



**WARRANTED SURVEILLANCE?
EVALUATING THE ECONOMIC CASE
FOR SPACE-BASED ADS-B**

by

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January 2017



The authors prepared this report as an independent, self-funded research endeavor. (The research grew out of discussions with Aireon but we ultimately chose to pursue it independently.) We want to acknowledge the many individuals who agreed to be interviewed as part of our research and who reviewed the report in draft. We specifically want to thank Aireon for its cooperation, including its willingness to share the results of the ISA analysis described in Section IV. All results and any errors are the responsibility of the authors.

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Summary

The Federal Aviation Administration (FAA) is considering whether to adopt space-based Automatic Dependent Surveillance-Broadcast (ADS-B) to supplement the existing surveillance capability provided by terrestrial radar and ADS-B networks. Radar and ADS-B provide a real-time, electronic “picture” of aircraft positions, allowing air navigation service providers (ANSPs) to separate airplanes by only 3-5 nautical miles (NM). However, because surveillance technology requires a direct line of sight to the aircraft, radar and ADS-B coverage is limited to the airspace over land. For the airspace over oceans and remote land areas that cover 70 percent of the earth, ANSPs must rely on periodic position reports from the aircraft, and the infrequency of those reports requires that aircraft be separated by 30-120 NM. With space-based ADS-B, low-earth-orbit satellites equipped with ADS-B receivers will take the place of ground-based infrastructure, making it possible to track airplanes in real time anywhere above the earth’s surface.

This report seeks to help inform the FAA’s decision as to whether space-based ADS-B represents a wise investment. Although the report is not a cost-benefit analysis, we look at three issues through an economic lens. First, after tracing the evolution of aircraft surveillance, we identify shortfalls in the current system that space-based ADS-B will address and we describe the benefits that may result. As economists, we focus on the operational efficiencies, as opposed to the safety benefits, of space-based ADS-B, recognizing that both have economic value. Second, we try to reconcile the widely varying estimates of fuel savings in oceanic airspace that competing analyses of space-based ADS-B have generated. Third, we offer recommendations on how the FAA should carry out a comprehensive cost-benefit analysis of space-based ADS-B.

Background

The two prospective providers of space-based ADS-B are Aireon, a joint venture between Iridium Communications, NAV CANADA (Canada’s ANSP) and three other ANSPs; and Globalstar, through its partnership with ADS-B Technologies of Alaska. Our analysis focuses largely on the Aireon system, whose capabilities are better suited to the FAA and other ANSPs. Aireon plans to offer space-based ADS-B as a commercial service to ANSPs beginning in 2018, with NAV CANADA and the United Kingdom ANSP (NATS) scheduled to introduce the service in the North Atlantic Region in that year. Operators that are equipped for ADS-B, the de facto global standard for ground-based surveillance, will need no additional equipment to access (Aireon’s) space-based ADS-B.

Shortfalls Addressed by Space-Based ADS-B

By providing radar-like surveillance on a global basis, space-based ADS-B will allow for reduced aircraft separation in oceanic and other airspace that lacks coverage by radar or ADS-B (also known as procedural airspace). In this way among others, space-based ADS-B addresses shortfalls in the current approach to air traffic tracking and surveillance, yielding a range of benefits.

Capacity Limits: The need for large separation minima in areas not covered by radar or ADS-B limits available airspace capacity, which reduces operators' ability to obtain their preferred profile (altitude, speed and lateral track) at the start of the flight and their flexibility to make enroute adjustments. By allowing for reduced separation minima, space-based ADS-B can increase airspace capacity in areas not covered by radar or ADS-B. Under conditions of higher traffic density, having additional capacity will increase operators' ability to fly their optimal profiles, generating concrete benefits in the near term, including fuel savings, incremental cargo revenue, reduced greenhouse gas emissions, longer flights, shorter flight times, and improved schedule predictability.

Bottlenecks and Upstream Delays: The inefficiencies caused by large separation minima are not confined to procedural airspace. They spill over to "upstream" regions, both adjacent and non-adjacent, because of the bottlenecks created when air traffic gets funneled from radar-controlled airspace into procedural airspace—equivalent to automobiles going from a crowded six-lane interstate onto a two-lane country road. For example, in New York, the need to space out flights bound for Europe or the Caribbean contributes to local (adjacent) congestion, which in turn can delay flights departing for (say) the West Coast (non-adjacent). By reducing the differential between separation minima—in effect, widening the funnel—space-based ADS-B can ease these bottleneck-caused delays.

Inability to Use Oceanic Airspace to Relieve Terrestrial Delays: Large procedural separations also limit the use of oceanic airspace to relieve terrestrial delays. For example, when radar-controlled routes along the East Coast are blocked by convective weather, the FAA institutes ground stops and diverts traffic inland—actions that can cause delays that propagate for hundreds of miles. If procedural separations were reduced, the FAA could instead divert traffic out over the Atlantic Ocean. Although operators would need to train their pilots and equip their aircraft for over-water operations, those expenses could be justified by the reduction in delays.

High Cost of FANS: FANS (Future Air Navigation System) is an onboard system whose automated position reporting capability, ADS-Contract (ADS-C), enables reduced separations in procedural airspace: the FAA allows aircraft equipped with FANS and the appropriate navigation software to take advantage of 30 NM (rather than 80 NM) separations in U.S. oceanic airspace. However, FANS is expensive to install and operate, and there appear to be limits on ADS-C's ability to cost-effectively support significantly lower separation minima. Space-based ADS-B may give some operators—particularly those with narrow-body aircraft, many of which are not FANS-equipped—an alternative way to take advantage of reduced oceanic separations.

Challenge of Oceanic Search and Rescue Operations: The loss of Air France Flight 447 in 2009 and the mysterious disappearance of Malaysian Airlines Flight 370 in 2014 underscored the need to track aircraft in oceanic airspace with greater precision so as to reduce search and rescue costs and increase the likelihood of retrieving critical flight data that can help prevent future incidents. Space-based ADS-B can meet this need: while the common ADS-C update interval of 15 minutes translates to a search area of 55,000 square kilometers, with a worst-case 8-second update interval (in most parts of the globe it will be 1-2 seconds), space-based ADS-B will reduce the search area to only 4 square kilometers.

Challenges to Terrestrial Surveillance: Even in terrestrial areas, there are challenges to achieving comprehensive real-time surveillance, including the expense of installing and maintaining ground-based systems (radar and ADS-B), gaps in coverage, and lack of redundancy. Although the United States has an extensive ground-based surveillance infrastructure, the FAA may be able to reduce its future investment in that infrastructure at the margin by relying on space-based ADS-B. For example, satellite surveillance could reduce the resources that the FAA spends securing leases to keep ADS-B ground stations positioned on oil platforms in the Gulf of Mexico.

Limits on Regional/International Cooperation and Harmonization: Despite significant progress, the management of international air traffic is far from seamless: ANSPs do not share information routinely, and their use of non-uniform tools and procedures adds to the inherent difficulty of handing off traffic across airspace regions. Because of its global coverage, space-based ADS-B will facilitate shared situational awareness, making it easier for ANSPs to exchange information, engage in collaborative traffic flow management, and jointly implement programs to upgrade airspace capabilities. As the world's largest ANSP and one that other ANSPs and regulators often look to for guidance, the FAA can accelerate the global adoption of space-based ADS-B, much as it has done with ADS-B; conversely, FAA inaction on space-based ADS-B could slow adoption.

Surveillance and National Security: From a national security perspective, the current, global approach to ATC surveillance is lacking in ways that space-based ADS-B is well suited to address.

- The Department of Defense (DoD) is a major user of the global air traffic system. Currently, if a U.S. military plane goes down in the ocean, its precise whereabouts may be unknown.
- U.S. defense and intelligence agencies cannot now monitor global traffic flows in real time; nor do the data exist to allow them to do historical analysis.
- When DoD destroys the enemy's radar infrastructure, the U.S. military uses deployable radar platforms to provide enroute and terminal surveillance, which while effective can distract from the primary mission of these platforms—namely, combat air control.
- Recent experience reinforces the need to restore basic services following a conflict, and civil aviation is one such service. Surveillance is key to supporting safe and reliable joint civil-military aviation during critical post-conflict restoration and stabilization efforts.

Longer-Term Transformative Impact on Competition in Air Services and Air Traffic Management:

In the medium to long term, space-based ADS-B can support new operational concepts whose impact on aviation could be transformative. For example, by facilitating more direct routing and allowing aircraft to fly farther on the fuel they can carry, space-based ADS-B (together with new, longer-range aircraft) can help new entrant airlines challenge the existing hub-and-spoke market for transatlantic service with long-haul point-to-point service, much as low-cost carriers challenged traditional domestic air service in the United States and Europe. In addition to upsetting the airline order, space-based ADS-B could facilitate fundamental changes in the current, national approach to air traffic management: armed with a common, global air picture, monopoly ANSPs could conceivably compete as well as collaborate in the same airspace.

Disparate Estimates of Fuel Savings in Oceanic Airspace

Various stakeholders have quantified the potential benefits of space-based ADS-B relative to the alternative of ADS-C in U.S. oceanic airspace. Their focus has been on the reduction in fuel burn associated with going from the existing 30/30 NM separation minima (30 NM longitudinal and 30 NM lateral) with FANS/ADS-C to 15/15 NM separation minima with spaced-based ADS-B. Although all of the studies have found some level of benefits, there is a significant disparity between the estimates generated by aircraft operators and foreign ANSPs, on the one hand, and most of the (preliminary) estimates generated by the FAA, on the other.

The disparity largely reflects differences in the concept of operations, or CONOPS, used as the basis for the analysis of space-based ADS-B:

The CONOPS used in the FAA's analysis of space-based ADS-B (test-case CONOPS) represents only an incremental change from the existing (base-case) CONOPS for U.S. oceanic airspace—largely, the increased ability to climb to efficient flight levels that a reduction in separation from 30/30 NM to 15/15 NM would allow. The FAA leaves in place the other key elements of the existing CONOPS, including constraints on route and speed profiles, and the requirement that aircraft be FANS-equipped to take advantage of reduced oceanic separations. The FAA's (preliminary) estimate of fuel savings using this test-case CONOPS is predictably small.

A separate analysis performed by consultant ISA with support from Aireon replicates the FAA test-case CONOPS (Scenario #1) and then relaxes key assumptions. Under Scenario #2, where non-FANS aircraft are allowed to take advantage of somewhat reduced oceanic separations (60/25 NM), the fuel savings are two to three times greater than under Scenario #1. And when aircraft also are allowed to fly Great Circle Routes (Scenario #3), fuel savings are five to six times greater than under Scenario #1. Allowing for variable speed operations (Scenario #4) increases fuel savings yet more.

Recommendations for the FAA Analysis

Expand the CONOPS: The concept of operations on which the FAA is basing its analysis of space-based ADS-B (test-case CONOPS) is grounded in current practice and incorporates only incremental changes in existing procedures. Such an approach seems self-defeating: current air traffic management procedures are designed to work within the significant limitations of existing surveillance and tracking technologies—limitations that space-based ADS-B lessens or removes altogether. Unless it considers the new operational approaches that this technology makes possible, the FAA is destined to undervalue the potential benefits of space-based ADS-B.

Several changes in the FAA's test-case CONOPS seem merited. First, the analysis should look at the impact of space-based ADS-B both with and without the current FANS requirement. The requirement that, in a world of space-based ADS-B, aircraft must still install FANS to access more advantageous oceanic spacing is controversial on substantive grounds. Although we are not qualified to evaluate fully the arguments for and against the requirement itself, we believe there is ample justification for including a no-FANS-requirement option in the test-case CONOPS. Second, the analysis should include other changes in oceanic procedures in the test-case CONOPS,

including variable speed operations and more optimal routing. Variable speed operations are a component of the CONOPS that NAV CANADA and NATS have proposed for space-based ADS-B in the North Atlantic. Although Great Circle Routes and direct routing “are not in any ANSP’s CONOPS” (the FAA’s rationale for not quantifying their benefits), more direct routing includes a range of improvements that ANSPs will likely introduce incrementally and over time.

Account for the Full Range of Potential Benefits: The FAA analysis focuses largely on the impact of reduced separation standards on fuel burn in oceanic airspace. However, many other benefits that could flow from a decision by the FAA to adopt space-based ADS-B, and a comprehensive evaluation should account appropriately for all of them. Specifically, the FAA analysis—which simulates traffic in U.S. oceanic airspace—neglects some if not all of the bottleneck-caused delays in upstream regions, leading to an understatement of the benefits of space-based ADS-B. And it is unclear whether the FAA plans to quantify the potential benefits of oceanic diversion in reducing terrestrial delays. We appreciate the challenges to simulating the complex interactions embodied in these scenarios, and we recognize that it may be appropriate for the FAA analysis to focus on the direct benefits of space-based ADS-B in oceanic airspace. However, the analysis should not assume that these secondary benefits do not exist simply because they have not been modeled in a rigorous way.

The FAA analysis should consider other potential benefits of space-based ADS-B as well. These include the non-fuel-related efficiencies that operators could realize with an increase in available airspace, such as improved schedule predictability, increased access to polar routes, and more direct routing, which could support point-to-point service in new, long-haul markets—a potential boon to long-haul competition more broadly. Additional benefits include: allowing some operators to avoid the cost of FANS; reducing the investment the FAA needs to make in its ground-based ADS-B system, and strengthening that system by filling gaps and providing a layer of redundancy; facilitating more rapid location of aircraft that are lost or in distress; strengthening the FAA’s global leadership role and facilitating information sharing and collaboration among ANSPs at a regional and international level; and addressing U.S. national security and intelligence needs.

As with reductions in bottleneck delays and improved flow control due to oceanic diversion, many of these benefits would be difficult to analyze with the same degree of rigor that the FAA brings to its evaluation of how changes in separation standards affect fuel burn. However, the test for whether a potential benefit is both real and quantitatively important ought not be the ability to measure it using airspace modeling and simulation tools.

Account for All Affected Parties: Precisely because the introduction of space-based ADS-B will provide a range of potential benefits, multiple parties will be affected. For example, a decision by the FAA to support space-based ADS-B would benefit DoD and U.S. intelligence agencies directly, through the improved efficiency and safety of U.S. oceanic airspace and the availability of information on global traffic flows, as well as indirectly, by making it more likely that foreign ANSPs will subscribe to space-based ADS-B.

An economic analysis of space-based ADS-B should take into account the impact of the technology on *all* affected parties. The FAA has framed its task as one of evaluating the “Business Case” for space-based ADS-B—a term that typically refers to an investment analysis that considers only private costs and potential returns. By contrast, a “Cost-Benefit Analysis” considers the gains and losses to all potential stakeholders, regardless of where they occur. While we are confident that the FAA will adopt a broader perspective than that of a purely private sector actor, the analysis it has conducted to date looks almost solely at the impact on operators.

Consider Costs as well as Benefits: The analyses of space-based ADS-B done to date are striking for their near-exclusive focus on benefits. The cost side of the equation is no less important.

First, the FAA analysis should compare the relative costs of ADS-C and space-based ADS-B. By definition, the FAA’s base case (ADS-C) entails no incremental costs (although the FAA’s assumptions regarding the natural rates of FANS equipage may be artificially high). However, the RTCA is looking at other ADS-C scenarios, some of which assume an oceanic separation standard of less than 30 NM and higher rates of FANS equipage. Those scenarios would impose incremental costs on operators, including: FANS equipage and operating costs, including pilot training and communications charges for (currently) non-FANS aircraft; similar operating costs for aircraft that have installed but not activated FANS; and higher communications charges (for more frequent transmission of position reports) for aircraft already using FANS. By contrast, space-based ADS-B would not impose any incremental costs on operators, since they already face a deadline to install and use ADS-B, but the FAA would incur a subscription charge. That charge is estimated to be tens of millions of dollars a year, depending on the geographic scope of the coverage.

Under any scenario that includes reduced oceanic separation minima (less than 30/30 NM), the FAA would incur one-time implementation costs, including procedure development, software upgrades and controller training. According to former FAA officials, these costs might be somewhat lower for ADS-C than for space-based ADS-B but not significantly lower.

Second, the FAA should put the absolute costs of space-based ADS-B in perspective. While the estimated subscription charge (tens of millions of dollars a year) is not a trivial expense, neither is it a budget buster, in the context of the FAA’s \$2.8 billion annual budget for facilities and equipment. As for the one-time costs to implement reduced oceanic separations (with either ADS-C or space-based ADS-B), oceanic operations represent a tiny share of the FAA’s budget (only 250 of the agency’s 15,000 controllers handle oceanic operations, and oceanic’s capital and operating costs account for only about one percent of FAA spending). Thus, even a significant increase in the oceanic budget (which no one is projecting) would be small in absolute dollars.

Focus on the Magnitude, not the Incidence, of Costs and Benefits: Because of the way it is funded, the FAA cannot pass on the costs of space-based ADS-B directly to operators, as other ANSPs plan to do. Although operators pay indirectly for most of the FAA’s budget, in the form of ticket taxes and other taxes collected from passengers, the FAA’s budget has been flat for five years and that trend is likely to continue. Under this funding arrangement, the FAA would directly bear most of the costs of space-based ADS-B whereas operators would enjoy most of the benefits.

The disparity between who pays and who benefits may be relevant to the budgetary “politics” of the FAA’s decision regarding space-based ADS-B, but it should not affect the economic analysis. Generally speaking, a cost-benefit analysis measures the balance of gains and losses of a proposed project; whether or not a project has a positive benefit is not affected by the incidence of those gains and losses. This approach reflects a fundamental principle of economics: if the overall net benefits are positive, it should be possible to devise an institutional structure and payment scheme that leaves all parties better off. Potential options include: shifting to user-fee funding of the FAA; having aircraft operators pay for space-based ADS-B directly even though the service (i.e., data) would be delivered to the FAA; and having other federal agencies that would benefit from the service share the cost with the FAA.

Heed the Lessons of Iridium: FAA officials responsible for analyzing space-based ADS-B should understand the history of the Iridium satellite system and the federal government’s role in preserving it. When Iridium filed for bankruptcy in 1999, the parent company, Motorola, sought to destroy the satellite constellation so as to avoid future liability. The federal government, by then a major user of satellite phones, quietly facilitated the acquisition of Iridium by private investors, who upended the business model and succeeded where Motorola had failed. Since then, Iridium phones have saved tens of thousands of lives and proved indispensable in war zones, disaster areas, and for hundreds of commercial and scientific uses—*almost none of them anticipated by the federal government at the time*. Recognizing how difficult it is to predict the value of a potentially transformative new technology, the FAA should approach its task of evaluating space-based ADS-B with humility—and a sense of history.

I. Introduction

Aviation is a strong catalyst for economic growth. Between 1978, when the U.S. airline industry was deregulated, and 2014, demand for scheduled air passenger service grew by an average of 4.0 percent a year, compared to 2.6 percent for the U.S. economy overall.¹ All told, civil aviation directly supports 11.8 million jobs and \$1.5 trillion in economic activity in the United States.² International flights, particularly transoceanic flights, account for a disproportionate share of this economic activity. Oceanic flights account for only 8.5 percent of all miles traveled in U.S.-controlled airspace,³ but they generate 31 percent of passenger revenue and 40 percent of cargo revenue.⁴

Our nation's air traffic control (ATC) system, operated by the Federal Aviation Administration (FAA), is an essential input to this vital sector of the economy. The operation of the ATC system (also known as the air traffic management, or ATM, system) depends on a three-part foundation of Communications, Navigation and Surveillance (CNS): pilots and air traffic controllers must be able to *communicate* with one another; pilots must be able to *navigate* using on-board equipment; and controllers must be able to monitor aircraft location through *surveillance* technology. The system is designed to be able to function even if one of the three legs of the foundation is missing, and higher performance by one leg can sometimes compensate for lower performance by another.

The FAA's Next Generation Air Traffic Control System (NextGen) is, at its core, a program to supplement or replace the traditional technology for each of these three foundational functions with a digital, high-precision equivalent. Europe has a similar effort underway, the "Single European Sky ATM Research (SESAR) programme," and Australia, Japan and other countries are also modernizing their ATC systems.

For surveillance, the NextGen/SESAR effort involves the partial replacement of a 1940's era technology, radar, with something known as Automatic Dependent Surveillance-Broadcast, or ADS-B. Whereas radar sends out radio waves to detect and plot the location of an aircraft, ADS-

¹ U.S. Department of Transportation (U.S. DOT), Bureau of Transportation Statistics, T-100 Market and Segment, System wide Enplanements; and Department of Commerce, Bureau of Economic Analysis (calculation of compound annual growth of real GDP is based on chained 2009 dollars).

² U.S. DOT, Federal Aviation Administration (FAA), "The Economic Impact of Civil Aviation on the U.S. Economy," June 2014. See: https://www.faa.gov/air_traffic/publications/media/2014-economic-impact-report.pdf.

³ FAA, Office of Financial Analysis, "Overflight Fee Rate Development Report in Support of 'Update of Overflight Fees' Notice of Proposed Rulemaking," April 21, 2015, Table 2: "Enroute and Oceanic Activity: Total Traffic Worked" (FY 2013).

⁴ FAA, "Ocean Flying Becoming a Breeze with NextGen," July 2013. See: <https://www.faa.gov/nextgen/snapshots/stories/?slide=26>.

B relies on signals that the plane itself transmits to anyone with the appropriate receiver. The FAA contracted for the installation of more than 600 ground stations to receive ADS-B signals, and aircraft operating in most U.S. airspace must be equipped with ADS-B transponders by 2020.

Although ADS-B represents a major advance in surveillance technology, ADS-B ground stations, like radar towers, require a direct line of sight to the aircraft, which means that their coverage is limited to terrestrial airspace (i.e., the airspace over land). For the airspace over oceans and remote land areas that cover 70 percent of the earth, air navigation service providers (ANSPs) must rely on periodic position reports from the aircraft, and the infrequency of those reports requires that aircraft be separated by 30-120 nautical miles (NM)—compared to the 3-5 NM separations in airspace covered by radar or ADS-B. To enforce these large separations in oceanic/remote airspace, ANSPs apply procedures that strictly control the route, speed and altitude that the planes must fly.

As a result of advances in satellite communications technology, certain low-earth-orbit satellites will soon have the capability to receive the ADS-B signals that aircraft transmit. Because these satellites can “see” the entire globe, they will be able to give controllers a real-time, on-screen view of aircraft positions in areas that fall beyond the reach of radar and ground-based ADS-B. Many ATC experts believe that this new capability, known as space-based ADS-B, will transform air traffic surveillance.⁵

While space-based ADS-B is a technology seemingly rich with possibilities, the question remains: will the benefits it generates outweigh its cost? A number of ANSPs have decided to commit to space-based ADS-B based on their analysis of the benefits to them and their operator-customers. Other ANSPs, including the FAA, are still considering whether to take that step. Some FAA officials are skeptical about the benefits case for space-based ADS-B, based in part on preliminary analysis which projects that the fuel savings in U.S. oceanic airspace will be limited relative to what can be achieved with the current, position-reporting technology.

Recognizing the importance of the decision it faces, the FAA recently asked its NextGen Advisory Committee (NAC) to fully evaluate the business case for space-based ADS-B. This report seeks to help inform the NAC analysis and the FAA’s decision process more broadly. Although an analysis of the business case for new technology is never straightforward, space-based ADS-B poses a number of particularly challenging issues. The significant disparity in the preliminary estimates of benefits as calculated by the FAA, on the one hand, and by operators and non-U.S. ANSPs, on the other, is a reflection of these challenges. This report is not a cost-benefit analysis of space-based ADS-B: we make no attempt to quantify and comprehensively compare the costs and benefits of this new technology. Rather, we identify and describe in qualitative terms the range of potential

⁵ In a recent report, the Civil Air Navigation Services Organisation (CANSO), which represents ANSPs worldwide, writes that “space-based ADS-B has the potential to revolutionise air traffic services (ATS) surveillance in the aviation industry.” CANSO, “ANSP Guidelines for Implementing ATS Surveillance Services Using Space-Based ADS-B,” April 2016, p. 6. See: <https://www.canso.org/ansp-guidelines-implementing-ats-surveillance-services-using-space-based-ads-b>.

benefits, try to reconcile the disparate results of the benefits analyses done to date, and then offer some recommendations on how the FAA should conduct such a challenging analysis.

Space-based ADS-B will deliver both operational efficiencies and safety benefits to aviation stakeholders. As economists, we focus largely on the operational efficiencies. However, we recognize that operational efficiency and safety are interdependent and that both types of benefits provide economic value.

The remainder of the report is structured as follows. In Section II, to lay the groundwork for our analysis, we trace the evolution of air traffic tracking and surveillance, contrasting the approach used in terrestrial airspace with that used in oceanic/remote airspace. In Section III, we identify shortfalls in the current approach to tracking and surveillance, and we discuss how space-based ADS-B will address these shortfalls and the economic benefits that could result. In Section IV, we examine the disparity in the competing estimates of one category of benefits: reduced fuel burn in oceanic airspace. In Section V, we offer recommendations for the FAA's analysis of space-based ADS-B.

II. The Evolution of Air Traffic Surveillance

The purpose of air traffic control is to keep planes at a safe distance from one another and guide them along an efficient flight path. Surveillance, which ICAO describes as the ability to accurately and reliably determine the location of an aircraft, is critical for these tasks.⁶ The provision of ATC separation services depends largely on the ability of an ANSP to determine the position of the aircraft and communicate with the pilot.⁷

A. REAL-TIME SURVEILLANCE AND TACTICAL CONTROL

In areas with radar and/or ADS-B coverage—known as “surveillance airspace”—ANSPs provide “surveillance separation services” or “positive control,” also termed “tactical control.” Radar is the traditional means of air traffic surveillance. Developed for military purposes in the 1930s, radar was first used by U.S. civilian controllers in 1945 at LaGuardia Airport, where it helped triple the landing rate to 15 planes per hour. In the 1960s, the Federal Aviation Agency (later the Federal Aviation Administration) began deploying long-range radar along important air routes.

There are two types of ATC radar: primary and secondary. With primary radar, ground stations send out high-power radio signals that bounce off of objects in their path. The radar determines an aircraft’s position based on the elapsed time between the transmission of the signal and the reception of its echo. Primary radar is considered a “non-cooperative” surveillance system, because (in keeping with its military origins) it can detect a plane that does not want to be seen.

With secondary radar, the ground station sends a signal to a radio transponder in the cockpit—a process known as “interrogation”—and the transponder responds with information on the location, altitude, direction and speed of the aircraft. Secondary radar is considered a “cooperative” surveillance system, because it cannot detect an aircraft that does not have a transponder or whose transponder has been turned off.

Although the technology underlying these systems has continued to improve, radar (like any surveillance system) requires a line of sight to the aircraft; because of the curvature of the earth, that requirement limits the range of radar to around 100-250 NM, depending on the altitude of the aircraft. Because it is nearly impossible to site and maintain radar towers in the ocean and on certain remote terrain, the majority of the globe is beyond the reach of radar surveillance. In addition to having a limited range, radar systems are expensive to build, operate and maintain, which makes them economically impractical in poor countries and in sparsely populated areas.

⁶ ICAO, “Guidance Material on Comparison of Surveillance Technologies (GMST),” Edition 1.0, September 2007, p. 3.

⁷ CANSO, *op. cit.*, p. 8.

The FAA and other ANSPs began deploying ADS-B ground infrastructure a decade ago, with the goal of phasing out most short-range secondary radars. With ADS-B “Out” technology, the aircraft transponder determines its location from the onboard GPS (satellite) navigation system and broadcasts that location automatically to anyone within range with the appropriate receiver, allowing the aircraft to be tracked. With ADS-B “In” technology, which is only beginning to become operational, other aircraft will be able to receive and act on this information directly.

Although it lacks primary radar’s ability to detect non-cooperative aircraft, ADS-B Out represents an improvement on radar surveillance in other respects. ADS-B is more accurate and reliable: in addition to using GPS to determine the aircraft’s position, ADS-B provides position information every second, compared to radar’s 4-12-second update interval. And because an ADS-B ground station is comparatively small and has no moving parts—many ADS-B receivers nest in cellular towers—it can be installed and maintained at a fraction of the cost of radar.

These advantages have made ADS-B the de facto global standard for the next generation of surveillance technology. ADS-B transponders are standard equipment on all new Boeing and Airbus aircraft, and operators face deadlines for ADS-B Out equipage in the United States, Europe, Singapore, Indonesia and a growing list of other countries. ADS-B is already in use in a few places that previously lacked radar coverage, including Australia, with its vast remote areas; parts of Europe; the Gulf of Mexico, where by leasing space on offshore oil platforms for ADS-B stations, the FAA was able to triple the traffic on oceanic routes between the United States and Mexico; and Canada’s Hudson Bay, where strategic placement of ADS-B ground stations allowed Canada’s ANSP, NAV CANADA, to reduce the in-trail separation standard from 80 NM to 5 NM.

B. POSITION REPORTING AND PROCEDURAL CONTROL

In areas without radar or ADS-B coverage, ANSPs rely on periodic position reports from aircraft to track their locations. Because of the infrequency of such reports, ANSPs separate planes by large distances in three dimensions (longitudinal, lateral and vertical), and they enforce these distances—known as separation standards or separation minima—through the use of procedures that dictate the route, speed and altitude of an aircraft.⁸ ANSPs refer to the services provided on the basis of position reports as “procedural separation services” or “procedural control,” and airspace subject to procedural control is known as “procedural airspace.”

In the 1980s, ICAO worked with Boeing and Airbus to develop a system that would use satellite communications to improve flight operations under procedural control. Implemented beginning in the 1990s, the Future Air Navigation System (FANS) embodies two technical advances. First, it allows controllers and pilots to communicate directly using a digital data link—in effect, texting. Traditionally, communication in oceanic/remote airspace relied on high frequency (HF) radio to transmit voice signals; the communication was often of poor quality and required a radio operator

⁸ According to CANSO, the required spacing between aircraft is based on the frequency and reliability of the position reports as well as on the ease and frequency of communications between pilots and ANSPs. CANSO, op. cit., p. 8.

to relay the message. In contrast, FANS employs the Controller-Pilot Data Link Communications (CPDLC) application, which is designed for the direct exchange of relatively short, simple messages regarding clearances, requests for altitude changes and the like. Among other advantages, CPDLC requires less attention from the flight crew, freeing crew members up for other tasks, and a CPDLC message can be transmitted via satellite as well as HF radio.

Second, FANS supplemented voice reporting of aircraft position with automatic digital reporting, using an application known as Automatic Dependent Surveillance-Contract (ADS-C). With ADS-C, which uses the same data link network as CPDLC, the aircraft transmits position reports to an ANSP with which it has a contract. Based on the contract, position reports are transmitted under one or more of three arrangements: 1) at defined time intervals (typically ranging from 10 to 60 minutes), 2) when specific events occur such as a deviation from the ATC-cleared route or altitude, or 3) in response to a request from the ANSP.

FANS has enabled major improvements in operations in procedural airspace, largely because event-reporting contracts (arrangement #2) allow ANSPs to more closely monitor aircraft adherence to procedures (“conformance monitoring”). We discuss below the sharp reduction in separation minima that the combination of FANS and advanced navigation technology has made possible on certain North Atlantic tracks and in U.S. oceanic airspace. Moreover, some additional reduction in separation minima may be possible if ADS-C can demonstrate the ability to transmit position reports more frequently on a routine basis.

There may well be a technical limit to how far that process can go, however. In oceanic airspace, where very high frequency (VHF) radio channels are unavailable, ADS-C and CPDLC both operate over the Aircraft Communication, Addressing and Reporting System (ACARS), a data link network that was designed for the transmission of aeronautical information.⁹ Because of the bandwidth and capacity limitations that are inherent in ACARS, and the resulting long latency period between

⁹ ACARS handles the enormous volume of operational information that flows continuously from an aircraft to the carrier’s operations center, ranging from data on how an aircraft engine is performing to information on the passengers who are onboard. Moreover, ACARS lacks the ability to prioritize data transmissions. Although some ADS-C position reports may be transmitted relatively rapidly, during periods when the volume of message traffic is high, the position report goes into a long queue of data transmissions that are competing for bandwidth and other limited system resources. As a result, the latency period—i.e., the time it takes for a position report to go from the aircraft to the ANSP via satellite—is as long as three to four minutes (longer if the report is transmitted via HF radio). The FAA’s oceanic separation minima are based on performance requirements for Direct Controller Pilot Communications, such as CPDLC and ADS-C, which assume a latency period of three to four minutes. See, FAA, “Advisory Circular: Operational Authorization Process for Use of Data Link Communication System,” AC No. 120-70C, August 3, 2015, Section 8.2.2, p. 11.

the transmission and receipt of a position report, technical experts are skeptical that ACARS-based ADS-C could ever support the 3-5 NM separations applied in surveillance airspace.¹⁰

1. New Concepts of Operations in the North Atlantic Region

The North Atlantic (NAT) Region, a “bridge” that connects Europe and North America, is the most heavily traveled oceanic airspace in the world: about 1,400 planes a day cross the NAT on average,¹¹ and traffic is expected to increase by 4.5 percent annually from 2016 to 2021.¹² Half of all transatlantic flights, including most high-value commercial traffic, use the Organized Track System (OTS), while the rest fly via less structured “Random” routings. The OTS typically consists of five to seven parallel routes that (with the exceptions discussed below) are spaced one degree of latitude, or approximately 60 NM, apart. These routes are reconfigured twice a day based largely on shifts in the powerful jet stream.¹³ The OTS falls almost entirely within the Gander Oceanic Control Area, or OCA (also known as the Gander Flight Information Region), which is managed by NAV CANADA, and the Shanwick OCA, managed by the United Kingdom ANSP, NATS. About five percent of the time, the OTS falls partially within the New York OCA.

ANSPs assign each aircraft to a specific track, and with that assignment goes a set flight level and speed. (NAV CANADA plans the assignments for eastbound flights and NATS for westbound flights.) In making these assignments, the ANSPs take operator preferences into account, but not all requests can be met, and the competition is particularly strong for the two most wind-optimal, or “core,” tracks. Although operators can request changes enroute, generally speaking, they are expected to maintain their assigned flight level and speed for the duration of the flight.¹⁴

¹⁰ ICAO, “Guidance Material on Comparison of Surveillance Technologies (GMST),” op. cit., p. 5. Although the ICAO document cited here is nine years old, the technical experts with whom we spoke in recent months expressed the same skepticism.

¹¹ Rudy Kellar, “NAV CANADA Space Based ADS-B Business Case Analysis for Gander-Shanwick,” Slide Presentation to RTCA Enhanced Surveillance Task Group,” Washington, DC, October 13, 2016.

¹² ICAO, North Atlantic Economic Financial and Forecasting Group, NAT EFFG/31-WP/04, September 19, 2016.

¹³ The tracks reverse direction every 12 hours. During the day, all traffic on the OTS travels from Europe to North America, and the tracks are configured to minimize the impact of headwinds from the westerly jet stream. At night, the OTS is devoted exclusively to traffic moving from North America to Europe, and the tracks are positioned to maximize the impact of tailwinds.

¹⁴ For an excellent description of the North Atlantic tracks and the track assignment process, see Henry H. Tran and R. John Hansman, “Fuel Benefit from Optimal Trajectory Assignment on the North Atlantic Tracks,” Massachusetts Institute of Technology (MIT) International Center for Air Transportation, Report No. ICAT-2016-03, May 2016, pp. 12-16. According to Tran and Hansman, only one or two tracks typically offer a highly favorable route in terms of wind conditions and distance traveled (the northern-most routes are shorter but require operators to fly farther to reach the entry point). So that

In the last few years, ICAO has introduced two new concepts of operations (CONOPS) that are designed to improve procedural control of the NAT Region. First, in response to a safety concern over deviations by aircraft from their assigned vertical and lateral positions, ICAO instituted its Data Link Mandate (DLM), which gives FANS-equipped aircraft exclusive access to the most desirable airspace in the NAT. The logic of the mandate is to reward those aircraft with the equipment necessary to allow for systematic conformance monitoring—and to penalize those without it.¹⁵

Second, in a related effort to accommodate the traffic growth in the NAT Region, ICAO has begun implementing reduced lateral and longitudinal separations for aircraft equipped with FANS and the appropriate navigation system. Phase 1 of the Reduced Lateral Separation Minimum (RLatSM) program, which began in 2015, decreased the distance between the two core OTS tracks from a nominal 60 NM (one degree of latitude) to 25 NM, allowing for the insertion of an additional core track.¹⁶ In addition to FANS, aircraft must be equipped with a navigation system capable of calculating its position within 4 NM (Required Navigation Performance 4, or RNP4¹⁷). Phase 2 of RLatSM, which has yet to take effect, will extend that spacing to all OTS tracks. The Reduced Longitudinal Separation Minimum (RLongSM) program began on a trial basis in 2011, when NAV CANADA and NATS reduced the in-trail separation on the core tracks from 10 minutes, or 80 NM, to 5 minutes, or 40 NM, for FANS-equipped aircraft. Thus, on the three core tracks, the longitudinal and lateral separations are 40 NM and 25 NM, respectively, which is abbreviated as 40/25 NM.

2. U.S. Oceanic Airspace

Like NAV CANADA and NATS, the FAA applies reduced separation minima for better equipped aircraft in the oceanic airspace it controls. However, in contrast to the approach taken in the North Atlantic, the FAA does not set aside any “exclusive” airspace for such aircraft. Rather, while equipped and non-equipped aircraft continue to share the same airspace, pairs of better equipped aircraft are allowed to take advantage of reduced oceanic separations, as shown below.

no one track is significantly better than the next best track, the ANSPs that manage the OTS “split” the most optimal route into two adjacent tracks.

¹⁵ Phase 1 of the DLM, which took effect in 2013, set aside the two core OTS tracks, between 36,000 and 39,000 feet, for FANS-equipped aircraft, and Phase 2a, which took effect in 2015, expanded the exclusionary airspace to include *all* OTS tracks between 35,000 and 39,000 feet. Phases 2b and 2c will extend the airspace reserved for FANS-equipped aircraft to all NAT airspace between 35,000 and 39,000 feet (proposed for 2017) and all NAT Minimum Navigation Performance Standards (MNPS) airspace at or above 29,000 feet (proposed for 2020). The DLM excludes the New York OCA and airspace north of 80 degrees, as well as any airspace in the NAT Region that has radar or ADS-B coverage.

¹⁶ Consistent with the DLM, the RLatSM program includes flights between 35,000 and 39,000 feet.

¹⁷ The number following “RNP” indicates the accuracy of the system as measured in NM. The lower the number, the more accurate the system.

FAA Criteria for Oceanic Separation

- 10 minutes (80 NM)/80 NM for aircraft with HF communications
- 50/50 NM for pairs of aircraft with RNP10 and ADS-C/CPDLC (FANS)
- 30/30 NM for pairs of aircraft with RNP4 and ADS-C/CPDLC (FANS)

C. SPACE-BASED ADS-B: REAL-TIME SURVEILLANCE ON A GLOBAL BASIS

Although ADS-B receivers have to date been deployed only on ground-based infrastructure, they will soon be able to take advantage of orbital infrastructure in the form of low-earth-orbit (LEO) satellites. Because these satellites have lines of site covering the entire planet, they will be able to track aircraft in real time anywhere above the earth's surface, including the oceanic and remote areas that currently rely on procedural control. This space-based ADS-B capability relies on the same radio signal as ground-based ADS-B systems, meaning that *aircraft equipped with ADS-B transponders will need no additional equipment to take advantage of the leading space-based ADS-B system (Aireon)*—a critical advantage, given the expectation of universal ADS-B equipage in oceanic airspace.

There are two prospective providers of space-based ADS-B service: Aireon, a joint venture between Iridium Communications and four ANSPs; and Globalstar, through its partnership with ADS-B Technologies of Alaska. Both systems will rely on LEO constellations (Iridium and Globalstar, respectively) that were built to provide global satellite telecommunications service. Despite a parallel history—both Iridium and Globalstar were launched in 1998 by entities that quickly went bankrupt—the systems differ in key respects, including their architecture and coverage.¹⁸ As a result of these differences, Aireon has attracted far more interest from ANSPs, and the FAA has signed a memorandum of understanding (MOU) with Aireon (but not Globalstar). Although our research focused largely on Aireon because of its greater appeal to ANSPs, we view the potential for competition in the market for space-based ADS-B as highly desirable.

¹⁸ In terms of architecture, Iridium's constellation functions as a giant switchboard: the ADS-B receiver infrastructure will be housed on the satellites themselves, and the signal received from the aircraft will travel among crosslinked satellites before being sent to a terrestrial gateway. By contrast, Globalstar's hardware and software will be situated on the ground or in the aircraft, and the satellites will function as "mirrors," reflecting the ADS-B signal back to the nearest terrestrial gateway, which will then route it to its destination. Because of this architecture, operators that use the Globalstar system (unlike Aireon users) will need an additional piece of equipment (other than the ADS-B transponder). The two systems also differ in the coverage they will offer. Because of the size and configuration of the Iridium constellation (66 satellites in polar orbit), Aireon will be able to surveil the entire planet, including polar regions. Globalstar's constellation is smaller (24 satellites) and configured to focus on the most populated parts of the globe, leaving some geographic areas—principally polar regions—without coverage.

Ten ANSPs have made major commitments to space-based ADS-B—specifically to Aireon. NAV CANADA pledged \$150 million in equity to become a 51 percent owner of Aireon, and the ANSPs from Ireland, Denmark and Italy have committed to an additional \$120 million, which makes Aireon 75.5 percent ANSP-owned. NATS signed a 12-year contract with Aireon, making it the fifth launch customer, and five other ANSPs have become launch customers on the same basis.¹⁹ In addition, to these contractual arrangements, Aireon has signed MOUs with at least ten ANSPs or aviation authorities, including the FAA.²⁰

Both Aireon and Globalstar say they expect to begin commercial operation in 2018.²¹ NAV CANADA and NATS plan to introduce the Aireon service in the North Atlantic in that year. Under their phased implementation plan (and subject to approval by ICAO), NAV CANADA and NATS will begin by applying a 15/15 NM separation (compared to the current 40/25 NM separation) on the core OTS tracks. On the non-core OTS tracks, where FANS is not required, NAV CANADA and NATS will begin by applying a 25/25 NM separation for aircraft with the appropriate navigation and communications equipment (RNP4 and HF voice).²² (This compares to the current separation of 80/60 NM on the non-core OTS tracks, which will go to 80/25 under Phase 2 of RLatSM.) Over time, NAV CANADA and NATS plan to extend the 15/15 NM separation to all OTS tracks as well as Random routings.²³ Because Aireon’s system has an update interval of at most 8 seconds (in the airspace covering most of the globe it will be 1-2 seconds), with the

¹⁹ They include: South Africa’s Air Traffic Navigation Services (ATNS); the Curacao-based Dutch Caribbean ANSP (DC-ANSP); the Seychelles Civil Aviation Authority; the Civil Aviation Authority of Singapore; and Iceland’s Isavia.

²⁰ Aireon has signed MOUs with ANSPs or regulatory authorities from Argentina, Australia, Germany, India, Myanmar, New Zealand and Russia, as well as with two regional organizations: the Senegal-based Agency for Aerial Navigation Safety in Africa and Madagascar (ASECNA), which serves as the ANSP for 17 countries in Africa; and the Blue Med Functional Airspace Block cooperative, which includes the ANSPs of Cyprus, Greece, Italy and Malta. Aireon has also signed an MOU with the FAA. Although it declined to be an equity investor, the FAA entered into an arrangement with Aireon to ensure that the system will meet U.S. requirements if the United States decides to become a customer.

²¹ Although it is not yet operational, space-based ADS-B is composed of well-understood technologies (ADS-B and LEO satellites) whose performance can be modeled. CANSO, op. cit., p. 6. Space-based ADS-B will be installed on Iridium’s next generation of satellites, which are being launched from Vandenberg Air Force Base on SpaceX Falcon 9 rockets in 2017 and 2018. The first of seven planned launches occurred on January 14, 2017. Andy Pasztor and Rolfe Winkler, “SpaceX Resumes Rocket Launches by Lofting Cluster of Iridium Satellites,” *Wall Street Journal*, Jan. 16, 2017. See: <http://www.wsj.com/articles/spacex-resumes-rocket-launches-by-lofting-cluster-of-iridium-satellites-1484417292>.

²² Rudy Kellar, op. cit.

²³ Aireon, “Space Based ADS-B: Transforming the Way You See the Sky,” Slide Presentation, March 2015. See also, “Space-Based ADS-B: Signals from Space,” *Airspace*, Quarter 3, 2014.

appropriate communications equipment (e.g., satellite voice), it could eventually support a 5 NM longitudinal separation in the NAT.

In anticipation of the new systems becoming operational, ICAO has tasked its Separation and Airspace Safety Panel (SASP) with determining what separation standards space-based ADS-B can safely support in oceanic/remote airspace. SASP is developing a menu of standards that will correspond to the range of communications capabilities found within the global fleet: the better the performance of a given communications capability, the smaller the separation standard can be.

Importantly, SASP is investigating whether longitudinal and lateral separation standards of 15 NM or less can be supported by space-based ADS-B based on the current performance exhibited by CPDLC communications with HF voice communications as the backup.²⁴ Operators can equip with CPDLC as a standalone capability for a fraction of the cost of FANS. Thus, an affirmative finding from SASP would provide support for the position that the combination of space-based ADS-B (surveillance) and CPDLC/HF (communications) represents a way for non-FANS aircraft to access reduced oceanic separations (albeit not necessarily as small as with FANS).

²⁴ CANSO, *op. cit.*, p. 19.

III. Key Shortfalls Addressed by Space-Based ADS-B

Space-based ADS-B has the potential to address key shortfalls in the current approach to air traffic tracking and surveillance. Below, we discuss eight such shortfalls and the corresponding benefits that the incorporation of space-based ADS-B may produce.

A. LARGE SEPARATION MINIMA LIMIT CAPACITY IN OCEANIC/REMOTE AIRSPACE

The large separation minima in areas not covered by radar or ADS-B, which create the equivalent of a giant “bubble” around each plane, significantly limit available airspace capacity. If air traffic is sparse, as it is in many such areas, this limitation may not matter. However, if traffic is dense—that is, if many aircraft want to fly the same profile at the same time—capacity constraints reduce operators’ ability to obtain their preferred profile (altitude, speed and lateral track) at the start of the flight or their flexibility to make enroute adjustments, including climbing to a higher altitude as fuel burns off, varying their speed to conserve fuel or reduce delay, and deviating from course to avoid storms and other disturbances. Lack of capacity can also harm the performance of the air traffic control system, by limiting ANSPs’ ability to plan for convective weather, respond to operator requests and near-term disruptions, and accommodate market growth over the long term.

1. Improved Operational Efficiencies

By supporting reduced separation minima—i.e., by shrinking the “bubble” around individual aircraft—space-based ADS-B can increase the available airspace capacity in areas not covered by radar or ADS-B. Under conditions of higher traffic density, having additional capacity will increase operators’ ability to fly their optimal flight profiles, generating several concrete benefits.

Fuel Savings: The amount of fuel an aircraft consumes is sensitive to variations in the plane’s flight level (the higher the altitude, the less the atmospheric drag), speed and lateral proximity to headwinds or tailwinds. By allowing aircraft to more closely approximate their optimal flight profiles, space-based ADS-B can potentially generate significant fuel savings.²⁵

²⁵ As a plane burns off fuel, its optimal flight level increases, because there is less atmospheric drag at higher altitudes. The most efficient flight profile would allow for a continuous climb in altitude, to the point at which the benefits of lower drag are offset by reduced engine performance. When longitudinal and vertical separation minima are large, there is a greater probability that a pilot’s request to climb to a more fuel-efficient altitude will be denied because it would trigger a “conflict”—i.e., it would breach the bubble around another aircraft flying at a higher altitude. Conversely, with smaller separation minima, a request to climb is less likely to trigger a conflict and thus more likely to be granted—and to be granted sooner. Smaller longitudinal separation minima also contribute to fuel efficiency by allowing an aircraft to change its speed: on an organized track system with large in-trail separation distances, an aircraft may have to maintain the same speed throughout the trip, thereby missing the opportunity to

Fuel savings come about through three distinct but related mechanisms. First, with a more optimal flight profile, as defined by route, speed, and altitude (including climb/descent rate), an aircraft consumes less fuel. Second, the ability to *plan* on flying an optimal profile permits reductions in the amount of contingency fuel carried. Because contingency fuel accounts for about 10 percent of an aircraft’s fuel load, a reduction in that reserve can produce meaningful savings. Third, a reduction in the amount of fuel that an aircraft consumes or carries in reserve will reduce the fuel burned merely to carry other fuel (“cost to carry”).

Incremental Cargo Revenue: If a plane is carrying less weight in the form of fuel, it may be able to transport more revenue-generating cargo. Incremental cargo revenue is typically even more valuable than fuel savings, although the opportunity to trade off fuel for cargo may be declining, as operators replace older, cargo-limited aircraft with newer models that have no such limitation.

Reduced Greenhouse Gas (GHG) Emissions: Reduced fuel consumption also means reduced GHG emissions. Aviation accounts for about two percent of human-induced carbon dioxide emissions, and nearly two-thirds of that impact is due to international flights. According to ICAO, the cost of carbon offsetting will represent 0.2-0.6 percent of total revenues from international aviation in 2025 and 0.5-1.4 percent in 2035.²⁶ Some aviation experts believe that the cost of carbon offsetting is almost certain to go up over time, as efforts to combat climate change intensify.²⁷

Longer Flights: As an alternative to consuming less fuel, operators can opt to have aircraft fly farther on the same amount of fuel. Combined with opportunities for more direct routing—another potential benefit of space-based ADS-B, discussed below—the ability to fly longer distances could enable operators to provide point-to-point service in unserved long-haul markets.

Shorter Flight Times: Like fuel burn, flight time is sensitive to variations in the flight level and route flown. Allowing aircraft to more closely approximate their optimal flight profiles will reduce flight times, which will increase passenger welfare and decrease operator costs. In addition to the direct impact, there could be an indirect impact: the ability to *plan* on flying a more optimal profile permits operators to reduce scheduled flying times.

change speed to conserve fuel. Finally, smaller longitudinal and lateral separation minima contribute to fuel efficiency by allowing more aircraft to utilize the most wind-optimal tracks.

The inefficiencies due to large oceanic separations take many forms. In the Western Atlantic, the pilots of one U.S. carrier reportedly request the highest possible flight level early in the flight, because they cannot count on being granted a step climb later on. Because the requested level is not the most efficient one at the time of the request, the pilots accept a fuel-cost penalty for the first several hours of the flight in order to ensure that they will be able to fly at an efficient altitude for the duration of the flight.

²⁶ ICAO (Environment, Air Transport Bureau), “2016 Global Aviation Dialogues (GLADS) on Market-Based Measures to Address Climate Change,” Slide 19. See: <http://www.icao.int/Meetings/GLADS-2016/Documents/20160316%20Overview%20of%20ICAOs%20work%20on%20a%20global%20MBM.pdf>.

²⁷ Lauren Reddy, NEXTOR 20th Anniversary Workshop, September 29-30, 2016, Adelphi, MD.

Improved Schedule Predictability: In addition to shorter flight times, optimized flight profiles will yield more predictable schedules, which benefits operators and passengers in multiple ways. First, improved predictability will allow carriers to increase the number of flights that arrive on time (AO, in airline lingo) or within 15 minutes of their scheduled arrival (A14). The U.S. Department of Transportation (DOT) maintains A14 statistics, and operators sometimes opt to consume more fuel in order to improve the A14 performance of a chronically late flight. DOT statistics aside, for some operators—particularly cargo carriers—getting aircraft to their destination on time may be as important as saving fuel. Second, predictability facilitates more efficient use of ground staff, gates, and other airport resources—a critical issue for hub-and-spoke operators, whose aircraft and crew must transition to their next flight on a tight schedule. For example, if an operator can more accurately predict when flights will arrive, it can schedule its surface crews (ramp agents, gate agents, baggage handlers, fueling crew) more tightly, thus reducing the overall number of crew it needs. The operator can also track the duty time and flight time of crew more accurately, making it easier to recover from schedule disruptions by swapping crews or using standby crews. By reducing the time that a plane is on the ground between flights, an operator can squeeze in more flights, yielding important benefits for overall productivity.²⁸ Third, improved predictability makes it easier for operators to avoid some disruptions altogether. For example, congested European airports often manage demand through the use of aircraft arrival slots, and if an aircraft cannot meet its slot time, the operator may have to divert or cancel the flight. The ability to more accurately forecast flight arrival times at slot controlled airports will allow operators to reduce the number of flight diversions and cancellations.

2. Improved System Performance

In the same way that they improve operational efficiency in procedural airspace, reduced separation standards improve the overall performance of the ATC system. According to Russell Chew, who ran the FAA’s Air Traffic Organization (ATO) from 2004 to 2007 before becoming the chief operating officer and president of JetBlue, the real goal of NextGen is to allow the National Airspace System (NAS) to run as efficiently and predictably on a bad weather day as it currently does on a good weather day. In his view, space-based ADS-B can be a major contributor to that goal by, among other things, improving flow control, particularly at the boundary between oceanic and terrestrial airspace (discussed below), and by reducing uncertainty and lack of predictability. “Uncertainty decimates the performance of the system,” according to Chew.²⁹

²⁸ Vitaly Guzhva and Ahmed Abdelghany, Embry-Riddle Aeronautical University, “Note on Benefits of Increased Arrival Predictability,” August 2016. We also want to acknowledge Michael J. McCormick for the valuable insights he provided on improved schedule predictability among many other issues.

²⁹ Russell Chew, Personal Interview, Washington, DC, June 24, 2016. Chew is a member of Aireon’s U.S. Advisory Board.

3. Longer-Term Improvements in Efficiency and System Performance

Many of the gains to operational efficiency and system performance described above are achievable in the near term. Over the medium and longer term, as space-based ADS-B allows ANSPs to move from position report-enabled conformance monitoring to genuine ATC surveillance, other improvements may become feasible. These improvements include new operational concepts, such as continuous climb and descent profiles; use of Great Circle and wind-optimal routes; and direct routing that crosses organized tracks and/or allows operators to get on and off of the tracks at intermediate points (currently entry and exit on the NAT OTS are restricted to endpoints).

Ultimately, space-based ADS-B could allow ANSPs and operators to eliminate altogether the distinction between procedural and surveillance airspace. Such a change would have profound implications, ranging from training of pilots and controllers (e.g., operators could potentially eliminate the extensive training that pilots get in the intricacies of procedural control) to flight scheduling (e.g., the NAT could move from twice-daily fixed-track routes for peak traffic to a daily network of user-preferred routes).

4. Implications of Long-Haul, Direct Routing for Airline Competition

Although the NAT OTS, like other less organized track systems, is designed to connect major hub airports, advances in aircraft technology are making it possible for operators to serve long-haul markets directly.³⁰ Space-based ADS-B can support and extend that capability in two ways. One is by allowing aircraft to fly longer distances on a given amount of fuel, as discussed above. The other is by facilitating more direct routing: as the demand for service in point-to-point markets grows, operators will find it ever more valuable to be able to cross the NAT OTS and other track systems and to get on and off of them at intermediate points.

In a recent analysis of “disruptive influences” in aviation, the editor of *Air Traffic Management*, Aimee Turner, argues that space-based ADS-B could “open up huge new opportunities in terms of routes and optimal operations that could not only transform the ATM landscape but also challenge the airline order....” In Turner’s example, Norwegian Air’s potential launch of long-haul transatlantic operations from all over Europe with Ryanair as the feeder airline could challenge the existing hub-and-spoke market for transatlantic service much as point-to-point service by low-cost carriers challenged traditional domestic air service in Europe and the United States.³¹

³⁰ A key development was the FAA’s regulatory action in 2014 allowing the Boeing 787 to fly extended-range twin-engine operations (ETOPS) of up to 330 minutes (the previous limit was 180 minutes).

³¹ Aimee Turner, “Disruptive Influences,” *Air Traffic Management*, Autumn 2016, pp. 14-16. See: <http://www.airtrafficmanagement.net/2016/10/disruptive-influences/>. Turner quotes an industry expert on why space-based ADS-B is key to this disruptive development: “If there was an opportunity for Ryanair to operate transatlantic services using Norwegian aircraft, there would be an even bigger chaos than today where ATC struggles to managing existing point to point operations....You stick a load

5. Polar Routes

Polar regions constitute a sizable fraction of the world’s airspace, and as technology makes ultra-long-range flights more feasible, polar routes are becoming increasingly attractive. In 2015, 14,000 flights used NavCanada’s polar routes—a 15-fold increase from 2003.³² However, the use of polar routes is constrained by the state of existing tracking technology: a majority of FANS-equipped aircraft have ADS-C systems that lack polar coverage. The separation standards are correspondingly large (in FAA-controlled polar airspace, the in-trail separation minimum is 120 NM), which means that polar routes experience “congestion” even with limited traffic volumes. By allowing for reduced separation minima, space-based ADS-B could facilitate much greater usage of polar airspace.

B. THE TRANSITION BETWEEN DIFFERENT SEPARATION STANDARDS: BOTTLENECKS AND “UPSTREAM” DELAYS

The inefficiencies caused by the large separations in areas without radar or ADS-B coverage are not confined to the directly affected (procedural) airspace. They spill over to adjacent and non-adjacent airspace, because of the difficulty of transitioning air traffic between different separation minima. Space-based ADS-B can address that difficulty by reducing the size of the differential.

1. Current Inefficiencies

Most of the transition challenges arise at the seam between terrestrial and oceanic airspace. The major transition points between terrestrial and oceanic airspace are complex to begin with. Hubs like New York, Miami, Los Angeles and San Francisco handle diverse flows and large volumes of traffic. For example, controllers at New York’s Terminal Radar Approach Control center (TRACON) manage domestic origin-destination traffic, international traffic and overflights. The New York TRACON handles a non-trivial amount of all national and global air traffic.

One contributor to this complexity is the need to move oceanic flights from surveillance control, with 3-5 NM separations, to procedural control, with separations of 30-80 NM, depending on the aircraft equipage. This handoff poses a challenge analogous to that of funneling automobiles from a crowded six-lane interstate highway onto a two-lane country road. For major airports like New York’s John F. Kennedy and San Francisco International, the terrestrial-oceanic bottleneck accounts for a significant share of congestion.

more traffic on those routes [and] you are going to need an Aireon-type system to be able to control the new environment.”

³² “Aireon Plans to Exploit Early Polar Gains,” *Air Traffic Management*, Nov. 22, 2016. Use of NAV CANADA’s polar routes allows operators to reduce their annual GHG emissions by an estimated 600,000 tons.

These bottleneck-related delays affect not just the immediate (adjacent) region but non-adjacent regions as well. For example, at JFK Airport, where there are only two takeoff runways, planes headed for California often wait in the same queue as those destined for, say, London or Paris. When a controller holds the London-bound plane so as to position it for entry onto the OTS, the California-bound flight can also experience delay.³³

Transoceanic flights are not the only contributor to the terrestrial-oceanic bottleneck. Narrow-body aircraft flying from East Coast airports to the Caribbean or Bermuda can also contribute, because most of them are not FANS-equipped and thus must be spaced 10 minutes, or around 80 NM, apart. This spacing requirement is particularly burdensome on days when the airport is experiencing a ground-stop delay, due to inclement weather or other capacity-limiting events (e.g., airport construction or the arrival or departure of a VIP). The same phenomenon occurs on the West Coast, where narrow-body planes flying north-south routes compete with international flights for scarce air traffic capacity in and around Los Angeles and San Francisco.

Although most challenges have to do with terrestrial-to-oceanic transitions, transitions between adjacent oceanic airspaces with different separation standards can pose similar challenges. Because the FAA separates FANS-equipped aircraft by 30 NM in the New York OCA, whereas NAV CANADA applies a 40 NM standard on its FANS-reserved tracks, the FAA must sometimes hold aircraft in U.S. oceanic airspace to space them for entry into the Gander OCA.

2. Space-Based ADS-B Can Help Relieve the Bottlenecks

Space-based ADS-B can potentially ease these problems by, in effect, widening the funnel—primarily between terrestrial and oceanic regions. Thus, in contrast to oceanic airspace, where reduced separations will benefit the system largely by allowing more aircraft to fly more efficiently, *at the complex seam between terrestrial and oceanic airspace, the benefits of space-based ADS-B will come largely from the improved flow of aircraft into and out of the terminal airspace at the ends of each oceanic track.*

The gains would be even greater if the FAA were to allow operators equipped with space-based ADS-B and CPDLC/HF, but not FANS, to take advantage of reduced oceanic separations. Recall the scenario in which Caribbean-bound narrow-body aircraft exacerbate delays in New York because of the need for 80 NM separations. If non-FANS aircraft could be spaced at a reduced separation, New York airports would be able to recover more quickly from major congestion.

3. Impact of Uneven Adoption of Space-Based ADS-B

Note that where two procedural airspaces are adjacent to one another, the introduction of space-based ADS-B in one airspace but not the other can create *new* seam issues like the ones described

³³ In DOT's on-time statistics, such a delay would likely get recorded as a generic "ATC delay," thus obscuring the role of separation standards in contributing to the problem. The FAA's allocation of runway capacity on a first-come, first-served basis can be seen as another contributor to such delay.

above. For example, if NAV CANADA adopts space-based ADS-B but the FAA does not, it could create a bottleneck as westbound aircraft that are spaced 15/15 NM apart in the Gander OCA enter the New York OCA, with its 30/30 NM spacing requirement.

The potential impact of this bottleneck scenario is unclear. Although some aviation experts believe that having a Canada-U.S. separation differential would significantly dilute the benefits of space-based ADS-B for aircraft crossing the North Atlantic, others disagree, noting that the North Atlantic OTS enters U.S. oceanic airspace only 5 percent of the year. Regardless of who is correct, the point remains: uneven adoption of space-based ADS-B by neighboring ANSPs can introduce new boundary issues that adversely affect the non-adopter and dilute the benefits to the adopter.

C. MISSED OPPORTUNITIES: INABILITY TO USE OCEANIC AIRSPACE TO RELIEVE TERRESTRIAL DELAYS

In some cases, the transition from terrestrial to oceanic airspace can be so cumbersome that ANSPs and operators forego use of the oceanic airspace altogether, thereby missing a valuable opportunity to relieve terrestrial delays and improve flow control in the NAS. Consider the dense traffic from Boston, New York and Washington, DC to Florida, which travels along radar-controlled routes that hug the East Coast. When convective weather blocks those routes—a common occurrence after summer storms—the FAA holds flights on the ground and diverts airborne traffic inland, creating delays that can propagate for hundreds of miles.

Although, in theory, the FAA could divert traffic out over the Atlantic to avoid these actions, oceanic diversion is not currently an option. Granted, pilots that fly on radar-controlled routes are typically not trained in oceanic procedures, nor are the planes equipped to fly over-water operations (e.g., they would need life rafts). However, operators could address those issues if the benefits from protecting their schedules were sufficient. The real impediment to oceanic diversion is the large separation standards that apply in oceanic airspace. On East Coast routes, where planes are spaced 5 NM apart, diversion to the Atlantic would require separations of up to 80 NM.

By reducing oceanic separation minima (and the resulting oceanic-terrestrial differential), space-based ADS-B can make it easier for the FAA to use the Western Atlantic and other oceanic airspace to relieve terrestrial delays. The ability in this way to move the boundary between terrestrial and oceanic airspace in real time is an example of the much-discussed concept of dynamic airspace reconfiguration and a step toward the long-term goal of eliminating the terrestrial-oceanic distinction altogether. Because of the potential for improved flow control in the NAS, some industry experts see this as one of the most significant ways in which space-based ADS-B can benefit U.S. aviation.

D. HIGH COST OF FANS REQUIREMENT IN OCEANIC AIRSPACE

The introduction of space-based ADS-B in procedural airspace may yield another benefit if it gives some carriers an alternative to FANS. As discussed above, although FANS has enabled significant improvements in procedural control, FANS/ADS-C faces potentially significant limitations. In addition to the constraints on communications capacity, which are likely to limit the potential for

reduced oceanic separations, cost is a drawback. Although FANS has been standard equipment on new Boeing and Airbus wide-body aircraft for many years, many narrow-body aircraft are not FANS-equipped—either because of the high cost of equipage or because certain aircraft types cannot be retrofitted for FANS. In addition to being expensive to install, FANS—specifically, ADS-C—is expensive to operate in the view of price-sensitive air carriers. Position reporting accounts for some of the cost: the communications service provider charges a fee for each individual message transmission. Carriers transmit messages infrequently in part because of this cost, according to ICAO.³⁴ In addition, pilots must be trained to use FANS. As has been widely reported, some operators that have installed FANS do not activate it, presumably to avoid these operating costs. Finally, coverage is a limitation on FANS; as noted earlier, a majority of FANS-equipped aircraft have ADS-C systems that lack polar coverage.

Currently, the FAA requires carriers to be FANS-equipped in order to take advantage of reduced separations in oceanic airspace, and the agency has indicated that it plans to maintain that requirement even if it adopts space-based ADS-B. The FAA maintains that ADS-C is unique among tracking and surveillance technologies in its ability to communicate the intent of the aircraft: because ADS-C communicates data on the trajectory of the flight, controllers know not just where an aircraft is (or where it was when the position report was transmitted) but where it is going. However, flight crews are required to communicate their trajectory at key waypoints, and that requirement will remain in place even if space-based ADS-B replaces ADS-C. Moreover, some operators say that they have no plans to put FANS in many of their aircraft because of the high cost of installing and using it (including providing the necessary pilot training), and they are urging the FAA to treat the combination of space-based ADS-B and CPDLC/HF as an alternative to FANS for accessing reduced oceanic separations—an option ICAO is examining.

Faced with similar resistance to FANS installation by one group of operators, the European Union (EU) appears to be considering a limited exemption to the FANS requirement in ICAO's Data Link Mandate. Narrow-body operators who shuttle holiday travelers from Northern Europe to Spain and the Canary Islands fly on oceanic tracks known as TANGO routes. The TANGO routes were established to allow operators to avoid the use of continental tracks which, while more direct, have less capacity and are vulnerable to controller strikes and other disruptions. After TANGO operators threatened to resume flying over the continent rather than incur the cost of FANS as required by the DLM, European stakeholders floated a proposal that would exempt operators that have an ADS-B surveillance capability (supported by either ground-based or space-based infrastructure) as well as CPDLC/HF communications.

³⁴ ICAO, “Guidance Material on Comparison of Surveillance Technologies (GMST),” op. cit., p. 18.

E. SEARCH AND RESCUE IN OCEANIC/REMOTE AREAS: COSTLY AND OFTEN UNSUCCESSFUL

The high profile loss of Air France Flight 447 in June 2009 triggered a discussion worldwide about the need to track aircraft in oceanic airspace with greater precision so as to reduce search and rescue costs and increase the likelihood of retrieving critical flight data that can help prevent future incidents. In the subsequent five years, there were eleven more over-water accidents, and in only one of the eleven cases were authorities able to recover the black boxes.³⁵ What's more, search and rescue costs have reached new levels. The AF447 search operation, with an estimated final bill of \$44 million, was at the time the most expensive such undertaking. However, the search for Malaysian Airlines Flight 370, which vanished in March 2014 enroute to Beijing and has still not been found, incurred similar costs *in the first month alone*.³⁶

In response to these tragedies, ICAO recently issued two standards and recommended practices (SARPs). The first, which comes into force in 2018, requires the operator of a large aircraft (45,500 kilograms (kg) or more) routinely to track the aircraft's position at least every 15 minutes when it is flying over oceanic areas. (ICAO recommends but doesn't require that operators of smaller aircraft follow the same practice.) The second SARP, which comes into force in 2021, requires that any aircraft weighing more than 27,000 kg autonomously transmit information from which its position can be determined at least once a minute when it is in a distress condition.³⁷ Distress condition is defined as a state that, if left uncorrected, could result in an accident.

Once space-based ADS-B is operational, the technology will allow for the location of a downed plane with far greater precision than ICAO requires (assuming the transponder is turned on). To take the example of a Boeing 777 traveling 493 knots, the ICAO-mandated routine update interval of 15 minutes (which is the common update interval for ADS-C) translates to a search area of 55,000 square kilometers. By contrast, assuming an 8-second update interval for space-based ADS-B (it will be far less in most parts of the globe), the search area would be only 4 square kilometers.

³⁵ Stuart Baskcomb, "Losing an Aircraft in Today's World," *Space Safety Magazine*, July 8, 2014. See: <http://www.spacesafetymagazine.com/space-on-earth/malaysia-flight-370/losing-aircraft-todays-world/>

³⁶ Stuart Baskcomb, op. cit. At the end of 30 months, the search for MH370, which covers a 120,000-square kilometer zone in the southern Indian Ocean, had cost the governments of Australia, China and Malaysia more than \$120 million USD. "Search for MH370 May be Extended by Australia if Funding Can be Found," *The Guardian*, August 19, 2016. See: <https://www.theguardian.com/world/2016/aug/19/search-for-mh370-may-be-extended-by-australia-if-funding-can-be-found>.

³⁷ ICAO is still determining what "autonomous" means in this context. One option would be to have the aircraft transponder installed in such a way that it could not be disabled by the flight crew.

For the ICAO-mandated distress update interval of one minute, the corresponding search area is 242 square kilometers.³⁸

To be sure, the prospect of reduced search and rescue costs is not a sufficient reason for an individual ANSP to introduce space-based ADS-B. For one thing, many technologies, some of them less expensive than space-based ADS-B, can support a one-minute tracking requirement. For another, Aireon's emergency tracking capability will be available, free of charge, to any ANSP that needs it regardless of whether the ANSP subscribes to space-based ADS-B services on a regular basis.³⁹ However, space-based ADS-B may be an efficient way to meet the new ICAO requirements given that all new aircraft come equipped with ADS-B transponders and many older aircraft will have them installed by a date certain in response to various national mandates.

F. CHALLENGES TO SURVEILLANCE OF TERRESTRIAL AIRSPACE

Even in terrestrial areas, there are challenges to achieving comprehensive real-time ATC surveillance using ground-based systems (radar and ADS-B). Space-based ADS-B can address many of these challenges.

One challenge is the sheer expense of installing and maintaining ground-based systems. Some ANSPs may opt to rely largely on space-based ADS-B for surveillance, so as to avoid the cost of a ground-based surveillance infrastructure. This strategy is analogous to one that some developing countries have followed in telephony, where they have leapfrogged landline technology and gone directly to wireless. Other ANSPs see space-based ADS-B as a way to avoid the need to replace aging ground stations in sparsely populated areas.

Although the United States has an extensive ground-based surveillance infrastructure, the FAA may be able to reduce its future investment in that infrastructure at the margin by relying on space-based ADS-B. For example, space-based ADS-B would reduce the resources that the FAA spends securing leases to keep ADS-B ground stations positioned on oil platforms in the Gulf of Mexico. As another example, in 2015, the RTCA strongly recommended that the FAA install additional ADS-B ground stations in the Caribbean both to widen the existing "funnel" of routes into and out of the region that have radar separation and to provide backup surveillance for use

³⁸ Vitaly Guzhva, Professor, Embry-Riddle Aeronautical University, and consultant to ISA. At a speed of 493 knots, a Boeing 777 will travel 123.25 NM (228.26 kilometers, or km) in 15 minutes, 8.22 NM (15.22 km) in one minute, and 1.1 NM (2.03 km) in 8 seconds. The search area is calculated by using the distance traveled as the radius of a circle and taking that portion of the circle that corresponds to the change of course that the aircraft is assumed to have made. Guzhva's calculations assume a plus or minus 60-degree change of course, which is equivalent to one-third of a circle (360/120 degrees).

³⁹ Andy Pasztor, "Iridium Venture Offers to Track Planes," *Wall Street Journal*, September 21, 2014. See: <http://www.wsj.com/articles/iridium-venture-offers-to-track-planes-1411351382>.

during those times when legacy radar systems are out of service.⁴⁰ Although the RTCA did not look at alternatives to ground-based ADS-B in its analysis of the Caribbean, presumably space-based ADS-B could meet some or all of those same needs.

The fact that space-based ADS-B can serve as a substitute for ground-based ADS-B may have a secondary benefit if it puts downward pressure on the price of ADS-B ground stations. In a deal with the Agency for Aerial Navigation Safety in Africa and Madagascar (ASECNA), Indra, a provider of air surveillance systems, recently agreed to deploy one of the largest ground-based ADS-B networks anywhere in the world—it will cover 17 countries in Africa and several French overseas departments in the Indian Ocean—for a seemingly bargain price.⁴¹ Although the catalogue price of the system reported by Indra (7 million EURO or about \$7.7 million USD) may not be all-inclusive, some aviation authorities cite this deal as a possible indication that space-based ADS-B is already exerting competitive pressure on providers of ground-based systems.

A second challenge to terrestrial surveillance is gaps in coverage. Even ANSPs with relatively comprehensive surveillance systems typically have coverage gaps in areas where it is difficult to site ground-based infrastructure. Since procedural rules apply, planes must transition at these gaps between procedural and surveillance separation standards, which increases controller workload. Although the United States has deployed 634 ADS-B ground stations, a few gaps remain, including parts of Alaska, the Rocky Mountains, Hawaii, Guam and Puerto Rico.⁴²

A third challenge is lack of redundancy in ATC surveillance. In the rare case that the primary surveillance system malfunctions, the absence of a backup system can mean that operations are adversely affected. In 2015, Airways New Zealand had to ground all commercial aircraft for several hours because a problem with its internal network resulted in a radar blackout.⁴³ In 2014, the ATC center in Copenhagen, Denmark, lost access to surveillance data when the secondary network malfunctioned during a scheduled outage of the primary network.⁴⁴ And in Bermuda, when the

⁴⁰ RTCA, “Recommendations to Improve Operations in the Caribbean,” July 2015. See: <http://www.rtca.org/Files/Miscellaneous%20Files/Final%20DRAFT%20ERTG%20Caribbean.pdf>.

⁴¹ According to a press release issued by Indra, the catalogue price of the system is 7 million euros. <http://www.indracompany.com/en/noticia/asecna-indra-deploy-ads-b-system-network-monitor-airspace-17-african-countries-indian-ocean>.

⁴² For a map of ADS-B coverage in the United States, see: <http://www.faa.gov/nextgen/programs/adsb/ICM/>.

⁴³ “Airways Air Traffic Control Radars to be Decommissioned by 2021,” *Stuff*, June 29, 2015. See: <http://www.stuff.co.nz/business/industries/69698659/airways-air-traffic-control-radars-to-be-decommissioned-by-2021>.

⁴⁴ Naviair, “Continental Denmark: Space-Based ADS-B as a Contingency Surveillance Layer,” Case Study, 2016. See: <http://aireon.com/resources/brochures-guides/naviair-aireon-case-study/>. According to Naviair, while the event had a limited impact on operations because it happened during off-peak hours,

FAA, which controls the enroute traffic in Bermuda airspace, takes the island’s lone radar off-line for repair, it can disrupt terminal traffic, harming tourism and the local economy.⁴⁵

The deployment of space-based ADS-B will provide an additional layer of surveillance. For example, with access to satellite surveillance data, the FAA’s center in New York could help Bermuda manage its terminal traffic when the radar there is offline, and the Houston center could manage traffic in the Gulf of Mexico if a hurricane were to damage the ADS-B ground stations there. More broadly, as the FAA phases out radar in favor of ground-based ADS-B, space-based ADS-B can provide valuable redundancy.⁴⁶

G. LIMITS ON INTERNATIONAL COOPERATION AND HARMONIZATION (AND COMPETITION)

The aviation sector has long worked to establish global safety standards, maximize standardization on equipment and technical matters, and promote information sharing and cooperation among civil aviation authorities and ANSPs. ICAO has been key to this effort, which is aimed at expanding the flow of passengers and cargo across national borders. Standardization and cooperation further this goal by, among other things, increasing the level and consistency of safety enforcement, which encourages consumers to fly; simplifying avionics equipage, which allows equipment manufacturers to capture economies of scale; and making it easier for ANSPs to manage the handoff of traffic from one flight information region (FIR) to another.

Despite enormous progress, the management of international air traffic is far from seamless. Neighboring ANSPs do not necessarily share information routinely. And ANSPs use non-uniform tools and procedures, which adds to the inherent difficulty of handing off traffic across FIRs.⁴⁷

had it happened during peak hours, it would have generated up to 26,000 minutes of delay and a potential loss of \$2 million (USD) for the affected airlines.

⁴⁵ “New Radar Installation Completed at Airport,” *The Royal Gazette*, August 18, 2013. See: <http://www.royalgazette.com/article/20130818/NEWS/130819744>.

⁴⁶ Although some people worry about the vulnerability of the GPS system—a resource on which all ADS-B systems rely—space-based ADS-B offers redundancy in the sense that the satellite surveillance data will be sent to an ANSP over a different network from the one used to send ground-based surveillance data. CANSO, op. cit., p. 20.

⁴⁷ For example, the FAA and NAV CANADA use different automation platforms to manage oceanic traffic, and their respective tools for identifying open flight levels in response to climb and descent requests are not synchronized. According to one ANSP representative who was interviewed, the process of harmonizing the two tools “has been slow and painstaking.” Lauren Reddy and Dan DeLaurentis, Purdue University, “Characterizing Uncertainty in Investment Analysis of Air Navigation Service Provider Improvements, Slide Presentation, Fall 2015, p. 22.

Safety statistics show that aircraft position errors on or near the boundaries between FIRs are still relatively common.⁴⁸

ICAO has been a strong proponent of ADS-B technology because of its potential to become the globally accepted successor to radar, much as GPS (or GNSS, for Global Navigation Satellite System, as GPS is known outside of the United States) has become the unquestioned replacement worldwide for traditional navigation technology (inertial guidance systems). As a member of the ADS-B “family,” space-based ADS-B will reinforce this positive trend and extend it to areas that ground-based ADS-B cannot reach.

Precisely because satellite coverage is global, space-based ADS-B represents a platform for shared situational awareness, making it easier for ANSPs to exchange information, engage in collaborative traffic flow management, and jointly implement programs to upgrade airspace capabilities.⁴⁹ One such program is ICAO’s Framework for Airspace System Block Upgrades (ASBUs). According to the Civil Air Navigation Services Organisation (CANSO), which represents ANSPs worldwide, numerous ASBUs would provide even more benefits if they were implemented in an environment in which global air traffic management surveillance (read space-based ADS-B) was available.

The United States has long been a leader in the effort to promote international aviation safety through greater standardization and cooperation. President Franklin Roosevelt convened the 1944 Chicago Convention on International Civil Aviation whose accomplishments included the creation of ICAO, and the FAA, almost since its beginning, has played a dominant role within that organization. Among other things, the FAA has been a champion for the use of advanced technology—in the control tower and cockpit alike—to enhance aviation safety. This country’s leadership role in promoting international aviation safety has been both cause and consequence of the strong market position held by U.S. air carriers and aerospace manufacturers.

With other countries moving to embrace or prepare for space-based ADS-B,⁵⁰ some leaders in the U.S. aviation community have raised concerns that inaction could jeopardize the FAA’s reputation as a leader on international aviation safety.⁵¹ Moreover, as the world’s largest ANSP and one that

⁴⁸ Flight Safety Foundation, “Benefits Analysis of Space-Based ADS-B,” June 2016, p. 23.

⁴⁹ CANSO, *op. cit.*, p. 21.

⁵⁰ In addition to the ANSP commitments discussed above, the EU’s European Aviation Safety Agency has initiated the safety certification process for space-based ADS-B—a step that the FAA has yet to take.

⁵¹ Paul Rinaldi, the president of the National Air Traffic Controllers Association, has warned that the FAA could even lose its authority to manage large portions of oceanic airspace if it declines to adopt space-based ADS-B. In Rinaldi’s view, ICAO gave the FAA that authority in part because the agency was a technology leader; if the FAA were to fall behind on a capability so important to oceanic control, ICAO could transfer substantial authority to an ANSP such as NAV CANADA that had the capability. For a summary of Rinaldi’s comments, see Robert W. Poole, Jr., Reason Foundation, “ATC Reform News,” Issue 133, May 2016. See:

many other ANSPs and regulators look to for guidance, the FAA can influence the adoption curve for new technologies and practices. The FAA's strong embrace of ADS-B has, at a minimum, accelerated the acceptance of that technology among ANSPs and equipment manufacturers. FAA inaction on space-based ADS-B could have the opposite effect.

Finally, by providing seamless, global surveillance of air traffic, space-based ADS-B could facilitate fundamental changes in the current, national approach to the provision of ATC services. For example, in 2014, at a gathering of the world's ANSPs, the CEO of Ryanair, Michael O'Leary, challenged this approach. As reported by Andrew Charlton of Aviation Advocacy, O'Leary asked: "Why can't I go to DFS [the German ANSP] and say 'I'm Ryanair. This is all my flying. Control me.?" (*Aviation Intelligence Reporter*, November 2016.) Armed with the global air picture that space-based ADS-B provides, ANSPs could conceivably compete as well as collaborate in the same airspace. This is yet another way in which space-based ADS-B could have a transformative effect on air traffic management and the aviation sector more broadly.

H. AIR TRAFFIC SURVEILLANCE AND NATIONAL SECURITY

From a national security perspective, the current, global approach to ATC surveillance is lacking in several respects that space-based ADS-B is well suited to address.

- The Department of Defense (DoD) is a major user of the global ATC system. For example, DoD's transportation fleet (Air Mobility) is one of the largest "airlines" in the world. Currently, if a U.S. military plane goes down in the ocean, just as with a civilian plane, its precise whereabouts may be unknown.
- There is currently no way for DoD and U.S. intelligence agencies to monitor global traffic flows in real time; nor does the data exist to allow for historical analysis—e.g., to identify patterns.
- In remote locations such as the Arctic, where DoD currently has some form of ATC responsibility, monitoring can be difficult with the current technology.

<https://mail.google.com/mail/u/0/?tab=wm#search/bobp%40reason.org/154c4261df2f5e48>. Other, less drastic scenarios are easy to imagine. Bermuda could choose to have NAV CANADA manage its enroute airspace once space-based ADS-B is operational, allowing Bermuda to avoid the disruption that occurs when the FAA takes the country's single radar offline for repair. Bermuda has in the past expressed a desire to assume the management of its own airspace from the FAA. Similarly, the Bahamas has indicated that it wants to take a more active role in the management of its airspace, a function the FAA now performs. See: <http://bernews.com/2015/02/department-airport-operation-airspace-initiative/>. See also: http://www.thenassaeguardian.com/index.php?option=com_content&id=46217:us-and-bahamas-talk-airspace-management&Itemid=2. The advantage of having the FAA provide air navigation services in Bermudan and Bahamian airspace is that it creates a large area in the Atlantic Ocean with seamless ATC control, which facilitates efficiency and safety.

- When the U.S. military goes into hostile territory and destroys the enemy’s air traffic and military radar infrastructure—one of the first steps taken in a conflict—the military then has to land its own aircraft with limited surveillance resources. Although the military uses deployable radar platforms for this purpose, it may distract from the primary mission of these platforms—namely, combat air control.
- Recent experience reinforces the need to restore basic services following a conflict. Civil aviation is a key basic service. Surveillance is critical to supporting safe and reliable joint civil-military aviation during critical post-conflict restoration and stabilization efforts.

Space-based ADS-B offers other potential benefits for national security and homeland defense. By making real-time surveillance affordable in large parts of Africa and South America that currently lack radar coverage, space-based ADS-B can facilitate joint training exercises and other forms of military cooperation between the United States and its allies in the developing world. Within U.S. airspace, space-based ADS-B can provide DoD with another source of information on transponder-equipped aircraft that enter the Air Defense Identification Zone (ADIZ) without having announced themselves. By allowing the military to better identify “false positives,” this information would reduce the resources devoted to scrambling fighter jets.

DoD was the “anchor tenant” for Iridium’s satellite communications service when it was launched in 1998. Among other things, DoD built its own, secure gateway, or teleport, in Hawaii, and it developed a secure Iridium handset. In 2000, after Iridium went bankrupt and its parent company, Motorola, sought to de-orbit the constellation, DoD was the key to making it possible for private investors to reorganize the company and continue to operate the satellite system.

Two unique features of Iridium’s commercial satellite communications system led DoD to become—and remain—a major customer: Iridium’s coverage of the entire globe, including polar regions; and its cross-linked architecture—calls are passed securely among satellites without being relayed to the ground—which ensures that an enemy cannot trace, or “geolocate,” a call. Because it uses the Iridium constellation, Aireon’s service will likewise have the complete global coverage that is so important to the military. And while geolocation is not a concern when an aircraft transmits its GPS position, the Iridium architecture allows users to access signals with only minimal ground-based telecommunications infrastructure. The architecture also ensures a low latency period, so that the ANSP is receiving information in what amounts to real time.

IV. Estimates of Fuel Savings in Oceanic Airspace: Disparate Findings

Various stakeholders have sought to quantify the benefits of space-based ADS-B relative to the alternative of ADS-C. The focus has been on what is arguably the biggest potential source of such benefits: reductions in fuel burn and the associated GHG emissions in oceanic airspace. Although all of the studies have found some level of benefits, there is a significant disparity between the results obtained by aircraft operators and non-U.S. ANSPs, on the one hand, and most of the (preliminary) results obtained by the FAA, on the other.

A. ESTIMATED BENEFITS: U.S. OCEANIC AIRSPACE

Two detailed simulations, one by Virginia Tech in collaboration with the FAA's NextGen Office and the other by ISA with support from Aireon, look at the estimated benefits from space-based ADS-B in U.S.-controlled airspace in the Atlantic and the Pacific regions. The FAA study is ongoing and hence the results shown below are preliminary.

The FAA/Virginia Tech analysis seeks to quantify the impact on fuel burn associated with a reduction in separation minima in U.S. oceanic airspace from 30/30 NM, the current, FANS/ADS-C-enabled standard (i.e., the base case), to 15/15 NM, the likely starting minima with space-based ADS-B (i.e., the test case). Specifically, the model calculates how the reduction in separation minima affects the ability of an aircraft to fly at its preferred altitude. The FAA/Virginia Tech analysis assumes that the FAA's FANS requirement would remain in place, which means that non-FANS aircraft would have to maintain separations of 80/80 NM. In addition, the FAA/Virginia Tech analysis assumes that existing route and speed profiles would remain constant.

ISA uses the same 30/30 NM baseline as FAA/Virginia Tech and, in the first of four scenarios, it adopts assumptions similar to those of FAA/Virginia Tech in an effort to replicate their results. In the second scenario, ISA allows non-FANS aircraft to take advantage of somewhat reduced oceanic separation (ROS) minima (60/25 NM). In the third and fourth scenarios, ISA further relaxes the FAA assumptions regarding route and speed profiles, respectively. Specifically, in Scenario #3, operators are allowed to fly Great Circle Routes (GCRs).⁵² In Scenario #4, operators are allowed to vary their speed so as to improve the tradeoff between fuel consumption and flight times.

⁵² ISA uses GCRs as a basis for estimating the benefits from flying optimal routes. GCRs are designed to minimize the distance an aircraft flies. They are distinct from wind-optimal routes, which are designed to minimize travel time. For the cruise phase of a flight, fuel burn is proportional to time flown; thus a wind-optimal route is also the route that requires the least fuel use. James P. Donley, "Fuel Savings of Optimally Routed Flights," *Journal of Air Traffic Control*, Summer 2012. See: https://www.researchgate.net/publication/265144535_Fuel_Savings_of_Optimally_Routed_Flights. ISA is carrying out additional analysis using, among other things, wind-optimized User Preferred Routes

Tables 1 and 2 show the results of the FAA/Virginia Tech and ISA studies for the Atlantic and Pacific regions, respectively.⁵³ The first thing to note is that the FAA/Virginia Tech estimate of fuel savings from space-based ADS-B in U.S. oceanic airspace is quite small. In 2025, the fuel savings is only 28 kg per flight for operations in the Atlantic and 89 kg per flight for operations in the Pacific. That corresponds to a savings of about \$30 per Atlantic flight and less than \$100 per Pacific flight.⁵⁴ ISA’s Scenario #1 results are roughly in line with those of FAA/Virginia Tech, at least for the Pacific.

Table 1: Fuel Savings/Flight from Space-Based ADS-B in U.S. Atlantic Airspace (kg)

	2020	2025
FAA/VA Tech	19	28
ISA		
Scenario 1: Preferred Altitudes	38	71
Scenario 2: ROS without FANS	129	125
Scenario 3: Plus GCRs	319	338
Scenario 4: Plus Variable Speed	446	467

instead of GCRs. The ISA model incorporates daily average wind grids for all modelled days. Email exchange with Vitaly Guzhva, Jan. 30, 2017.

⁵³ The Virginia Tech/FAA results are from: FAA (NextGen Office), “Reduced Oceanic Separation: Initial Investment Decision Benefits Analysis,” Draft Slide Presentation, February 18, 2016. The ISA results are from: ISA, “Space-Based ADS-B in US: Operational Analysis of Reduced Separation in FAA-Controlled Airspace,” Slide Presentation, August 29, 2016.

⁵⁴ As its source for jet fuel prices in this analysis, the FAA’s NextGen Office says only that it uses “FAA 2015 Aerospace Forecasts.” According to Table 18 of that document (“U.S. Mainline Air Carrier Forecast Assumptions: Jet Fuel Prices”), the per-gallon cost of fuel will be \$2.5651 in 2020 and \$3.2967 in 2025 (FY 2014 dollars). The relationship between gallons (a measure of volume) and kilograms (a measure of weight) depends on the temperature of the fuel; if we assume a temperature of 15 degrees Celsius (59 degrees Fahrenheit), one gallon of Jet A fuel weighs 3.066 kg. Thus, if the price of fuel is \$2.5651 per gallon, the price per kg will be $\$2.5651/3.066$, or \$0.8366. If the price is \$3.2967 per gallon, the price per kg will be \$1.0426.

Table 2: Fuel Savings/Flight from Space-Based ADS-B in U.S. Pacific Airspace (kg)

	2020	2025
FAA/VA Tech	66	89
ISA		
Scenario 1: Preferred Altitudes	59	108
Scenario 2: ROS without FANS	341	313
Scenario 3: Plus GCRs	703	686
Scenario 4: Plus Variable Speed	916	899

The second main finding from Tables 1 and 2 is that ISA’s estimated fuel savings are significantly higher under the second, third and fourth scenarios, which relax assumptions that are built into the first scenario. Specifically, when the FAA’s FANS requirement is relaxed (Scenario #2), the fuel savings from space-based ADS-B in 2025 are nearly two to three times greater than under Scenario #1, and when, in addition, aircraft are allowed to fly Great Circle Routes (Scenario #3), fuel savings are around five to six times greater than under Scenario #1. Allowing for variable speed operations increases fuel savings yet more.

In short, the research done to date indicates that the benefits from space-based ADS-B in U.S. oceanic airspace are highly sensitive to the concept of operations used as the basis for the analysis. As one analyst put it, “It’s all about the CONOPS.”

B. ESTIMATED BENEFITS: NORTH ATLANTIC AIRSPACE

Various stakeholders have also calculated the potential fuel savings from space-based ADS-B in the North Atlantic, where the business case for satellite surveillance is generally thought to be the strongest, and the results are similarly divergent. The studies use a range of methodologies and thus are not precisely comparable. Nevertheless, we can highlight some key findings and patterns.

1. Analysis by NAV CANADA, NATS and Operators

NAV CANADA and NATS have issued the results of their own analyses. NAV CANADA used as its base case the current separation minima on the NAT (including RLongSM and RLatSM on the core tracks); as its ADS-B test case, it used a 15 NM longitudinal and 30 NM lateral separation (note that this is a more conservative lateral separation standard than the 15 NM standard that NAV CANADA and NATS are proposing to apply on the core OTS tracks beginning in 2018). NAV CANADA estimated that in its first year of operation (2018), space-based ADS-B will lead to a per-

flight fuel savings of 365 kg (802 pounds).⁵⁵ The NATS estimate is somewhat lower: 262-346 kg (576-761 pounds).⁵⁶

Individual operators that fly in the North Atlantic have done their own analyses and/or provided data to NAV CANADA and NATS. The operators' estimates of the per-flight fuel savings range from 300 to 1,296 kg (713 to 2,851 pounds).⁵⁷ The wide variation in these estimates may be due to the use of different research methodologies. In addition, operators have different business models, and some operators are more burdened than others by procedural controls in the North Atlantic. For example, FedEx operates about ten flights each weekday on the North Atlantic using Boeing 777s and MD 11s, and most of its planes fly against the dominant traffic flows. As a result, FedEx aircraft receive less wind-efficient flight levels. FedEx has estimated that its Boeing 777s would burn 4.8 percent less fuel if they could vary their speed and change altitude without restriction.⁵⁸

2. FAA-Supported Analysis

The FAA (ATO's Systems Operations Services Office) is working with Virginia Tech to model fuel savings from space-based ADS-B in the NAT as part of a study that the FAA and NAV CANADA are leading for ICAO's North Atlantic Systems Planning Group. As with their study of U.S. oceanic airspace, the FAA/Virginia Tech analysis of the NAT finds only limited benefits: 149 kg (329 pounds) of fuel savings per flight, according to a preliminary estimate presented in 2015.⁵⁹

Moreover, as with the analysis of U.S. airspace, the gap between the FAA/Virginia Tech results and those of the other stakeholders appears to largely reflect their differing CONOPS assumptions. Most important, whereas the FAA holds flight paths constant, some of the NAV CANADA-NATS-operator models allow operators to "straighten their routes." Although those models do not go so far as to allow operators to fly optimal profiles, they do give operators more flexibility to find the most fuel-efficient flight path (the amount of flexibility varies by study). For example, under some of the scenarios modeled, an operator can choose to join the OTS at a midpoint and fly only those portions that line up with its preferred path (currently it can enter and exit only at the endpoints).

The FAA is also supporting research at the Massachusetts Institute of Technology (MIT) on the potential benefits of space-based ADS-B in the North Atlantic. The MIT researchers are using a

⁵⁵ NAV CANADA, "Satellite Based ADS-B," December 2013.

⁵⁶ NAV CANADA and NATS, "Shanwick & Gander Space Based ADS-B Economic Workshop," Slide Presentation, April 21, 2016, p. 13.

⁵⁷ NAV CANADA and NATS, *op. cit.*, p. 14.

⁵⁸ "Impact of Space-Based ADS-B Surveillance and Reduced Oceanic Separation [on] U.S. Aviation Stakeholders," Slide Presentation, April 6, 2016.

⁵⁹ Virginia Tech, "Modeling Oceanic Traffic in the Era of Satellite-Based ADS-B Surveillance Technology," NEXTOR2 Research Symposium, Washington, DC, May 28, 2015, p. 24.

different approach in order to measure the impact of variables that the FAA/Virginia Tech analysis does not examine. MIT's results, which are preliminary, can be summarized as follows:⁶⁰

- When track assignment is fixed but operators are allowed to fly at their optimal speed and altitude, including unlimited step climbs, fuel burn is reduced by 2.83 percent, or 1164 pounds (529 kg) per flight, on average. For the poorest performing quartile of flights, the average fuel savings is 3.96 percent, or 1422 pounds (645 kg). (These calculations ignore the potential for conflicts.)
- Under the current longitudinal separation standard (10 minutes), 45 percent of flights will be unable to fly that trajectory (optimal speed and altitude) because of conflicts. When the separation standard is reduced to 15 NM, that figure drops to 21 percent, and with a 5 NM separation standard, it drops to 14 percent.
- These figures indicate that “reducing minimum [longitudinal] separation would have significant benefit potential.” However, they also imply that more than half of all flights should be able to fly their optimal speed and altitude today.⁶¹
- When altitude and speed are fixed at current levels but operators receive their optimal track assignment, the average reduction in fuel burn is 3.20 percent for all flights and 4.51 percent for the poorest performing quartile of flights.
- Although 12 percent of flights are already operating on their optimal track, 88 percent are not (hence the significant potential for reduced fuel burn).
- With reduced lateral separation standards, more flights could realize the savings from optimal track assignment. In addition, more flights would be able to fly at their optimal speed and altitude.
- Interviews with operators suggest that the greatest benefits (fuel savings, reduced block time) would come from the ability to fly direct routes. However, direct routing would also impose significant costs on ANSPs, because of the new procedures, staffing and training that would be required.

⁶⁰ R. John Hansman, “Evaluation of Potential Benefits of Flexibility and Predictability from Satellite Based ADS-B Surveillance,” MIT International Center for Air Transportation (ICAT), Slide Presentation, NEXTOR 20th Anniversary Workshop, September 29-30, 2016, Adelphi, MD. For the underlying analysis of optimal speed and tracking, see Tran and Hansman, *op. cit.*

⁶¹ The researchers do not look at why operators are not taking advantage of flexibility that this result implies they already have. One possible explanation is that operators do not request step climbs and changes in speed because many if not most such requests have traditionally been denied. See, for example, Reddy and DeLaurentis, *op. cit.*, pp. 23-24.

V. Recommendations for the FAA’s Analysis of Space-Based ADS-B

An economic analysis of space-based ADS-B poses a number of challenging issues. In this section, we offer six recommendations for the FAA’s consideration on how to approach this task.

A. EXPAND THE CONOPS

At a recent ATC conference, several participants sparred over whether space-based ADS-B is a “transformative technology.” One participant cited a recent report by CANSO, which says that “space-based ADS-B has the potential to revolutionise air traffic services (ATS) surveillance in the aviation industry.”⁶² An FAA official countered that space-based ADS-B is not the Internet—merely a way to space planes more closely together.

This is an important disagreement. Although only time will tell whether space-based ADS-B is truly “transformative,” the technology will enable significant changes in air traffic control, in the view of most industry experts. The fact that key potential changes are not reflected in the FAA’s analysis of space-based ADS-B will limit the estimate of potential benefits.

To elaborate, as described in Section IV, the CONOPS that the FAA is using as the basis for its analysis of space-based ADS-B (test-case CONOPS) is heavily grounded in current practice and incorporates only incremental changes in existing procedures.⁶³ Such an approach seems self-defeating: current air traffic management procedures are designed to work within the significant limitations of existing surveillance and tracking technologies—limitations that space-based ADS-B lessens or removes altogether. Unless it considers the new operational approaches that this technology makes possible, the FAA is destined to undervalue the benefits of space-based ADS-B.

To be sure, this is not a simple endeavor. The evaluation of a technology that represents a step-change improvement in current practice poses challenges that test the limits of the quantitative methods typically employed to evaluate technologies that offer only incremental improvements. Almost by definition, such a technology creates new capabilities. These new capabilities may be unfamiliar to those likely to use them, making it difficult to establish their value. A technology that offers a step-change improvement can also bring about major changes in behavior and large shifts in related markets. Such shifts can include changes in where these markets reach their equilibria, with concomitant changes in the quantities consumed, prices paid and costs incurred. The possibility of such changes reduces the relevance of price and cost parameters drawn from current market conditions to the technology evaluation process.

⁶² CANSO, *op. cit.*, p. 6.

⁶³ In this section, our critique of the FAA refers to the NextGen/Virginia Tech analysis of spaced-based ADS-B in U.S. oceanic airspace. Our comments may not reflect changes to their methodology that have been made since we met with the FAA analysts in the first half 2016.

Recognizing the challenges, several changes in the FAA’s test-case CONOPS seem merited. First, the analysis should look at the benefits of space-based ADS-B both with and without the FANS requirement. The notion that, in a world of space-based ADS-B, aircraft must still equip with FANS to enjoy more advantageous oceanic spacing is controversial for the reasons discussed in Section III. Both the EU and ICAO are looking at exemptions to such a requirement. Although we are not qualified to evaluate fully the arguments for and against the requirement itself, we believe there is ample justification for including a no-FANS-requirement option in the test-case CONOPS.

Second, the analysis should include changes in oceanic procedures in the test-case CONOPS, including variable speed operations and more optimal routing. Variable speed operations are a component of the CONOPS that NAV CANADA and NATS have proposed for space-based ADS-B in the North Atlantic. Although Great Circle Routes and direct routing “are not in any ANSP’s CONOPS” (the FAA’s rationale for not quantifying their benefits), more direct routing includes a range of improvements that ANSPs will likely introduce incrementally and over time.

B. ACCOUNT FOR THE FULL RANGE OF POTENTIAL BENEFITS

The FAA analysis focuses principally on the impact of reduced separation standards on fuel burn in oceanic airspace. However, in Section III, we identified a range of additional benefits that could potentially flow from a decision by the FAA to adopt space-based ADS-B, and a comprehensive evaluation should account appropriately for all of them. Specifically, the FAA should:

1. Incorporate Reductions in Bottleneck-Related Delays in Adjacent and Non-Adjacent Regions

In Section III, we looked at the problems that can arise at the “seams” between airspace regions with different separation standards, where the ATC system has to do the equivalent of funneling automobiles from an interstate highway to a country road. We identified several distinct scenarios in which such a bottleneck can adversely affect air traffic “upstream.” As we discussed, the introduction of space-based ADS-B can potentially reduce bottleneck-related delays by, in effect, enlarging the funnel.

The FAA’s analysis—which simulates (existing) traffic in U.S. oceanic airspace—neglects some if not all of the effects of bottleneck delays on upstream regions. Insofar as the FAA’s approach assumes away interaction effects with adjacent and non-adjacent regions, it may understate the potential benefits of space-based ADS-B. Nor does the FAA’s analysis take into account whether neighboring ANSPs are taking advantage of space-based ADS-B—although the FAA may be trying to address this shortcoming. This is a critical issue because the benefits of space-based ADS-B depend heavily on interactions with other ANSPs, and uneven adoption by neighboring ANSPs can create new bottlenecks much like the ones that already exist.

We appreciate the analytical challenges that would confront efforts to model the complex interactions embodied in our bottleneck scenarios, and we recognize the need for simplifying assumptions that reduce the analysis to manageable proportions while preserving the ability to

answer questions of primary interest. Thus, it may be necessary and appropriate for the FAA to focus primarily on the benefits of space-based ADS-B in the directly affected oceanic airspace. However, the FAA analysis should not assume that these secondary benefits do not exist simply because they have not been modeled in a rigorous way.

Note that the analysis of bottleneck delays turns in part on the treatment of the FANS requirement. For example, narrow-body aircraft flying to the Caribbean exacerbate congestion in New York, because most of them are not FANS-equipped and thus must be spaced 80 NM apart. The impact of space-based ADS-B on this type of bottleneck will be far greater if the test-case CONOPS allows non-FANS aircraft to take advantage of reduced oceanic separations.

2. Take into Account Opportunities to Use Oceanic Airspace to Relieve Terrestrial Delays

The size of procedural separations also limits the use of oceanic airspace to relieve terrestrial delays. By reducing the separation minima in oceanic airspace (and the terrestrial-oceanic differential), space-based ADS-B could make it easier for the FAA to implement oceanic diversion as a response to convective weather and other disruptions to traffic flow in radar-controlled airspace.

It is unclear if the FAA plans to measure this potential benefit of space-based ADS-B. Granted, oceanic diversion may be even more challenging to analyze than reductions in bottleneck delays: it deals with a foregone opportunity (use of oceanic airspace to reduce terrestrial delays), and most of the delays are due to convective weather. The FAA's airspace simulations reflect traffic patterns on a sample of 16 days. If that sample does not include days in which the relevant inclement weather occurred, then the FAA's modeling efforts would not be able to address this issue. In addition, an assessment of this scenario would require an analysis of potential interactions between terrestrial and adjacent oceanic airspaces, which as noted earlier, the FAA modeling efforts currently do not appear to address. However, given the importance of oceanic diversion—some industry experts see it as the most significant opportunity for satellite surveillance to improve flow control in the NAS—the FAA should evaluate it qualitatively if not quantitatively.

3. Consider Other Potential Benefits

The FAA should consider other potential benefits as well. In Section III, we identified a number of non-fuel-related efficiencies that operators could realize as a result of having access to additional airspace, including: improved schedule predictability, the ability to schedule longer flights, and increased access to polar routes. We noted the potential for more direct routing to facilitate service in long-haul point-to-point markets, with possible implications for long-haul competition more broadly. Additional benefits that we identified in Section III include: allowing some operators to avoid the cost of FANS; reducing the investment the FAA needs to make in its ground-based ADS-B system, and strengthening that system by filling gaps and providing a layer of redundancy; facilitating more rapid location of aircraft that are lost or in distress; strengthening the FAA's global leadership role and facilitating information sharing and collaboration among ANSPs at a regional and international level; and addressing U.S. national security and intelligence needs.

To be sure, many of these benefits would be difficult to analyze with the same degree of rigor that the FAA brings to its evaluation of the impact of reduced separation standards on fuel burn. For example, although search and rescue operations can be extremely costly, fortunately they occur very infrequently, and each operation depends on unique circumstances. These facts make it challenging to estimate the value of a reduction in search and rescue costs. Similarly, benefits of international harmonization, FAA leadership in aviation safety, and national security are real and important, but they are difficult to reduce to dollars and cents.

The fact that these effects are difficult to measure is not a justification for ignoring them, however. Although not all claimed benefits may stand up to scrutiny, the test for whether a potential benefit is both real and quantitatively important ought not be the ability to measure it using airspace modeling and simulation tools. It would be more helpful if the FAA were to acknowledge the potential for these additional benefits, evaluate the quality of the information regarding their existence, and if possible provide even rough order-of-magnitude estimates of their impacts.

C. ACCOUNT FOR ALL AFFECTED PARTIES

Precisely because the introduction of space-based ADS-B will provide a range of benefits, multiple parties will be affected. For example, a decision by the FAA to support space-based ADS-B would reinforce current trends toward adoption of ADS-B as a global standard, and the emergence of such a de facto global standard would support interoperability and generate substantial efficiencies for aircraft manufacturers, aircraft operators and ANSPs around the world. To take another example, FAA adoption of space-based ADS-B would benefit DoD and U.S. intelligence agencies directly—through the improved efficiency and safety of U.S. oceanic airspace—and indirectly—by making it more likely that foreign ANSPs will subscribe to space-based ADS-B.

An economic analysis of space-based ADS-B should take into account the impact of the technology on *all* affected parties. The FAA has framed its task as one of evaluating the “Business Case” for space-based ADS-B—a term that typically refers to an investment analysis by a private sector actor that considers only its own costs and potential returns. By contrast, a “Cost-Benefit Analysis” attempts to consider the gains and losses to all stakeholders with “standing,” regardless of where the gains and losses occur, and to determine whether society as a whole would be better off if the investment in question were made.

While we are confident that the FAA will adopt a broader perspective than that of a purely private sector actor, the analysis that it has conducted to date adopts a fairly narrow perspective, looking largely at the impact on U.S. operators. Although that is the obvious place to start, it stops short of recognizing that the decision that the FAA makes regarding space-based ADS-B will have far reaching consequences; in addition to U.S. carriers, it will affect U.S. aerospace manufacturers and other parts of the U.S. aviation sector, multiple federal agencies, neighboring ANSPs, and global aviation interests generally.

D. CONSIDER COSTS AS WELL AS BENEFITS

The analyses discussed in Section IV, which compare space-based ADS-B with ADS-C, are striking for their near exclusive focus on benefits. With the exception of MIT's ongoing analysis of the North Atlantic airspace, the cost side of the equation has been largely overlooked in this debate. Although they may be hard to estimate, costs are a key consideration.

1. Consider the Relative Costs of ADS-C and Space-Based ADS-B

First, the FAA should compare the costs of ADS-C and space-based ADS-B under the same scenarios for which it is measuring the benefits. The FAA analysis described in Section IV uses as its only ADS-C scenario the base case, with a 30/30 NM oceanic separation and a corresponding update interval of (we assume) about 14 minutes. However, the RTCA Enhanced Surveillance Task Group is looking at a broader range of options, including some in which ADS-C supports smaller oceanic separations based on a higher rate of position reporting and a lower latency period (the feasibility of some of these options has not been demonstrated). These reduced oceanic separation scenarios also assume a higher rate of FANS equipage than the one used in the base case.

By definition, the FAA's base case entails no incremental costs for operators or the FAA.⁶⁴ By contrast, the ADS-C scenarios that assume reduced separation standards (less than 30/30 NM) do entail incremental costs, and they fall largely on operators. These costs include equipage and operating costs (pilot training and communications charges) for aircraft that are currently not equipped with FANS; similar operating costs for aircraft that have installed but not activated FANS; and higher communications charges (for more frequent transmission of position reports) for aircraft already using FANS.

By contrast, space-based ADS-B would impose no equipage or operating costs on aircraft operators, because they are required to equip with and use ADS-B Out by 2020 regardless of the FAA's decision on space-based ADS-B. However, the FAA would incur an annual subscription charge for space-based ADS-B services, much as it does for ADS-B services. This charge likely would be in the tens of millions of dollars a year, the exact amount depending on the geographic scope of the coverage.

Finally, under any scenario that includes reduced oceanic separation minima (i.e., less than 30/30 NM)—whether with space-based ADS-B or ADS-C—the FAA will incur one-time implementation costs, including procedure development, software upgrades and controller training. According to former FAA officials, these costs might be somewhat lower for ADS-C than for space-based ADS-B but they would not be significantly lower.

⁶⁴ This is true only if the FAA's assumed rates of equipage for ADS-C/FANS are accurate. It is our understanding that, at one point, the FAA was treating aircraft that had installed but not activated FANS as "FANS-equipped," and we do not know whether that error was corrected. The effect of an artificially high estimate of FANS equipage would be to overstate the benefits in the base case (30/30 NM) and thus to understate the incremental benefits in the test case (15/15 NM).

2. Put the Absolute Costs of Space-Based ADS-B in Perspective

In addition to looking at the relative costs of ADS-C and space-based ADS-B, the FAA should put the absolute costs of space-based ADS-B in perspective. To be sure, the estimated annual subscription charge (tens of millions of dollars a year) is not a trivial amount of money. Moreover, the FAA has competing budget priorities, and its budget is likely to remain flat. But neither is the estimated annual charge a budget buster, in the context of the FAA's \$2.8 billion annual budget for facilities and equipment.

With respect to the one-time costs that the FAA would incur under any scenario that includes a reduced oceanic separation standard, it is important to recognize that oceanic operations represent a tiny share of the FAA's budget. Only about 250 of the FAA's 15,000 controllers handle oceanic operations, and oceanic's capital and operating costs account for just over one percent of the FAA's budget.⁶⁵ Thus, even a significant increase in the FAA's oceanic budget (which no one is projecting) would be small as measured in absolute dollars.

E. FOCUS ON THE MAGNITUDE, NOT THE INCIDENCE, OF COSTS AND BENEFITS

Because of the way it is currently funded, the FAA cannot pass on the costs of a new service such as space-based ADS-B directly to operators, as other ANSPs plan to do.⁶⁶ Although operators pay indirectly for most of the FAA's budget, in the form of ticket taxes and other taxes collected from passengers, the FAA's budget has been flat for five years and that trend is likely to continue. Under this funding arrangement, the FAA will directly bear most of the costs of space-based ADS-B whereas operators will enjoy most of the benefits.

This disparity may be particularly large when it comes to the use of space-based ADS-B to provide more direct routing. The analyses by ISA and MIT show that the ability to fly Great Circle Routes and take advantage of more direct routing would yield substantial benefits to operators. However, as noted earlier, MIT researchers believe that direct routing would also impose significant costs on ANSPs, because of the procedures, staffing and training that would be required.

The disparity between who pays and who benefits may be relevant to the budgetary "politics" of the decision that the FAA faces regarding space-based ADS-B, but it should not affect the economic

⁶⁵ See Robert W. Poole, Jr., Reason Foundation, "ATC Reform News," No. 111, March 19, 2014. According to an FAA report, in FY 2013, oceanic services accounted for less than four percent of the combined cost of enroute and oceanic services. FAA, Office of Financial Analysis, op. cit., Table 1, "Total Cost of Enroute and Oceanic Services" (FY 2013).

⁶⁶ For a discussion of the problems with the current approach to financing air traffic control, see "Options for FAA Air Traffic Control Reform," Testimony of Dorothy Robyn, House Committee on Transportation & Infrastructure, Subcommittee on Aviation, March 24, 2015. See also, Dorothy Robyn, "Air Support: Creating a Safer and More Reliable Air Traffic Control System," Hamilton Project, Brookings Institution, Discussion Paper 2008-11, July 2008 (with support from Kevin Neels).

analysis. Generally speaking, a cost-benefit analysis measures the balance of gains and losses of a proposed project; whether or not a project has a positive benefit is not affected by the incidence of those gains and losses. This approach reflects a fundamental principle of economics: if the overall net benefits are positive, it should be possible to devise an institutional structure and payment scheme that leaves all parties better off.⁶⁷ Potential options include: shifting to user-fee funding of the FAA; having aircraft operators pay for space-based ADS-B directly even though the service (i.e., data) would be delivered to the FAA; and having other federal agencies that would benefit from the service share the cost with the FAA.

Stated differently, the economic analysis should focus on economic efficiency (the size of the pie), while treating issues of stakeholder equity (the division of the pie) separately. The FAA has followed that approach with respect to ground-based ADS-B, where the tables are arguably turned. Although operators bear most of the direct burden of ADS-B in the form of equipage costs, the FAA will reap the majority of the direct benefits in the form of reduced radar operation and maintenance costs. Recognizing this disparity in the incidence of costs and benefits, the FAA has made use of financial subsidies to incentivize ADS-B equipage.⁶⁸

The net-benefit principle is no less relevant to the FAA's analysis of space-based ADS-B. Granted, the agency cannot permanently disregard the issue of incidence, any more than it has with ADS-B. However, for purposes of its economic analysis of space-based ADS-B, the FAA should ignore the incidence of costs and benefits and identify the course forward that maximizes overall benefits.

F. HEED THE LESSONS OF IRIDIUM, 2000

FAA officials analyzing space-based ADS-B should understand the history of the Iridium satellite system and the federal government's role in preserving it. When Iridium filed for bankruptcy in 1999, less than a year after it began service, the parent company, Motorola, sought to destroy the constellation so as to avoid future liability. The government eventually agreed to indemnify Motorola, making it possible for private investors to acquire Iridium and reorganize it as the company that operates today. However, that intervention came only after months of behind-the-

⁶⁷ See our recent blog post, "Warranted Surveillance: SpaceX Satellite Launch Holds Promise for Air Traffic Control." <https://www.brookings.edu/blog/fixgov/2017/01/17/warranted-surveillance-spacex-satellite-launch-holds-promise-for-air-traffic-control/>.

⁶⁸ For an analysis of the policy problem, see Joseph Post, et al., "Financial Incentives for NextGen Avionics: ADS-B Case Study," Office of Systems Analysis, FAA, 2011. Paper presented at the Ninth USA/Europe Air Traffic Management Research and Development Seminar. See: <http://www.atmseminar.org/seminarcontent/seminar9/papers/43-post-final-paper-3-31-11.pdf>. See also Karen Marais and Annalisa L. Weigel, "Encouraging and Ensuring Successful Technology Transition in Civil Aviation," Working Paper Series, MIT, Engineering Systems Division, ESD-WP-2006-07, March 2006.

scenes efforts by a handful of people in the White House, the Pentagon, and the Federal Communications Commission who faced strong bureaucratic inertia and opposition.⁶⁹

Iridium satellite phones, which had won kudos from deployed troops even before the bankruptcy, have continued to demonstrate their worth. Since 2001, they have saved tens of thousands of lives and proved indispensable in war zones, disaster areas, and for hundreds of commercial and scientific uses in parts of the globe that are otherwise inaccessible. They were the only phones that worked in New York City on 9/11 and in New Orleans after Hurricane Katrina. And following the 2010 earthquake in Haiti, when 50 organizations arrived with their Iridium phones, it was clear that Iridium had become standard operating equipment for disaster relief workers worldwide.⁷⁰ Iridium's "netted" phones, a 2009 innovation that allows every soldier or Marine in a unit to communicate in real-time with every other soldier or Marine in that unit, have been called the most dramatic advance in combat communications since Motorola's invention of the Walkie-Talkie during World War II.⁷¹

Although the decision facing the FAA today is very different from the one the federal government faced in 2000, there are relevant lessons. The major one is that it is difficult to predict the value of new technology and that those charged with doing so should approach the task with a great deal of humility. In retrospect, even the federal officials who fought aggressively to save Iridium were shortsighted: they acted largely out of a belief that it was foolish to destroy a valuable asset, not because they foresaw the many ways in which it would later prove indispensable.

Although the government reached the right conclusion, the internal debate about Iridium was flawed. The discussion focused on the downside risk to the federal government (liability), which was measurable, as opposed to the upside mission potential (e.g., improved catastrophe response), which was not. Unimaginable circumstances like 9/11 are, well, unimaginable.

Moreover, there was an implicit assumption that the (already valuable) technology would remain fixed, with little thought given to future innovations such as netted phones. And although it seems obvious now that a LEO system that covered every inch of the planet could have value for aviation

⁶⁹ One of the authors of this report (Robyn), as a member of President Clinton's White House economic team, was among the small group of people who fought successfully to block Motorola from destroying Iridium. Although the federal government's role in preserving Iridium was for many years a well-kept secret, it is recounted in a recently published book that chronicles the broader story of Iridium. See John Bloom, *Eccentric Orbits: the Iridium Story*, Atlantic Monthly Press, 2016. Bloom's account of the federal government's involvement in Iridium is based in part on 14,000 pages of documents that he obtained from the Clinton Presidential Library using the Freedom of Information Act. The *Wall Street Journal* named *Eccentric Orbits* one of the ten best non-fiction books of 2016.

⁷⁰ John Bloom, op. cit., pp. 427-453.

⁷¹ John Bloom, op. cit., p. 434. See also Barry Rosenberg, "Netted Iridium 'Radios' Prove Indispensable in Battlefield Test," *Defense Systems*, Jan. 21, 2010.

and air traffic control (and that potential market opportunity was uppermost in the mind of the lead investor in the bankrupt Iridium, a former airline executive), the federal government never connected those dots. In fact, the FAA, represented largely by its Office of Space Commercialization, was cool to the idea of indemnifying Motorola.⁷²

As Yogi Berra famously said, “It’s tough to make predictions, especially about the future.” Although the FAA has no choice but to “predict” the future of space-based ADS-B in the sense of estimating its costs and benefits, it should do so with humility—and a sense of history.

⁷² John Bloom, *op. cit.*, p. 400.

VI. Author Biographies

Dorothy Robyn is a public policy expert who writes and consults on transportation and infrastructure, telecommunications, and energy issues. From 2009 to 2014, as a member of the Obama Administration, she held senior management jobs at the Department of Defense and the General Services Administration. From 1993 to 2001, she was a Special Assistant to the President for Economic Policy on the staff of the White House National Economic Council, with responsibility for aviation, aerospace, and satellite telecommunications, among other issues. Dr. Robyn has been an assistant professor at Harvard's Kennedy School of Government; a Principal with The Brattle Group; and a Guest Scholar at the Brookings Institution. She has an MPP and Ph.D. in Public Policy from the University of California, Berkeley. She is the author of *Braking the Special Interests: Trucking Deregulation and the Politics of Policy Reform* (University of Chicago Press, 1987); *Toward an Evolutionary Regime for Spectrum Governance: Licensed or Unrestricted Entry* (Brookings Press, 2006) (with William J. Baumol); and *Making Waves: Alternative Paths to Flexible Use Spectrum* (The Aspen Institute, 2015). She has testified and written on reform of the U.S. air traffic control system, including a 2008 report for Brookings' Hamilton Project.

Kevin Neels is an economist who directs the Transportation Practice at The Brattle Group. He has more than 30 years of applied research and consulting experience in all segments of transportation, including airlines, air traffic management, aircraft manufacturing, freight and passenger rail, trucking, and postal delivery. Drawing on his expertise in competition, market structure, pricing, regulation, and public policy, Dr. Neels has addressed issues related to airport and airway system planning, airline competition policy, and congestion management. His clients have included airlines, trade associations, airport operators, equipment manufacturers and system integrators, and government agencies. He was a co-author of the 2010 FAA-sponsored report, "Total Delay Impact Study: A Comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States." Dr. Neels is a past Chairman of the Committee on Freight Transportation Economics and Regulation of the Transportation Research Board (TRB), an arm of the National Academy of Sciences. He is also a past member of the TRB Committee on Airline Economics and Forecasting and the Committee on Airport and Airway Capacity.

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