screen every six to twelve seconds, aircraft can be safely separated by as few as 3 nm. But, over the ocean, where there is no radar, and controllers get aircraft position reports only every 15-20 minutes, aircraft are separated laterally by an average of 50 nm, and on average 10 minutes when they are following each other. Aircraft that want to cross another aircraft's path must wait 15 minutes after that aircraft has left the crossing point. These rules have helped prevent midair collisions in even the busiest oceanic airspaces, but they also come with a heavy emissions penalty, because there isn't enough space on the optimal routes for all the aircraft that want to fly them and because aircraft often have to fly at speeds and altitudes that are not optimal from a fuel burn perspective.

What if instead of using these inefficient procedures, we could use the same rules over the ocean as we do over land?

We already have the technology to do just that: space-based ADS-B (automatic dependent surveillance—broadcast). Though the name is somewhat unwieldy, the technology allows air traffic controllers and pilots to precisely determine their position in the air, much like GPS in one's car.

Space-based ADS-B offers a near-term solution for the aviation industry to limit fuel emissions by improving operations and efficiencies in remote and oceanic airspace using more precise locating capabilities through ADS-B, enabling optimum altitudes, speeds and routes.

2. What is Space-Based ADS-B?

ADS-B is a system that allows pilots, airlines, and ANSPs to determine and share aircraft positions. Each equipped aircraft uses GPS to determine its position, and then shares that position with the ADS-B network. Where does that clumsy name come from? Well, ADS-B is **automatic** because it doesn't need any external stimulus, like a radar ping, it is **dependent** because it relies on systems on-board the aircraft to tell other parties where the aircraft is, and it is **broadcast**, because it broadcasts a signal just like a radio [Skybrary, 2016a]. An ADS-B *Out* transmitter broadcasts the aircraft's position, while an ADS-B *In* receiver allows aircraft to also receive a real-time picture of local traffic, based on ADS-B Out broadcasts.

Figure 1: How space-based ADS-B works

Until now, the ADS-B network was all ground-based, so that aircraft could only share their positions when within range of an ADS-B ground-based radio frequency transceiver (GBT). Terrestrial ADS-B already helps pilots fly more safely and precisely in the treacherous mountains of Alaska the remote vastness of Australia and Canada's East Coast and Hudson Bay. However, pilots must transition to less precise procedural rules as soon as they leave ADS-B ground or legacy radar coverage. But now, with the creation of space-based ADS-B, ADS-B can also be used over the oceans. With this system, ANSPs can track all equipped aircraft.

Three things are important when one is tracking aircraft flying at hundreds of kilometers an hour across the sky and determining how far apart they should fly to maintain safety—how well do we know where the aircraft is (accuracy), how often do we get updated on where it is (latency), and how much can we count on receiving the next update (reliability). To illustrate why these properties are important, consider for example if we knew exactly where two aircraft were, but could only obtain the next position update 10 minutes later. In 10 minutes, a 777 can easily cover 150 km (about 80 nm). In other words, two 777s that are 300 km apart can reach each other in as few as 10 minutes, and we would not know it. Over the ocean, it is not unusual for aircraft to go 20 to 30 minutes between updates, which is part of the reason aircraft are spaced so widely over the ocean.

The good news is that systems are being developed to allow air traffic controllers to monitor aircraft more closely in oceanic airspace making reduced separation possible. In particular, with proper communication equipment, two space-based ADS-B equipped aircraft can safely operate with 15/15 separation (15 nm laterally and 15 nm in trail) [Xie et al., 2013]. Recent FAA and industry analyses of aircraft passing through the New York Oceanic airspace found that if 86% of the aircraft were allowed to fly at 15/15 nm separation, and the remaining 14% at 10 min longitudinal separation, it would save, on average 30 to 38 kg per flight. Allowing that 14% of aircraft to decrease their separation to 60/25 nm, increases the average per flight savings to 129 kg [ISA, 2016].

Many aircraft are already equipped to fly in just such an operational environment and the percentage of equipped aircraft is growing every day. All new airliners come equipped with ADS-B. Worldwide, regulators are mandating that operators equip with ADS-B, because of the safety and operational benefits it offers. For example, in the United States, the FAA has mandated that all aircraft wishing to operate in controlled airspace be equipped with ADS-B Out by 2020 [FAA 2010]. Oceanic operators will be fully equipped and ready to take advantage of space-based ADS-B by virtue of their compliance with the 2020 mandate. No other navigation or communication equipment modifications will be necessary.

3. The North Atlantic Airspace

Several ANSPs like NAV CANADA and UK-NATS have signed up to use Space-based ADS-B when it becomes operational in 2018 over the busiest oceanic airspace in the world—the North Atlantic Ocean. Each day, ***an average of 1 200 flights*** cross the North Atlantic. To understand how space-based ADS-B can help reduce emissions, first we must understand how the airspace works.

3.1 The North Atlantic Jet Stream

While it may seem that there is plenty of room for all these aircraft, many of them end up wanting to use the same parts of the airspace, because of atmospheric phenomena called jet streams.

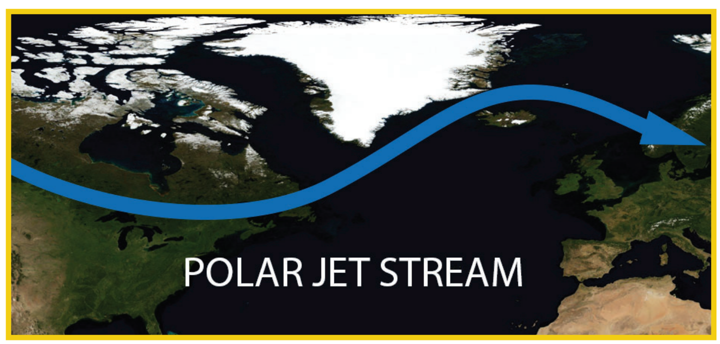
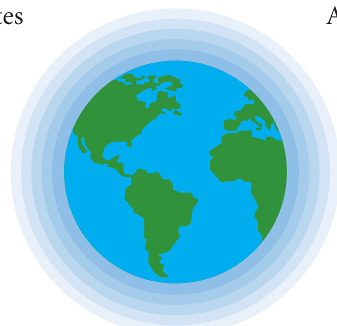


Figure 2: The jet stream

Jet streams are bands of strong winds that blow from west to east around the world (see Figure 2). They are typically a couple of hundred kilometers wide. The polar jet stream is usually located between 50°-60° North or South, and the tropical jet stream is usually at about 30°N. These jet streams are so desirable to aircraft travelling eastward because they can be very strong, reaching more than 400 km/h [NOAA, 2016]. Traveling in a strong tailwind allows an aircraft to maintain a high speed relative to the ground (groundspeed) while burning the same amount of fuel it would burn without the tailwind and resulting high groundspeed. In turn, aircraft travelling westward would like to avoid the jet stream, which would decrease their groundspeed. The jet streams meander across the globe with the seasons and from day to day. Ideally, each aircraft travelling eastward would make a beeline for that day's jet stream, and then fly right into the middle, where the wind is strongest (much like a river flows fastest in the middle, away from the banks). But with about 600-750 aircraft flying eastward every day, there simply isn't enough space for everyone, especially when they have to be at least 50 nm apart laterally and 10 minutes (about 80 nm, on average) longitudinally. For westward aircraft trying to avoid the jet stream, it's slightly easier, but these aircraft still want to take the shortest, or great circle routes, from their origins to destinations.

So, to share this resource safely and fairly, ANSPs establish a set of four to seven tracks in each direction, twice each day, based on the forecast winds and airlines' preferred routes [ICAO 2016]. Eastbound tracks use the jet stream as much as possible, westbound tracks avoid it as much as possible. About half of the North Atlantic flights use these widely spaced "highways in the sky", called the Organized Track System (OTS) or North Atlantic Tracks (NAT). Because we don't have detailed surveillance, these tracks are about 50 to 60 nm apart and aircraft are spaced at least 10 minutes in trail (about 80 nm) [NAV CANADA, 2013]. That means every day much of the jet stream goes unused to ensure safe separation. This "waste" means that aircraft burn more fuel and, therefore, emit more CO_2, than if they could fly on more optimal routes.



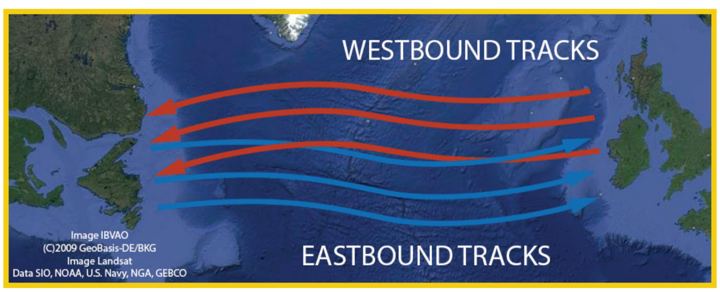


Figure 4: The North Atlantic Tracks

To get a sense of just how important the jet stream is, consider British Airways Flight 114, This Boeing 777-200 flight travels every day from New York's JFK airport to London Heathrow. If this flight were to take place in perfectly still air, on the great circle, and with no delays leaving New York airspace or entering London airspace, it would take about 6 hours and 9 minutes. If it made use of the jet stream, and again encountered no delays on arrival, it would take just 5 hours and 38 minutes on average, about half an hour less [Williams, 2016]! A 777-200 burns about 99.4 kg of fuel per minute during cruise, so the half hour gained due to the jet stream saves nearly 3000 kg of fuel. Accounting for departure and arrival delays, this flight usually takes about six and a half hours. On January 7, 2015, a particularly strong jet stream helped complete this flight in just five hours and sixteen minutes, about 20% faster than usual, and with commensurately less fuel. Other aircraft that could not get a space in the jet stream that day did not reap the same benefits.

Conversely, the jet stream can significantly reduce a westbound aircraft's groundspeed. An aircraft using the great circle route going westbound from London to New York would again take 6 hours and 9 minutes in still air and with no delays. But to avoid the jet stream's strong headwinds, aircraft must fly a more northerly route over Greenland and often also have to accept some time flying headfirst into the jet stream. As a result, the same journey takes about 6 hours and 40 minutes (again, assuming no other delays), or half an hour longer! Accounting for delays, this flight usually takes about 7 hours. Particularly strong jet streams can even force some aircraft to stop to refuel when they reach the North American landmass. Due to the limited space available on the North Atlantic Tracks, some flights must deviate even more from the great circle route, and pay an even higher fuel and time penalty.

Space-based ADS-B offers a way to use jet streams more effectively, by efficiently routing flights as close to their wind-optimal routes as possible: For example, placing aircraft on wind optimal routes can save up to 1110 kg per flight**.** Banavar et al. (2015) constructed wind optimal routes for the top ten busiest city-pairs across the North Atlantic. They varied the lateral routing but kept each flight at its filed flight altitude. They found that such routes offered savings of 280 to 1110 kg per flight, depending on the route and aircraft type. For Boeing 767s, the most common aircraft on these routes, the savings ranged between 420 and 970 kg. Since carbon dioxide emissions are directly proportional to fuel burn, these savings are equivalent to about 1425 to 3290 kg of carbon dioxide. To put these numbers in context, the fuel savings from one flight using wind-optimal routing can be as high as taking a car off the road for a year.

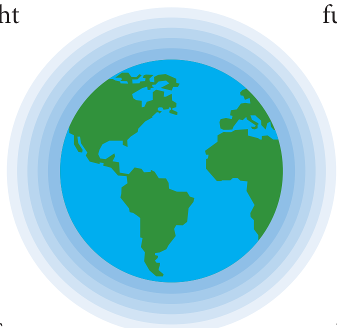
3.2 Route Straightening

Of course not all flights in the North Atlantic are crossing the Atlantic. For example, flights from South America to the US Northeast also pass through oceanic airspace. For these flights, the jet stream is less important, but other improvements in routing can help. Currently, aircraft must often fly on "bent" routes that require them to pass over specific position fixes. Straightening these routes to place them closer to the great circle route can provide significant savings. For example, a recent ISA analysis found that by 2020, flights passing through the New York Oceanic airspace could save on average 190 kg fuel per flight (about 0.7%), if all suitably equipped aircraft were allowed to straighten their routes in this airspace [ISA, 2016].

3.3 Optimal Cruise Flight Levels

Now that we understand how aircraft are spaced horizontally, let's consider the vertical dimension. Here, again, aircraft are not free to fly wherever they wish. The vertical airspace is divided into a series of flight levels, which are spaced 1000 ft apart above 29,000 ft. By convention, the flight levels are referred to in hundreds of feet, so 29,000 ft is Flight Level 290. In this system, for example, an aircraft may fly at 29,000 ft, (FL290) but not at 29,400 ft. Above 29,000 ft, odd levels are assigned to eastbound aircraft, while even levels are assigned to westbound aircraft. This system reduces the chances of aircraft travelling in opposite directions colliding with each other, but also means that aircraft may not be able to travel at their optimal altitudes.

What do we mean by optimal altitudes? Aircraft are designed to use the least cruise fuel burn at a specific altitude, and this altitude depends on their weight [Lovegren and Hansman, 2011]. The aircraft's weight in a given flight depends on its payload (passengers and/or cargo load) and how much fuel it has. Typically, at the beginning of a trans-oceanic flight, when an aircraft is heavy with fuel, it wants to fly at a lower altitude. As the flight progresses, the aircraft burns fuel, gets lighter and flies more efficiently at higher altitudes. Pilots and airlines optimize their altitude in two main ways: (1) they pick an average best altitude, or (2) they increase their altitude during the flight, as they burn fuel and lose weight. Let's consider first the average best altitude.



This average best altitude is based on the aircraft's total weight. Once a pilot knows what this altitude is for his aircraft, he must find the nearest available flight level. For example, if he calculates that the optimal flight level is 37,100 ft, but the flight direction is westward, the nearest available flight level is 38,000 ft. Now, the ANSP must see whether there is space available at this flight level (remember, aircraft have to be at least 50 nm apart laterally, and 10 minutes longitudinally). If it's on a busy route such as JFK to London, there may not be any space, so the flight will have to take another, even less optimal, flight level.

Not being able to access the optimal flight level can be costly. For example, a Boeing 767 that is only 2000 ft below its optimal flight level will burn 2% more fuel during cruise [CIFER 2014]. A recent Metron study estimates that aircraft blocked from ascending to their desired altitudes burn on average an extra 70 kg of fuel per flight [Bromberg et al., 2014]. The Reduced Vertical Separation Minima (RVSM) program nicely demonstrates how important cruise altitude is. Until about 20 years ago, all cruising aircraft had to be separated by at least 2000 ft, but this number was reduced with the implementation of RVSM. Now, all aircraft that are equipped with the necessary precision navigation equipment may fly within 1000 vertical feet of one another. Estimates suggest that in the United States, RVSM allows annual fuel savings of 1.8% ± 0.5% [Malwitz et al., 2007]. Similarly, an earlier Eurocontrol study attributed fuel savings of 1.6 to 2.3% to RVSM [Jelinek, 2002].

While there are currently no plans to further reduce vertical separation, reducing the lateral and longitudinal spacing requirements would allow more aircraft to fly at or near their optimal flight levels.

Space-based ADS-B offers a way to use existing flight levels more effectively, by safely allowing more aircraft onto each flight level and therefore allowing more aircraft to fly at their optimal levels: For example, NAV CANADA (2013) used a fast time simulation to assess the fuel burn of 597 actual flights representing two of the heaviest traffic days across the North Atlantic. They found that reducing lateral separation from 60 nm to 30 nm, and longitudinal separation from 10 minutes (about 80 nm on average) to 15 nm in the North Atlantic, and leveraging this reduced separation to add two additional jet stream tracks, reduced fuel burn by a total of 268,000 liters, or on average about 350 kg per flight. Additional reductions should be possible by further reducing separation to 15 nm laterally and longitudinally.

3.4 Climbing during Cruise

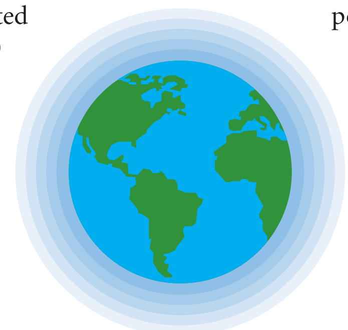
While cruising at the average best altitude can save a lot of fuel, accounting for the decrease in weight as the aircraft burns fuel can save even more fuel. As the aircraft weight decreases, it should slow down, or, fly at a higher altitude, or both.

Ideally, all aircraft would be allowed to gradually fly higher and slower in a "cruise climb"—and this idea remains a long term goal for airlines and air navigation service providers. Flying in this way can save a lot of fuel. For example, a flight from Los Angeles to New York could save on average 3.59% fuel [Lovegren and Hansman, 2011]. While aeronautical engineers have long understood this idea, it can be hard to implement in practice—imagine trying to manage a sky filled with aircraft at continuously varying altitudes! But, in the meantime, three other options are much simpler and offer signifi cant fuel savings.

Space-based ADS-B offers a way to use existing flght levels more effectively, by safely allowing aircraft to adjust flght speed: Though it may seem like changing flight speed would be a simple thing to do, it can actually be quite hard to do in practice, because many routes are like single-lane highways—if the aircraft in front slows down, aircraft behind must also slow down, because overtaking in a world of 60 nm lateral and 1000 ft vertical separation takes a lot of space. But if we knew exactly where each aircraft was, we could identify opportunities where slowing down would not obstruct other aircraft, or, where trailing aircraft that need to fl y faster could overtake the slower aircraft. That flight from Los Angeles to New York could save 2.50% fuel just by slowing down appropriately [Lovegren and Hansman, 2011]. Similarly, a recent ISA analysis found that by 2020, flights passing through the New York Oceanic airspace could save on average 127 kg fuel per flight (about 0.5%), if all suitably equipped aircraft were allowed to adjust their speed during long range cruise [ISA, 2016].

Space-based ADS-B offers a way to use existing fl ight levels more effectively, by safely allowing aircraft to ascend to higher altitudes: As the aircraft burns fuel and becomes lighter, even one altitude increase can help save fuel. Again, if we know exactly where all the aircraft are, air traffic controllers can identify gaps in higher flight levels and offer them to aircraft. A recent Metron study estimates that blocking aircraft from ascending to their desired altitude results in an average of 70 kg extra fuel per blocked flight [Bromberg et al., 2014, Table 7]. This option is already being offered in some airspaces. Over the past three years, under the Gander Oceanic Flight Level Initiative (GO-FLI) air traffic controllers have been contacting pilots to let them know when higher altitudes become available.

Combining these options can result in even more savings. For example, allowing aircraft to increase flight altitude or vary their speed resulted in an average of 416 kg savings per flight on 23 actual flights. The ENGAGE program, a joint effort between Air France, NATS, NAV CANADA, and SESAR was designed to assess the benefits of allowing altitude and/or speed changes [ENGAGE, n.d.]. Initial simulation results suggested that such changes could result in savings of about 200 liters of fuel (about 150 kg) per transatlantic flight. Subsequently, these options were exercised by 23 transatlantic flights with five different airlines. These flights saved from 100 to 907 kg fuel, or an average reduction of 1.9% (416 kg fuel per flight).



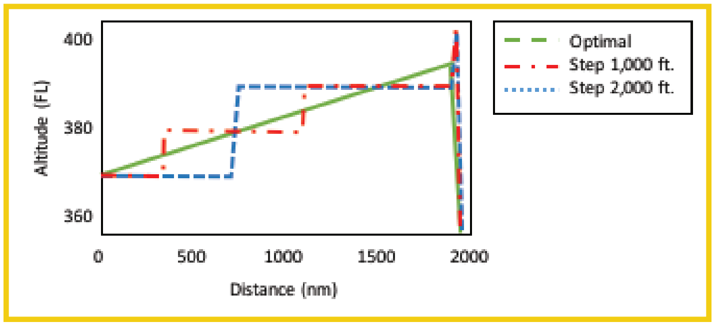


Figure 4: Cruise Climb and Step Climb Profiles [Adapted from Lovegren and Hansman, 2011, Fig. 19]

Space-based ADS-B offers one way to use existing flight levels more effectively, by safely allowing aircraft to perform step climbs: Step climbs, where aircraft gradually ascend in “steps” as they burn fuel, offer a reasonable and practical alternative to the operational challenges of a true cruise climb. A step climb consists of a series of progressively higher cruise segments, selected to minimize fuel burn while managing the number of transitions between levels. Allowing flights from Los Angeles to New York to perform step climbs with 2000 ft steps, could save on average 1.16% fuel [Lovegren and Hansman, 2011].

Oceanic airspace, surveilled using systems like space-based ADS-B, offers an opportunity to implement these concepts in the very near term. These three options are hard to implement over the land where airspaces are often very complex, with aircraft arriving and departing from cruise altitudes as they fly to and from cities across North America. They are also hard to implement in the current procedural airspace over the ocean, because the large spacing requirements mean that changing one aircraft’s altitude or speed potentially requires many other aircraft to adjust in turn, posing a complex problem to ANSPs. For example, often, when a pilot requests an altitude or speed change, by the time the controller has determined that such a change would be safe, it’s no longer needed or useful. With a system like space-based ADS-B, controllers would know aircraft positions in real time and could approve inflight requests with little or no collateral coordination.

The Pacific and Arctic Airspace

The Pacific and Arctic airspace also offers significant potential for emissions reduction. Because flights in this airspace tend to be longer and spend more time in currently unsurveilled airspace, the benefits offered by operational improvements are larger than for the North Atlantic. Reducing separation to 15/15 nm can, by 2020, save on average 59 kg per flight. Allowing all aircraft to straighten their routes and vary their speed results in total average savings per flight of 916 kg, or 2.1% [ISA , 2016]. By 2020, those fuel savings could add up to 330 million kg of fuel annually, and by 2025, 351 million kg.

4. Conclusion

In 2015, the White House announced that the United States would, by 2025, reduce its emissions by 26-28% below 2005 levels [Whitehouse, 2015]. As part of meeting this goal, the U.S. aims to reduce emissions by 1.2% per year on average from 2005–2020 and by 2.3–2.8% per year on average from 2020 and 2025.

There is an emerging consensus among all members of the commercial aviation community that aviation must contribute to these goals. The International Civil Aviation Organization (ICAO) has set global aspirational goals to improve fuel efficiency by 2 per cent per year and achieve carbon neutral growth from 2020. Earlier this year, ICAO established the first ever aircraft fuel-efficiency standards for new aircraft design. And this Fall, ICAO reached an historic carbon offset agreement for global international aviation. Called the Carbon Offset and Reduction Scheme for International Aviation (CORSIA), this agreement will encourage the global deployment of technologies like space-based ADS-B because of the operational efficiency improvements they offer. More fuel-efficient aircraft and alternative fuels offer much promise—but new technologies take a long time to propagate through the global fleet and alternative fuels face significant challenges in scaling up production capabilities [NRC, 2016]. Operational improvements offer immediate, tangible benefits [Marais et al., 2013].

Space-based ADS-B makes improvements such as reduced lateral and longitudinal separation, access to preferred altitudes, and speed changes possible today for the majority of aircraft crossing the Atlantic.

Airlines too are excited about the potential for space-based ADS-B [NAV CANADA, 2016]:

- **One large US carrier** estimates that better routing, access to higher altitudes as fuel is burned, and variable airspeed can result in annual savings of $18.25 M, or $475 per flight.
- **Another large US carrier** estimates that reduced oceanic separation through access to better altitudes and more efficient trajectories can save 2-4% fuel on average per flight.
- **Another carrier** estimates that access to higher altitudes and variable airspeeds can save 4.8% fuel per flight on their 777 fleet.
- **A carrier operating in the Caribbean** estimates that they can save $5M per year by reducing oceanic delays.

While the exact benefits all these improvements offer vary by flight and operator, space-based ADS-B can help airlines save on average about 2% fuel in currently unsurveilled oceanic and remote airspaces. Each year, US passenger airlines crossing the North Atlantic burn approximately 2000 million gallons of fuel [MIT Airline Data Project, 2016]. Adding up the benefits from the operational improvements discussed in this paper, airlines could, by 2020, save about 441 million kg of fuel annually, and by 2025, 480 million kg [ISA, 2016]. In terms of carbon dioxide reductions, implementing space-based ADS-B offers potential benefits equivalent to taking approximately 292 822 cars off the road by 2020, or 318 718 cars by 2025.

Space-based ADS-B can help the United States and FAA proactively contribute to reducing aviation's contribution to climate change today and meet current and future CO_2 reduction commitments and international agreements being considered by agencies such as the US EPA and the UN ICAO. Most aircraft are already equipped and ready to benefi t from space-based ADS-B.

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