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# Autonomous Flight Rules Concept: User Implementation Costs and Strategies

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## **Preface**

This report was submitted in partial fulfillment of NIA Task Order Prime Contract NNL13AA00B, Subcontract T13-6500-CAE, with NASA Langley Research Center, Hampton, VA. The NASA Point of Contact for the task for which this report was generated is David J. Wing, Crew Systems and Aviation Operations Branch.

## Executive Summary

This study was undertaken to discover and document the costs that would likely be borne by several classes of airspace users to equip their aircraft, train their personnel and conduct flight operations using Autonomous Flight Rules (AFR).<sup>1</sup> AFR is a proposed advanced operating concept enabled primarily by airborne surveillance and an onboard automation system for traffic separation and conflict-free trajectory planning. AFR flights would be responsible for their own separation from all other aircraft and other hazards in the airspace but be free of most constraints imposed in the traditional Instrument Flight Rules (IFR) system, thus achieving unprecedented levels of flight efficiency and flexibility in their operations. In addition to estimating user costs for AFR, the study also examined the factors influencing transition strategies likely to be used, especially by those operators with large fleets of aircraft. The study assumed that AFR rules and procedures have already been established by the FAA and that means for certifying the required avionics and approving the operational procedures are in place. The Air Navigation Service Provider (ANSP) costs of implementing AFR are not part of this study. AFR was designed to minimize the impact on the ANSP in accommodating AFR aircraft, and so the primary expense is expected to be borne by the operators.

To collect the necessary information to conduct this analysis, the investigators supplemented their own extensive aviation backgrounds with information gathering meetings held with avionics manufacturers, airline representatives, fractional ownership companies, representatives of the General Aviation (GA) and Business Flying community and Unmanned Aircraft Systems (UAS) manufacturers. Many of these meetings were held in person, and the rest were conducted via conference call using WebEx briefing presentations. Using the information obtained from these meetings, two representative avionics architectures were constructed for each class of airspace user, based upon different safety case outcomes that would dictate the certification difficulty and cockpit integration complexity. Analysis of these architectures enabled estimates of avionics acquisition costs to be made. The meetings also provided insight into the installation issues which enabled the estimation of those costs, in addition to the equipment acquisition costs. Training, maintenance, and other operations costs were also examined during these meetings.

The four classes of airspace users considered in this study were airlines, fractional ownership operators, GA users, and UAS operators. Military operations other than UAS were not considered in this study but it is likely that those operations would benefit as much from AFR as the other user classes. Avionics systems incorporating airborne surveillance have been evolving in recent years from separate systems like the Traffic Alert and Collision Avoidance System (TCAS) to integrated surveillance platforms incorporating both active detection and Automatic Dependent Surveillance - Broadcast (ADS-B) IN technology. The term "hybrid surveillance" is used to describe the integrated surveillance function and it is usually physically contained in a TCAS/Transponder Surveillance Unit. The surveillance-based applications of ADS-B IN currently under development would also be hosted in this avionics system, and AFR was considered by the aviation community to be just an application of ADS-B IN. This software application (and possibly the hardware it resides on) might be called the Air Traffic Unit (ATU). Other cockpit systems would connect to the ATU, most in a "read only" mode, but the AFR outputs, which carry the importance of an Air Traffic Control (ATC) clearance, would go to the Multi-Function Display or Navigation Display, the cockpit audio system and the Multifunction Control Display Unit or other pilot control interface. Additionally, a data communications system, either broadband internet equipment or other data radio, would be used to send the near-term intent trajectory, including conflict resolutions, to the ground ATC system for information only. The necessary degree of independence of the surveillance systems and redundancy of the cockpit avionics was determined to be an output of the system safety study, which must be accomplished before these operations can take place. For each of the four airspace user classes, avionics architectures were constructed representing the best and worst case outcomes of the safety study, from an avionics cost standpoint.

The cost categories making up the total cost of AFR implementation are equipment acquisition, equipment installation, training, and operations and maintenance. The factors influencing these costs were considered for each user class, with the most important discriminator being the operating category, Part 91 of the Federal Aviation Regulations or Part 121 or 135. The expected requirements in each of the cost categories come primarily from this "airline" versus "GA" distinction. Acquisition was found to be the largest cost item followed by installation. In general, the older the existing avionics, the more expensive the installation. Training of pilots can be a substantial cost item, and as a result, all operators plan to use computer-based training techniques as they do when introducing other new systems to control these costs. Operations costs would include any necessary upgrades to the flight planning system to take advantage of the operational freedoms permitted by AFR, and any feedback mechanism the company might need to monitor the transition to the new procedures. Maintenance of the ATU and related new equipment was found to be a relatively small cost, often completely hidden in the routine maintenance of the parent surveillance unit.

Many factors must be considered when calculating the expected cost of AFR implementation by any specific operator. In this study, all the factors were listed for each user category with representative costs associated with them and the rationale for determining these costs. The cost estimating method is presented so that an operator can substitute his own numbers for each cost factor to arrive at an estimate of his own implementation cost. An example is provided in each user category for illustration of the cost estimation method. Some of the variables in operator's costs include whether they contract out or do their own installations, pay for training or have the pilots do it on their own time, etc. In the example calculations, these assumptions were described such as the existing equipment on the airplane when upgrading for AFR, who did the installation, how training was accomplished, and who did the maintenance. The template permits any operator to compute his/her own cost estimates. For the examples presented in this report, a summary of "typical" cost estimates on a per aircraft basis is given in the following table, with a range reflecting possible variation.

	<b>Airline</b>	<b>Fractional</b>	<b>GA</b>	<b>UAS</b>
<b>Total Costs</b>	\$200 to 600K	\$50 to 200K	\$10 to 50K	\$10 to 45K

Cost ranges reflect both the variation in needed equipment, in installation, and the certification requirements that are expected to vary the cost by a factor of two to three. The estimated user cost of implementing AFR is comparable to navigation system upgrades for all four airspace user classes and therefore generally within reach for most operators.

Estimating the costs of implementation provides only one half of the information needed for a business case decision on whether to implement AFR. The other half is the benefit to be derived from using the procedures. This study did not contain a quantitative assessment of these benefits but does include a description of the benefit mechanisms from which those with operations experience can obtain a feel for the magnitude of the benefits. AFR is strong in this area compared to other ADS-B IN applications since the first to equip gets all the benefits, without waiting for a "critical mass" of the user population to equip or for any substantive change to the supporting ground services. Most of the benefits from AFR operations are a result of exemption from flow management constraints that are artifacts of human-centered air traffic control, but would be unnecessary when using automated separation. While AFR flights would participate in destination airport traffic flow management, they would be exempt from departure fix restrictions, airspace-related ground delay programs, overhead slot restrictions, miles-in-trail at Center boundaries, en route severe weather re-routes, terminal area departure procedures, and ATC preferred routes. Of course, the efficiency obtained by being able to operate on ad hoc trajectories and not waiting for approval to change the trajectory when optimizing the flight is also available in the AFR

concept. These and other benefits are described as they would be experienced by each class of airspace user.

Aircraft operators with large fleets would necessarily require several years to implement AFR in the whole airline. Thus, the strategy for implementation is important to minimizing costs while maximizing the achieved benefits during the implementation period. Done right, the benefits derived from the first equipped airplanes can pay for the balance of the transition. In the information gathering efforts, a number of common strategies emerged to optimize this aspect of the business case. The chosen first fleet to be modified would operate domestically to maximize the opportunity for benefit, already contain much of the required avionics so that software upgrades would comprise the bulk of the modification, and the installations would occur during regular maintenance visits without lengthening the scheduled “out of service” time for each airplane. A relatively small sub-fleet would maximize the exposure of pre-trained pilots to modified airplanes, especially if those pilots were not cross-qualified so that their numbers per aircraft was minimized. As the benefits can be used to offset the costs of implementation, it is important to achieve a high rate of implementation. This can be done by modifying several fleets simultaneously rather than doing it all sequentially. As soon as actual AFR operations validate the achievement of monetary benefits, every effort should be made to accelerate the transition, consistent with minimizing implementation costs. On the flip side of this argument, airplanes soon to be retired may not pass the cost/benefit test within the required, short return-on-investment period. This would be especially true if the older fleet required major hardware upgrades to participate in AFR operations, raising the implementation cost with only a limited time to recoup the payback. Analog avionics and Cathode Ray Tube (CRT) displays are examples of equipment that would be very expensive to replace to participate in AFR.

A byproduct of the information gathering meetings with many members of the aviation community was the feedback received from these people on the AFR concept itself. All of the airspace users felt it was important to continue the development of the AFR capability and make it an operational reality. Some called it the most important thing to come out of ADS-B. Among the recommendations for further work on the concept are performing a quantitative AFR benefit study and conducting the safety case to determine avionics requirements.

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# 1. Introduction

NASA's Airspace Systems Program and its predecessor projects span more than three decades of research and development of systems using automation in air traffic control functions. This research has led to important tools for air traffic management that were transferred to the Federal Aviation Administration (FAA) and placed into operational service. During the same period of time, air traffic has continued to grow and the delays and inefficiencies experienced by airspace users have grown along with it. The FAA has kept operations safe throughout this growth period by employing traffic flow management initiatives that limit the aircraft demand on constrained resources (runways, control sectors) to manageable levels. These limits on demand represent constraints to operations that are manifested in many ways in the current Air Traffic Control (ATC) paradigm. Departure fix restrictions, red sector limits, miles-in-trail "passbacks," ATC preferred routes, and bulk weather re-routes are examples of these constraints.

NASA's research has always focused on removing or reducing the impact of these constraints which are part of the very structure of today's ATC system. Most often, the approach has been to automate certain manual functions to reduce the controller's workload so that more aircraft will be accepted in any given sector. In some cases, the focus was on permitting more efficient flight profiles to be used without changing the number of aircraft accepted. In others, assistance was provided to de-randomize the flow of aircraft into a major airport, helping to get the aircraft spaced properly to achieve a more regular arrival interval. As such, NASA's goal has been to improve the capacity, efficiency, and safety of the National Airspace System (NAS).

The Next Generation Air Transportation System (NextGen) program, now a decade old, brought all the concerned federal agencies together in furtherance of the same goal, and was designed to be a transformative roadmap for Air Traffic Management (ATM) of systems and procedures to meet much higher targets for capacity, safety, and efficiency. A few of the enablers to achieve the goals have been implemented during the last decade, among them Required Navigation Performance (RNP) procedures to shorten arrival paths to some runways and the ground-based Automatic Dependent Surveillance-Broadcast (ADS-B) network - a backbone for NextGen surveillance. Additionally, a mandate to equip aircraft for ADS-B OUT (i.e., transmit) was established to take effect in 2020, that will transform the surveillance function. It also will enable applications of ADS-B IN (i.e., receive), permitting aircraft to share in separation responsibilities in an important new way.

The most transformational aspect of NextGen is automation of the separation function. Automated separation has the potential to eliminate those constraints to flights that have been established to ensure safety in a human-centered system for traffic separation. The regimentation of traffic flows and limits on the number of aircraft in a sector, for example, would not be necessary in an automated separation system. However, this important feature of NextGen, originally targeted for operational readiness by 2025, has been dropped from the FAA's current implementation plan. That decision has put responsibility for developing the automation necessary to overcome the majority of shortfalls in ATC capacity and flexibility back into NASA's Airspace Systems Program.

Specifically, automation of the separation process has been pursued in both the NASA Langley and Ames Research Centers, one examining an airborne implementation and the other a centralized ground-based solution. The airborne solution studied at the Langley Research Center has evolved into what is now called Autonomous Flight Rules (AFR).<sup>1,2</sup> AFR takes advantage of the surveillance available in aircraft resulting from the ADS-B mandate by placing the automated separation responsibility in the aircraft. The research done to date on AFR has established the feasibility of the concept in mixed IFR/AFR operations.<sup>3</sup> That was a major finding as it enables a viable transition path for the automated

capability. Additional AFR research will test the operations in the presence of various system failures and external anomalies, such as adverse weather. Another aspect of the AFR investigation is the business case for the concept - the cost associated with airspace users flying under AFR and the benefits accruing to its use. The present study is an examination of the costs to airspace users of AFR.

## 2. Background

The AFR concept is formally described in Reference 1. This description is the result of more than a decade of Langley research into airborne self-separation, beginning with Distributed Air/Ground Traffic Management in the late 1990s. Creating the capability to perform the traffic separation function from the cockpit consumed most of this research effort. The research included writing and refining the conflict detection and resolution (CD&R) algorithms, creating the pilot interfaces and procedures to effectively use the surveillance and the CD&R tools, and testing the validity of the concept against simulated traffic using much higher traffic densities and complexities than currently exist, for robustness to real world failures and to measure sub-system performance.

Once it was proven that airborne self-separation was a viable concept, the means for employing this capability for operational benefit in the NAS was examined. It was recognized that segregating airspace specifically for self-separation operations was untenable because it is neither fair to deny access to the unequipped nor reasonable to expect a large proportion of the traffic to equip for new operations prior to receiving any benefits.

Accordingly, self-separation would have to work in mixed airspace with other IFR and Visual Flight Rules (VFR) operations to see the light of day. The other essential principle for incorporating self-separation into the airspace was determined to be non-interference with existing operations. To meet this principle, it is necessary for the self-separating aircraft to give right of way to all IFR flights whenever a conflict would develop. In this way, conventional air traffic control procedures could be used with IFR aircraft while the AFR share the same airspace, similar to VFR with IFR.

Finally, the use of self-separation in mixed airspace was given its own set of proposed standards, procedures and rules for use under a separation name - Autonomous Flight Rules, or AFR. The use of a separate set of rules permits the clear delineation of the requirements for equipment, the procedures for its use, and the rules for pilot training and flight operations under AFR.

The next step in the research is to determine what it would cost for an airspace user to participate in AFR operations and what they would produce as benefits. This report is an examination of the first part of this cost/benefit exercise, the costs of AFR. While a comprehensive and quantitative benefit study for AFR remains as future work, the benefit mechanisms for each of the airspace user classes studied are also set forth in this report to provide context for the cost items. The Air Navigation Service Provider (ANSP) costs of implementing AFR are not part of this study. AFR was designed to minimize the impact on the ANSP in accommodating AFR aircraft, and so the primary expense is expected to be borne by the operators.

### 3. Methodology

The costs to equip and operate aircraft using AFR is highly dependent upon what equipment will be required, what avionics already exist in the airplane to be used, and the nature of the flight operations themselves. In other words, one size does not fit all. One way to divide this problem so that meaningful results can be obtained is to separate the analysis by airspace user class. In this study, four user classes were selected: airlines, fractional ownership operators, General Aviation (GA), and Unmanned Aircraft Systems (UAS) operators. Of course there are many distinctions possible within each of these but for this first cut at the costs of AFR participation, the airspace users have been generalized in this fashion. Military flying was not analyzed in this study but as that represents a major airspace user class, they should be considered in future studies of AFR operations.

It was decided to use the interview process, interviewing those with domain expertise garnered through personal experience and involvement, to gather information specific to the cost categories and the airspace user categories in this study. Knowing that the biggest cost drivers would be the acquisition cost of the avionics for AFR and the installation of that equipment into the aircraft, it was decided to meet with the avionics manufacturers first. From these discussions it would be possible to postulate representative avionics architectures needed by each class of airspace user in their aircraft. Armed with the avionics architectures, the following discussions with representatives of the airspace users would be more productive as they would have a better feel for what their installation, training and operating costs would likely be.

Some of the interviews were held face-to-face as this method provides more effective communication and produces better and more complete results from the information gathering effort. To interview more representatives and to economize on travel costs, some of the interviews were conducted by conference telephone and internet, using WebEx to assist with PowerPoint presentations and other written materials used in the discussions. At least one face-to-face meeting was to be held with a representative of each user class. Confidential reports of each of the meetings have been delivered to the NASA technical point of contact.

For each meeting, a one-page read-ahead explanation of AFR and the objective of the meeting in relation to its support for the current NASA research was sent to those who would be attending. A tailored, PowerPoint presentation was created for each representative meeting that explained the AFR concept and the relationship of the meeting to the current research. Then a prepared page of structured questions was used in each meeting to solicit specific cost-related information needed by the project as well as general feedback on the AFR concept and the research performed so far.

With the results of those meetings (interviews), a representative aircraft-operator example was created in each user category for use in defining the costs and preferred implementation strategy that would maximize the savings and other benefits from the use of AFR in each of their operational paradigms. To protect the competition-sensitive information provided by those interviewed, averages were used in the representative examples provided in the report for specific expected costs. Additionally, the factors that influence each of the cost items are identified so that variations from the average can be computed by anyone wishing to apply the method to their own operations.

In some cases, the dollar value costs were unknown to those interviewed or were considered so premature that they declined to quote a figure that could later be used against them. Whenever this occurred, cost estimates were created in consultation with those interviewed that were based on very similar experience with other avionics, training, etc. The results arrived at in this report thus represent the best possible estimate of costs available at this writing based upon consultation and honest input from those in the best position to know. In other words they are not "catalog" prices, but good enough to support initial investment planning.

## 4. Findings Regarding AFR Avionics Architecture

The cockpit systems used by the pilots in flying AFR are comprised of five functional elements: surveillance, computation, control and display, communication, and guidance. The Autonomous Operations Planner (AOP) developed at NASA Langley during their research into the AFR concept served as the initial model for the cockpit avionic systems.<sup>4</sup>

In the Langley implementation, the surveillance function was simulated by ADS-B IN supplemented with Traffic Information Service Broadcast (TIS-B). The computation function that took surveillance data and modeled the projected positions of both "ownship" and the other nearby aircraft was the heart of the AOP software and operated in parallel with the simulated Flight Management System (FMS). This location made sense because that is where the navigation function currently resides and the ownship state, intent and performance information is also available there. Control and display of the separation function resided primarily in the Multi-function Control Display Unit (MCDU) in the AOP implementation with the addition of an AOP hard key and dedicated AOP pages on which to view, select and execute strategic resolution options. The status of the system and traffic situation was displayed on a separate, small alphanumeric display called the SNAPI (Status Notification and Planning Information). Communication of the ownship trajectory to the Air Navigation Service Provider (ANSP) and surrounding aircraft was through the ADS-B OUT link, with Trajectory Change Points (TCPs) assumed to be activated. This communication is to provide intent information from ownship to the ANSP and other nearby aircraft. Finally, the flight guidance function was split among the SNAPI and FMS displays, the Primary Flight Display (PFD) and the Navigation Display (ND). Aural annunciation of tactical separation commands was simulated through the aural alerting system on the active audio channel and/or over the flight deck speakers. For a detailed description of the AOP, see Reference 4.

As all the previous research had used this experimental setup to enable pilots to simulate flight under AFR, the current study looked at the practicality and feasibility of this AOP implementation and alternative avionics architectures considering costs and certification difficulties inherent in integrating the AFR functions into existing cockpits and forward-fit installations for new aircraft. One of the major considerations was the impact of re-certifying complex avionics already resident in the aircraft to accommodate the AFR functions. From a cost-to-implement standpoint, this obviously needed to be minimized. Another consideration was the certification level, determined by the criticality of the AFR functions. This level should match that of the avionics box in which the function will reside. The need to add additional boxes in the radio rack or additional displays on the instrument panel is another important consideration. Space is at a premium in both areas, weight is always a factor, and the need to run additional wiring to and from the new equipment is always a major cost factor. Finally, the avionics changes taking place in the near-term to implement other functions either required or desired will alter the existing suite of avionics prior to the introduction of AFR and should be considered baseline to the AFR changes. This would include ADS-B OUT and any near-term ADS-B IN applications like In-Trail Procedures (ITP), Flight-deck Interval Management (FIM), Pairwise Traffic Management (PTM) or Traffic Aware Strategic Aircrew Requests (TASAR) that might be implemented first.

To address the avionics architecture questions, meetings were held with four of the primary avionics manufacturers in the US: Honeywell/ Bendix/King, Rockwell Collins, ACSS, and Garmin. The meeting with Rockwell Collins was in person at their Cedar Rapids headquarters. The others were conducted by conference call using WebEx to make the presentation, discuss the architecture graphics, and conduct the question and answer session regarding cost considerations. The first three manufacturers produce primarily for the transport aircraft market and Garmin produces primarily for GA, but there is some overlap reflected by Bendix/King of Honeywell and Rockwell Collins producing significant avionics lines for the high-end GA market (i.e., business jets and fractional ownerships), and Garmin is about to make some higher end offerings for larger jet aircraft.

In the meetings, the AFR operational concept was described and discussed in sufficient detail that the manufacturers were very aware of the AFR functions to be performed and the necessary integration with other system and displays. They were shown how the AOP implementation worked but were not constrained in their thinking to that particular architecture.

Probably the most significant finding from these meetings was the degree to which all the manufacturers are already integrating "surveillance-based functions" in their product offerings. The first foray into airborne surveillance was the Traffic Alert and Collision Avoidance System (TCAS) followed by TIS-B, and with the ADS-B mandate coming, ADS-B IN and OUT offerings are already available from many manufacturers as shown in Section 7.

The surveillance explosion has resulted in integrated box offerings to replace/combine the TCAS and Mode S Transponder boxes with a single "Surveillance Box" containing those two functions, amongst others, and also incorporating ADS-B radios for both IN and OUT. A number of ADS-B IN applications have been certified. The combination of ADS-B, TIS-B, and TCAS targets detected by any means are correlated so that only one target is displayed per aircraft, with the best source of information being used to display its position. For some applications, in certain conditions, ADS-B targets must be validated with active interrogation.

The adequacy of TIS-B to serve as back-up surveillance for AFR was also discussed. Since TIS-B targets are generally of lower quality than ADS-B, a TIS-B target aircraft could be avoided using a larger separation zone. For TCAS-equipped aircraft, active interrogation could be used to more accurately measure the distance to the target. In general, that distance will be more accurate than the ADS-B calculated distance. Another technique would be to track targets by fusing ADS-B, TIS-B, and active interrogation. The safety case will dictate which of those techniques is an acceptable minimum, as required for the AFR function.

Several manufacturers are already offering a surveillance box containing TCAS, TIS-B and ADS-B with one or more ADS-B IN applications.

The computation function is the heart of AFR, using the surveillance and intent information to do trajectory modeling, conflict detection and resolution and the communications of the executed resolutions to the ANSP and surrounding aircraft. This function is called the Air Traffic Unit (ATU). The NASA AOP (described earlier) is a research prototype of an ATU. The ATU function is expected to reside on a computer board in the surveillance box and is considered by the TCAS manufacturers to be just a TCAS upgrade, even though it is using primarily ADS-B information.

For aircraft without TCAS, the ATU is expected to reside in an integrated navigation system. Many GA aircraft have installed a Wide Area Augmentation System (WAAS) navigation system with a moving map that additionally displays terrain, weather, and traffic. Avionics manufacturers expect that a Cockpit Display of Traffic Information (CDTI) with AFR functions could be hosted in such a system. The major cost factor will be the level of certification required for AFR. In addition, if the FAA were to require a Letter of Authorization for AFR operations for certain user categories, the training and administrative burden might prevent some of these operators from participating in AFR. The key will be ensuring that the AFR implementation is intuitive enough so that extensive training is not required, such as was done for WAAS Localizer Performance with Vertical guidance (LPV). That may require limiting AFR to tactical resolutions only where the aural and visual resolutions mimic controller voice instructions.

The conflict detection and resolution function is divided into two modules, strategic and tactical, that are differentiated in several ways. The strategic module has a longer look ahead time; probably out to 10 minutes in the future. The tactical module would have a look ahead time of four minutes until projected loss of separation. Another distinction is that the strategic algorithms may produce several available resolution options from which the pilot may choose one to execute. The tactical logic produces a single directive resolution which must be followed, just like an ATC clearance or instruction. The tactical

CD&R algorithms are more safety critical and their implementation in hardware and software will have to be FAA-tested and approved. The avionics manufacturers will be incorporating the RTCA Minimum Operational Performance Standards (MOPS) compliant CD&R algorithms into their software and the pilots will be following their output, just like an IFR clearance, so traffic separation under AFR is still an FAA controlled and approved function.

There was a near universal opinion that "you should never break into a certified box that you don't need to" as it incurs the expense not only of certifying the new function but also re-certifying the old. For this reason, none of the manufacturers favored using the FMS to host the AFR functions in a retrofit scenario. The MCDU was chosen as the best place to control the AFR functions on airline aircraft and host the status display system including traffic conflict status. On general aviation aircraft the control and status display may be a part of the traffic/surveillance unit, or the crew interface device to the navigation system could be modified to accommodate AFR.

Traffic situational awareness was felt to be properly located on the ND / Multi-Function Display (MFD) in some aircraft. This is in the forward field of view and CDTI functions are already fairly well understood because of TCAS and are being further developed through ITP, FIM and CDTI-Assisted Visual Separation (CAVS). The additional symbology needed for AFR could be relatively easily added as long as a digital flat panel display is used, not a symbol generator-driven Cathode Ray Tube (CRT). Breaking into the PFD, however, was not considered desirable. If flight director guidance for resolution maneuvers is a wanted function, it would likely be requested as an option on a new delivery aircraft. However, speed commands and altitude changes can be shown on the PFD just as FMS and Mode Control Panel (MCP) changes are displayed.

Other systems that are integrated with the AFR functions either provide information to the ATU computer, take information from it, or both. The FMS is foremost in this category but unlike using the FMS to host the ATU function, it merely supplies information on planned trajectory and aircraft performance to the ATU and accepts routes, altitude and speed modifications from the ATU for execution by the pilot. Similarly, the MCP sends information on active flight mode, heading, altitude target, speed and vertical speed target information to the ATU for use in ownship trajectory modeling. On a few aircraft, the ability to accept an ATU output on the MCP will also be available, but it is not necessary where it can't now be done (see figure 1).

All manufacturers accepted that both 1090 Megahertz Extended Squitter (1090ES) and Universal Access Transceiver (UAT) receivers would be included in the surveillance package and that an antenna is available that accommodates both frequencies.

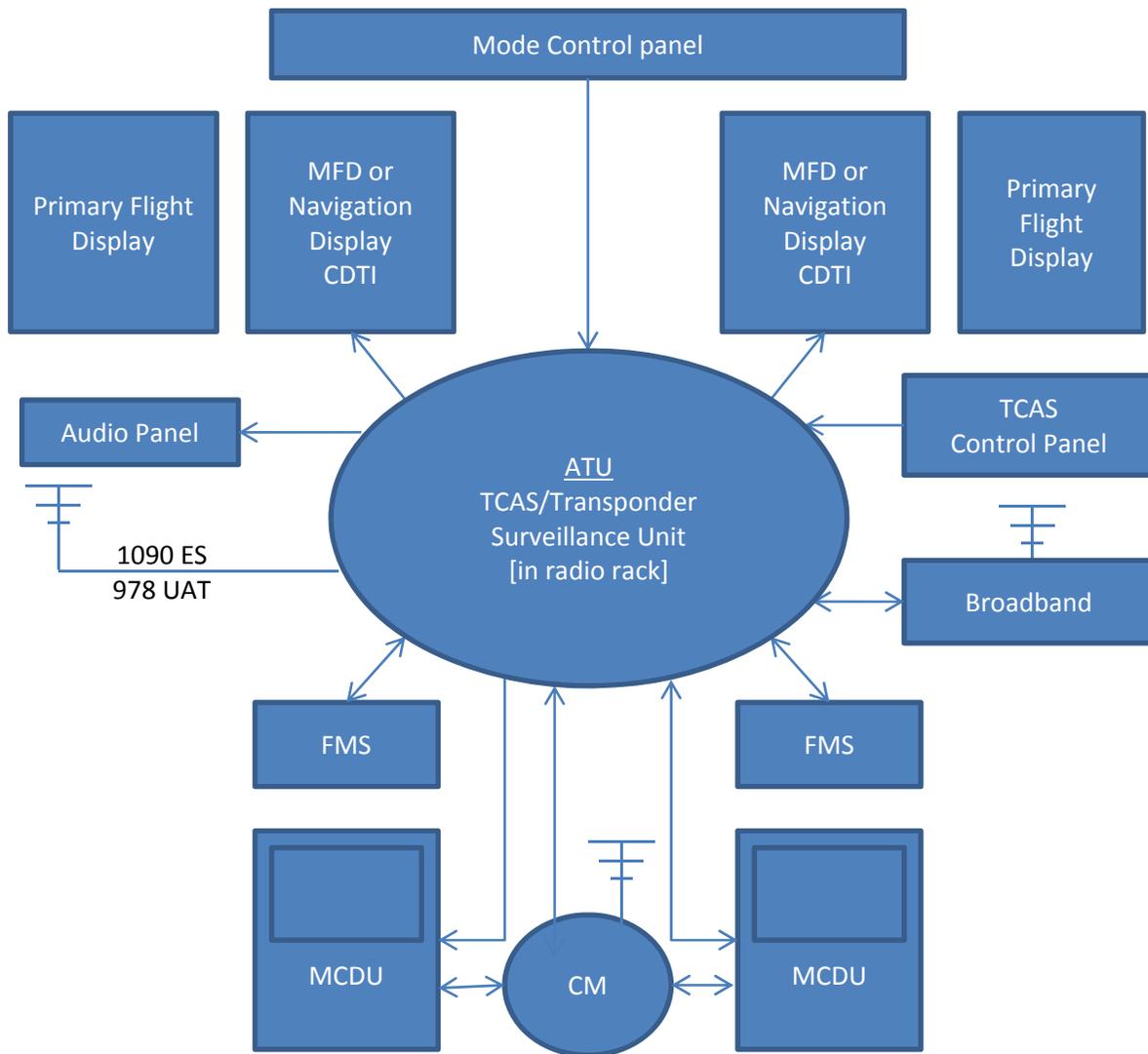
The issues of redundant equipment, independent sources of data and equipment, and software certification levels were discussed at length with all parties. Those issues all relate to the safety of the systems used to conduct AFR and the answers cannot be known until the conclusion of the NASA/ FAA safety case study for AFR. Because the certification level is unknown at this point, the true costs, especially the certification costs and risks, cannot be accurately determined *a priori*. None of the parties interviewed thought that Level A certification would be required. Level A certification is typically required only for aircraft control systems that ensure safety of flight such as autoland systems. For this analysis, two representative architectures were derived for each of the four airspace user categories as examples. The more stringent one assumed that complete redundancy of equipment and Level B certification of the software containing the CD&R algorithms would be required. The less stringent (and less expensive) option assumed redundancy of some elements, but not all, and that Level C certification of the software would be sufficient. Where a range of estimated costs is shown, it reflects these two options. In the section below, the avionics suites to support AFR are shown for each of the four studied classes of airspace users:

1. Airlines

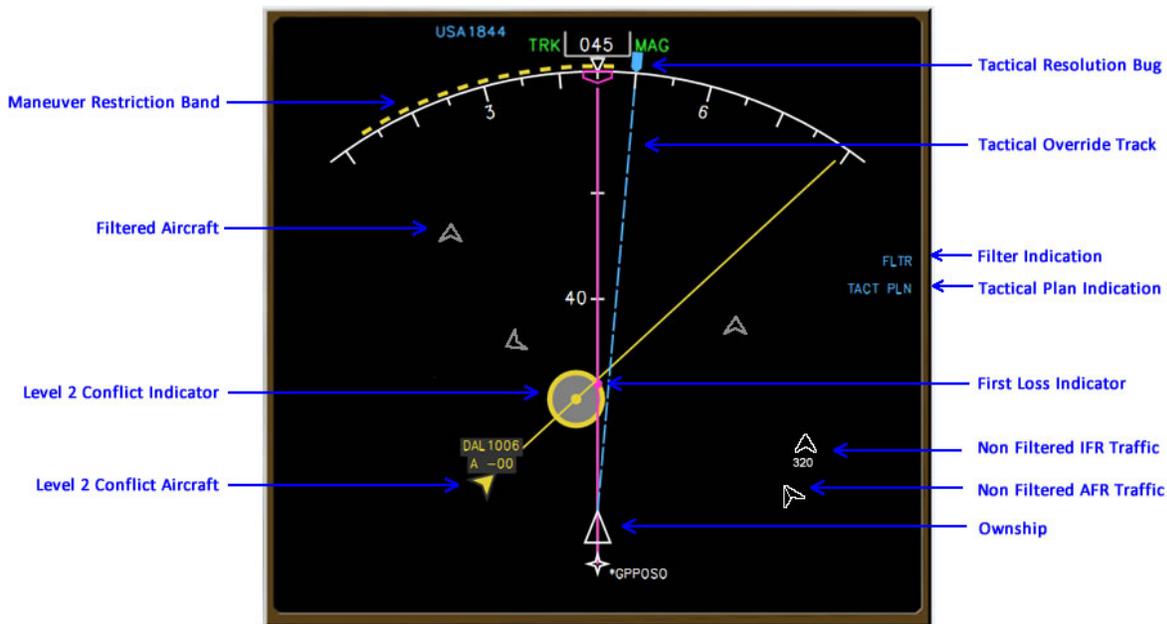
2. Fractional ownership operators
3. General Aviation owner/pilot
4. UAS operator

## 5. AFR Airborne Architecture Alternatives

Below are architecture alternatives for airborne equipment to implement an ATU as a retrofit on legacy aircraft in the 2020 time frame. A typical airline architecture is shown in Figure 1, and an airline ND showing notional AFR symbology is shown in Figure 2.



**Figure 1 Typical airline AFR architecture. Arrows indicate information flow.**



**Figure 2 Navigation Display showing AFR Symbology**

Architectures are proposed for each of the four classes of aircraft. It is assumed that a safety study will be accomplished that will determine a number of performance parameter requirements. In these preliminary architectures the design assurance and redundancy levels are presumed to be the major cost drivers. In each case, two architectures are described. One is considered worst case and the other, a “realistic” alternative. The assumed time frame is post 2020 when the current ADS-B OUT mandate is in place. It is also assumed that MOPS compliant and certified ATU CD&R algorithms (both strategic and tactical) and Traffic Flow Management (TFM) software are in place. Joint US/European Minimum Aviation System Performance Standards (MASPS) and Minimum Operational Performance Standards (MOPS) are assumed to be in effect, and International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPS) for the ATU function are assumed to be in effect. Note: In the following, \*indicates equipage assumed in the great majority of aircraft by 2020.

## 5.1. Proposed Airline Aircraft AFR Architecture

- Dual FMS with:
  - intent bus providing own aircraft four-dimensional (4D) trajectory to the ATU\*
  - ability to accept 4D trajectories from ATU\*
  - airspace information (sector boundaries, Special Use Airspace (SUA), ATC frequencies) in the navigation data base, and aircraft performance limitations available
- CDTI on ND with AFR and other ADS-B IN applications (Figure 2)
  - ability to display heading, airspeed, and altitude resolution guidance from the ATU\*.
- MCP with status (horizontal and vertical navigation modes, heading, airspeed, altitude) output to ATU
  - heading, airspeed, and altitude from ATU if that feature is implemented under Controller Pilot Data Link Communications (CPDLC).\*
- TCAS and/or Transponder Line Replaceable Unit (LRU) which includes:
  - hybrid surveillance\*
  - independent ADS-B IN system which includes UAT receiver, processes TIS-B and Flight Information Service Broadcast (FIS-B), hosts air traffic unit for strategic and tactical AFR, and perhaps other applications
  - receives and outputs to Communication Management Unit (CMU) and/or broadband and/or Overlay (weather, System Wide Information Management (SWIM), ownship and other aircraft trajectories, etc.)
  - outputs to FMS (and MCP if implemented) in Data Comm format ( or CPDLC or Airline Operational Control (AOC) formats)
  - outputs to aural alerting system\*
  - interfaces with MCDU or other input/output (I/O) device
- Upgrade 1090 antennas to 1090/UAT antennas
- Dual Very High Frequency (VHF) Data Radio\*
- Dual MCDU\*
  - ATU status, CD&R information pages and pilot interface

Architecture 1: dual TCAS as described above, Level B software

Architecture 2: single TCAS as described above, second Air Traffic Unit in TCAS LRU with independent power source and 2<sup>nd</sup> 1090/UAT receivers (share 1090/UAT antennas), Level C software (but without the TCAS function)

## 5.2. Proposed Fractional Jet Operator AFR Architecture

The architectures proposed for Fractional Jet Operators are twofold. The first is similar in functional capability to the airline equipment listed above. The second is more in line with high-end GA, described below. It is expected that the choice between these (or something in between) would be driven by the type of aircraft under consideration (size and installed equipment) and the nature of the operations such as the percentage of flights into the top 30 United States (US) airports.

- Dual FMS with:
  - intent bus providing own aircraft 4D trajectory to the ATU\*
  - ability to accept 4D trajectories from ATU\*
  - airspace information (sector boundaries, SUAs, ATC frequencies) in the navigation data base, and aircraft performance limitations available
- CDTI on large format Nav Display with AFR and other ADS-B IN applications
  - ability to display heading, airspeed, and altitude resolution guidance from the ATU\*.
- MCP with status (horizontal and vertical Nav modes, heading, airspeed, altitude) output to ATU
- TCAS and/or Transponder LRUs which includes:
  - independent ADS-B IN system which includes UAT receiver, processes TIS-B and FIS-B, hosts air traffic unit for strategic and tactical AFR, FIM, closely spaced parallel approaches and other applications
  - receives and outputs to CMU and/or broadband and/or Overlay (weather, SWIM, ownship and other aircraft trajectories, etc.)
  - outputs to FMS in Data Comm format ( or CPDLC or AOC formats)
  - outputs to aural alerting system\*
  - interfaces with MCDU or other I/O device
- Upgrade 1090 antennas to 1090/UAT antennas
- Dual I/O device\*
  - ATU status, CD&R information pages and pilot interface

Architecture 1: dual TCAS as described above, Level B software

Architecture 2: Single FMS and second navigation system with display capable of accepting traffic information to support AFR.\* Single TCAS as described above, second Air Traffic Unit in Traffic Advisory System (TAS) LRU with independent power source and 2<sup>nd</sup> 1090/UAT receivers (share 1090/UAT antennas), Level C software (but without TAS function)

### 5.3. Proposed General Aviation Aircraft AFR Architecture

The following proposed architecture for GA aircraft includes an ATU in which the CD&R software uses "tactical resolution" algorithms only, provided and certified by the FAA.

- Minimum required IFR equipment plus:
- Dual Global Positioning System (GPS) navigation system with:
  - ND capable of accepting traffic information to support AFR\*
  - Ability to display airspace information (sector boundaries, SUAs, ATC frequencies) from nav database or FIS-B
- I/O device with ability to display commanded heading, airspeed and altitudes from ATU\*
- TAS/surveillance unit which includes:
  - independent ADS-B IN system which includes UAT and 1090 receivers, processes TIS-B and FIS-B, hosts air traffic unit for tactical AFR
  - Interfaces with I/O device
  - aural alerting system or outputs to existing aural system where installed
- Upgrade 1090 or UAT antennas to 1090/UAT antennas
- Broadband internet connection\* (higher end GA. State vector provided over ADS-B is sufficient for others.)

Architecture 1: Dual TAS surveillance units with Technical Standard Order (TSO) compliance. Broadband internet connection.

Architecture 2: Single TAS surveillance unit as described above and second ATU in TAS LRU with battery power and independent 1090/UAT receivers.

#### 5.4. Proposed UAS AFR Architecture

- Dual GPS Navigation System
- TAS/surveillance unit which includes:
  - independent ADS-B IN system which including both UAT and 1090 receivers, processes TIS-B and FIS-B, hosts air traffic unit for tactical AFR
  - Interfaces with I/O device
- Upgrade 1090 or UAT antennas to 1090/UAT antennas
- Communications unit to communicate to remote operator and send velocity vector or trajectory to ANSP.

Architecture 1: Dual TAS surveillance units with TSO compliance. Broadband internet connection.

Architecture 2: Single TAS surveillance unit as described above and second ATU in TAS LRU with battery power and independent 1090/UAT receivers.

The four classes of airspace users represent a wide range of vehicles and operators in each class. "Airlines" include the remaining majors ( e.g., United, American, Delta), the so-called low cost carriers (e.g., Southwest, JetBlue, Virgin America, Alaska), and the regional carriers performing express service for the major carriers under their logos (e.g., United Express), using regional jet aircraft. The "Fractional Ownership" category includes the on-demand carriers using small to medium and some large business jet aircraft, such as NetJets, FlightOptions, etc. The General Aviation category is the largest comprising both personal and commercial services in all kinds of aircraft from small single-engine piston aircraft through piston twins, turbo-prop and light jets to specialized operations using transport category aircraft. Similarly, UAS encompasses an even wider range of vehicles and types of operations. Most private and commercial UAS uses in the NAS are still "proposed" as they don't yet have the freedom of access needed to accomplish most of the missions. The kinds of UAS that would be using AFR are in the medium to large vehicle category, used almost exclusively today by the military. The proposed architectures are based upon a "representative" example aircraft in each of the four categories. The chosen aircraft representatives used in the example cost calculations in Section 7 are, for the airlines, the 737-900; for the fractional operator, the Embraer Phenom; for the GA aircraft, the Piper Meridian; and the UAS, the Predator drone.

## 6. Cost Categories

This AFR cost analysis, performed with the aid of interviews with airspace user representatives, determined that the costs associated with AFR fall into four categories: 1) Equipment acquisition; 2) Equipment Installation; 3) Training; and 4) Operations and maintenance. The factors that influence the cost of each of these items are presented next, and actual cost examples appear in Section 7.

### *Equipment Acquisition*

The equipment acquisition cost will be based on what items of new or upgraded avionics are needed, what certification level was approved by FAA, how many items are being purchased (how many shipsets) and how many competitors are in the market selling this equipment. In a monopoly market, the manufacturers try to understand what the item will produce in the way of benefits for the customer, then price the item to get a substantial percentage of that value rather than relate it to development and production costs. If there is competition, the price quickly returns to a cost of production basis. In the equipment lists shown above under "Avionics Architecture", the starred items are assumed to be on the aircraft in the 2020 time frame and don't need to be purchased to support AFR. It can be seen that the primary purchase item is the TCAS/Transponder (Surveillance) LRU upgrade to include the necessary ADS-B radios and ATU software application. Software upgrades will also be needed for the FMS navigation data base to include additional airspace information, for the ND to include AFR specific traffic symbology, and the MCDU to incorporate control and display of ATU system information. As an alternative to an FMS data base upgrade, since the airspace sector boundaries and frequency information are in an FAA database, it may be necessary for manufacturers to have access to this database to include it as part of the AFR software and to update it periodically as the FAA makes changes to these parameters.

### *Avionics Installation*

The avionics installation is a major driver of AFR implementation costs. It could be as much as the acquisition cost of the hardware and software equipment itself but will generally be much less if only software upgrades are required. The variables associated with installation cost include availability of space, integration with other systems, wiring changes required and where the work is accomplished. The ATU "card" including the surveillance radios will likely fit into the latest TCAS/Transponder surveillance "boxes" or LRUs without modification. Therefore, they might not take up any room on the radio rack, or in or behind the instrument panel. However, to retrofit the capability on older aircraft it might be necessary to install a completely new box. Depending on the aircraft, this could take up space in the equipment bay or on and behind the instrument panel itself. In general, the older and less sophisticated the cockpit to be modified, the more expensive the AFR installation will be. Sample installations in an aircraft from each user category will be detailed in the next section. One of the biggest installation costs is to re-wire the aircraft for the new equipment. Wiring is required for power, for control, for antennas, and for connections to and from other systems used to provide information to the ATU or to accept and display or transmit the output from the ATU. The degree to which new wires require the airplane interior to be removed, other parts to be removed for access, passing through the pressure bulkhead or external skin of the airplane all directly affect the cost of the installation. Other avionics systems that the ATU "talks to" may be accessed on a standardized bus, but in some installations, they may require discreet wires to be run between them. The final variable for installation cost is who is doing the installation and how long does the aircraft need to be out of service to do the installation. Work done "in-house" can usually be combined with other installations and timed to coincide with routine maintenance. Often the technicians are salaried and this specific installation might not be traceable in their costs, but lumped together with all changes. On the other hand, it has become commonplace for aircraft operators to outsource maintenance and installation work to overseas locations to take advantage of lower wages and

other overhead costs. So the installation cost will be related to both the difficulty of accomplishing it and the accounting system used for the work done.

### ***Training***

Training is needed, primarily for the pilots who will operate the AFR equipment, and to a lesser degree, the technicians who will maintain it. Pilot training on new avionics systems is typically done with computer-based technologies (CBT) either on company computers at the flight office, or, more commonly today, on any-owned tablet devices like the iPad™. Today's computer-based training is usually interactive, enabling testing for system knowledge, comprehension and correct procedural actions at the time the pilot is engaged in the training. This has proven to be much more effective training than a flight manual bulletin only, or a bulletin accompanied by a short multiple choice quiz. A minority of those interviewed felt that the FAA might require some AFR training to be performed in a full flight simulator. If this were the case, training costs would be much higher. Even though many companies pay their pilots for time spent on required Computer Based Training (CBT) training, the fact that they don't have to travel to the simulator base and involve simulator instructors and technicians results in tremendous savings. One other training and checking tactic - the line check - might also be employed. In this, the pilot new to AFR would be paired on a flight with a pilot who has experience with the system. The experienced pilot might be a Line Check Airman, which complicates the crew scheduling, or any other pilot who has used the equipment before. The operational approval from FAA will specify the specific training techniques that may be used.

### ***Operations and Maintenance***

Actual AFR operations don't have any specific additional costs associated with them. There are two things that may be used to get the most in benefits from these operations, however, and these are the flight planning system and the pilot reporting and feedback system. AFR flights would be exempt from many delay-causing restrictions, preferred routes, and traffic flow management initiatives. Many of these constraints are built in to the flight planning software so that flight plans have a high likelihood of being accepted by the ANSP. For AFR flights to achieve their operating benefits, they must be planned to use optimum wind routes, speeds, and altitudes, disregarding the structure required for IFR flight until they are re-integrated with these flights near the destination runway. Some flight planning systems may have to be modified to disregard these IFR structures, which bears a cost. Many operators subscribe to flight planning services and contracts may have to be modified or re-negotiated to ensure the plans delivered permit AFR flights to maximize their flexibility benefits. In a similar fashion, the Collaborative Decision Making (CDM) used during flow programs must recognize the special status of AFR with respect to these delays.

During the start-up of AFR operations, it will be important to hear from the pilots how the system is working and if there are any procedural or equipment problems that need to be addressed. An information feedback system is thus important to the AFR implementation. It was determined that many companies, especially the airlines, already have such information feedback mechanisms in place that are well suited to fulfilling this task for AFR. There are others that don't have such a system, however, and there would be administrative costs associated with establishing and using such a system.

Maintenance of the avionics equipment that is added to perform AFR was found to be minimal and would probably be lumped in with the maintenance of the parent "black box" such as the surveillance unit that will be common on many aircraft. Another finding regarding maintenance is that service agreements are often negotiated with the avionics manufacturer at the time of equipment purchase. These agreements provide for lifetime maintenance of the equipment. If a unit fails or has a problem, it is simply swapped out with an exchange unit and no money changes hands.

## 7. Development of Cost Estimate Model

The purpose of this section is to present what has been learned during this study about the costs of implementing the capability to participate in AFR, in a manner that is truly useful to anyone in the selected user categories. To accomplish this, a list relating the items of identified avionics architecture supporting AFR and their projected costs, based on information obtained during the information gathering process, is presented first. Then, an example operation and an example aircraft is chosen in each airspace user category that is fictitious, but representative of the class. The baseline avionics for each example aircraft is assumed to be all the equipment expected to be installed and operational post 2020 so that the additions to use AFR represent the upgrade costs. Then, for each representative aircraft, the additional equipment and estimated costs for each item that might not already be present is given, so that any potential user can create a list that pertains to him/her, and arrive at a total cost estimate for their own aircraft/operation. The cost estimates shown represent the best forecast the authors could make in 2013 dollars on the basis of information obtained during the interviews and their own airline and GA years of operating and planning experience. Except for current product offerings in Table 1 and other kinds of implementation costs, no real data on the cost of an ATU and its peripherals exists yet, so these are by their very nature, projected costs, but they do represent very educated guesses.

**Table 1 General Aviation ADS-B avionics offerings with capabilities and prices (2013)**

Manufacturer	Product	Features	Current List Price
Garmin	GDL 88	ADS-B IN and OUT, 1090 and UAT	\$3,995
	GDL 39	ADS-B IN	\$875
Avidyne	AXP340 ES	ADS-B OUT (DO 260B)	\$5,995
	TAS 600 A	ADS-B IN, XPDR TAS	\$8,490
	VeriTAS 605A, 615A, 620A	ADS-B ADS-R XPDR active passive	\$10,990 to \$20,990
Aspen	ARX 100	ADS-B IN	\$1695
	ATX 200	ADS-B IN and OUT	\$3995
	ATX 200G	ADS-B IN and OUT plus GPS rcvr	\$4995
Dynon	SV-ADSB-470	ADS-B IN UAT only	\$995
FreeFlight Systems	FDL 978-TX	ADS-B OUT ES	\$1,995
	FDL 978-RX	ADS-B IN	\$1,200
	FDL-978-XVR	ADS-B IN and OUT	\$3,495

The following subsections present a cost buildup per user class, followed by an example calculation given for a "typical" installation to illustrate the use of the template.

## 7.1. Airline Cost Estimation Example

### Example Airline:

500 aircraft, domestic and international  
 150 B-737s of all types  
 60 B-737-900 selected to receive AFR first

<u>AFR-Enabling Equipment</u>	<u>Projected Unit Cost</u>
AFR upgrade to surveillance unit	\$40,000 to \$120,000
New surveillance unit with AFR	\$80,000 to \$200,000
Display software for CDTI features on Nav display	\$20,000 to \$100,000
UAT/1090 antenna upgrade	\$3000 to \$30,000
AFR software load for MCDU	\$0 to \$20,000
VHF Data radios	\$10,000 to \$30,000

### Equipment already installed in Example fleet of B737-900

Dual FMS with intent bus  
 CDTI on large format Navigation Display (PTM, FIM and TASAR applications)  
 MCP with active modes on bus  
 Dual 1090 antennas  
 Dual VHF Data Radio  
 Dual MCDU  
 Simple TCAS/ Transponder surveillance unit

<u>Needed equipment for the example aircraft</u>	<u>Cost</u>
AFR upgrade to TCAS/Transponder Surveillance Unit	\$60,000
Second AFR/ Surveillance unit /without TCAS	\$140,000
UAT/1090 antenna upgrade	\$10,000
AFR software pages for MCDU	\$20,000
<b><u>Total equipment cost per aircraft</u></b>	<b>\$230,000</b>

As is common industry practice, the example airline performs its own installations during regular maintenance visits, so it is assumed in this example that there is no additional unproductive downtime for the AFR installation. The second surveillance unit fits as a new "card" in the same box and does not require additional wiring. The example airline also develops its CBT programs in-house. They have a pilot reporting and feedback program in place.

<u>Installation cost per unit</u>	<u>Cost per Airplane</u>
100 man hours @ \$50/hr	\$5,000
<u>Unit Training Cost</u>	<u>Cost per Airplane</u>
5 pilots per airplane	
2 hours per pilot @ \$120/hr	\$1200
<u>Course development cost (non recurring)</u>	<u>Amortized cost per airplane (60 total)</u>
160 man hours @ \$75/hr = \$12,000	\$200
<b><u>Example implementation cost per aircraft for B737-900</u></b>	<b>\$236,400</b>

## 7.2. Fractional Operator Cost Estimation Example

### Baseline Fractional Company

150 aircraft, domestic and International  
40 Embraer Phenoms selected to receive AFR first

<u>AFR-Enabling Equipment</u>	<u>Projected Unit Cost</u>
FMS with intent bus or Navigation system with intent bus	\$20,000 to \$60,000
Display software for AFR CDTI features on Navigation Display	\$8000 to \$20,000
TAS Transponder unit with AFR capability	\$20,000 to \$80,000
UAT/1090 antenna upgrade	\$1000 to \$3000
AFR software pages for pilot I/O device	\$5000 to \$20,000
Broadband internet connection	\$20,000 to \$40,000

### Equipment already installed in the example Embraer fleet

FMS and second navigation system, each with intent bus  
CDTI with ADS-B traffic for awareness and TAS on ND  
MCP with flight mode status output to ATU  
Simple TAS/Transponder Air Traffic Control Radar Beacon System (ATCRBS) 1090 ES / 978 receivers for ADS-B IN and TIS-B  
UAT/1090 antenna upgrade  
Broadband internet connection

<u>Needed equipment for the example aircraft</u>	<u>Cost</u>
AFR upgrade for existing TAS/Transponder unit	\$15,000
Second Surveillance unit without TAS feature	\$40,000
Display software for AFR CDTI features on ND	\$15,000
AFR software pages for pilot I/O device	\$10,000
<b><u>Total equipment cost per aircraft</u></b>	<b>\$80,000</b>

The example fractional company has a contractual arrangement with an avionics shop for installation and maintenance on all its aircraft. The AFR installations will be done during maintenance downtime and no additional out of service time is required for the installation. In this example, the second surveillance unit does require additional wiring, and the installation cost is higher. The company also develops its own CBT programs for pilot training to be accomplished on their pilot-owned iPads, on their own time. The example company has a pilot feedback program to the flight office using their cell phones.

<u>Installation cost per unit</u>	<u>Cost per airplane</u>
240 man hours @ \$50/hr.	\$12,000

### Unit Training Cost

Pilots are to accomplish training on their own time \$0

### Course development cost (non recurring)

150 man hours @ \$75/hr amortized over 40 aircraft \$281

**Example implementation cost per aircraft for Phenom** **\$92,281**

### 7.3. General Aviation Owner/Pilot Cost Estimation Example

Baseline is a business owner/operator with one airplane that (s)he flies both for business and personal transportation, a Piper Meridian.

<u>AFR-Enabling Equipment</u>	<u>Projected Unit Cost</u>
Dual GPS navigation system capable of displaying traffic information and symbology to support AFR	\$14,000
TAS/ Surveillance unit with UAT IN and OUT, 1090 IN., Host ATU tactical software	\$8000
Second surveillance unit without TAS function	\$4500
Controls and status information integral with panel mounted surveillance unit	\$0
1090/UAT antenna upgrade	\$500

#### Equipment already installed in Piper Meridian

Dual GPS Navigation System with flat panel displays capable of supporting traffic.  
 TAS/Surveillance unit with UAT ADS-B OUT and both 1090 and UAT ADS-B IN, TIS-B  
 Dual frequency 1090/UAT antenna

<u>Needed equipment for the example aircraft</u>	<u>Cost</u>
AFR upgrade for the TAS/Surveillance unit	\$5,000
Second surveillance unit supporting AFR	\$8,000
Second UAT/1090 antenna	\$500
<u>Total equipment cost per aircraft</u>	<u>\$13,500</u>

The owner pilot has his installations and avionics maintenance performed at a shop at the local FBO. The purchase price includes installation (as is common) except for the second antenna. He accomplishes his AFR training on-line using a course provided by the avionics manufacturer - free of charge when you purchase an AFR surveillance unit. No feedback is required to a company. Problems with the system would be reported to the avionics shop or the manufacturer. Operational problems would be reported to the FAA General Aviation District Office or the NASA Aviation Safety Reporting System program.

Installation Cost for second antenna \$1,500

**Example implementation cost for the Meridian \$15,000**

#### 7.4. UAS Cost Estimation Example

Example vehicle is a Predator drone equipped for a civilian surveillance and monitoring role, operated by the US Environmental Protection Agency.

<u>AFR Enabling Equipment</u>	<u>Projected Unit Cost</u>
Dual GPS Navigation System	\$14,000
TCAS/Surveillance unit containing tactical AFR function	\$8000
Interfaces with flight control system and communications unit	\$2500
UAT/1090 antenna upgrade	\$500

#### Equipment already installed in example UAS

Dual GPS Navigation system  
Detect-and-avoid (DAA) system including TCAS, ADS-B IN and OUT and ATCRBS  
Interfaces from DAA to flight control system, ATSU and remote operator  
Dual frequency antennas

<u>Needed Equipment for the Example Aircraft</u>	<u>Cost</u>
DAA system upgrade to include tactical AFR function	\$5,000
Second surveillance system with tactical AFR function but without TCAS or non-cooperative surveillance	\$8,000

The government is purchasing the UAS new with the needed equipment installed by the manufacturer. Remote pilot familiarization with the AFR function is integral with the initial training for its entire operation.

**Example marginal AFR cost for Predator** **\$13,000**

The current operator of most large UAS is the US military. As a very significant user of the US airspace and provider of air traffic services, representatives of the military should be familiarized with the AFR concept and discuss its potential for their US domestic operations of both manned and unmanned aircraft.

## **8. Description of Benefit Mechanisms**

This report does not contain a comprehensive, quantitative assessment of the AFR benefits available to the identified airspace users. That activity is reserved to a future study. This section describes the benefit mechanisms that would be available to each of the users, emphasizing those that are most important to each user category. The benefits may be grouped into the following three broad areas:

1. Exemption from certain traffic flow management initiatives and procedures
2. Exemption from constraints in the IFR airspace structure
3. Improved access to airspace and freedom of operation within the airspace

The traffic flow management initiatives from which AFR flights would be exempt include airspace (red sectors and defined congestion areas) ground delay programs, miles-in-trail restrictions on departure and en route, and en route severe weather re-routes. The constraints associated with the IFR airspace structure include departure fix restrictions, overhead slot restrictions, terminal area departure procedures, and ATC preferred routes. The final benefit category includes the ability to depart at will, without waiting for a clearance to be coordinated with the Center, and to operate along ad hoc trajectories, not declared in advance.

### **8.1. Airline Benefit Mechanisms**

The airlines would derive the majority of their AFR benefits from mechanisms one and two. The IFR system has been designed around the needs of the scheduled air carriers so their access to airspace and most commonly used routings is accommodated. Improvements to ATC procedures are geared to obtaining greater efficiency for point to point transportation flights. The adoption of RNP terminal arrival procedures is an example of this kind of improvement. But the greatest causes of delay and inefficiency for the air carriers are the flow constraints and structural rigidity of flight paths established to maintain a manageable workload for human controllers, and thus ensure the safety of IFR operations.

When multiple flights are routed over the same departure fix, often from multiple airports in the same metropolitan area, the needed distance between flights at the fix causes takeoff delays to be issued to each of the flights. AFR flights would not be subject to this delay and could depart from an intersection or another runway to avoid the queue. At many airports, flights are delayed at takeoff to wait for a slot in the overhead stream of traffic on the filed airway. AFR flights would be exempt from these delays.

As air traffic has increased through the years, individual en route sectors in the airspace become "overloaded," in that the number of aircraft in the sector is projected to exceed that which can be safely handled by a human controller. An automation tool has been employed to predict when these overloads will occur and impose ground delays for takeoff on those aircraft whose flight plans traverse the impacted sector. As the overload is a human limitation rather than a lack of airspace, the AFR flights would be exempt from these delay programs.

In the en-route airspace, it is common practice to require a minimum miles-in-trail spacing, regardless of altitude, between aircraft crossing the center boundary. This may be 20, 30, or even 40 miles at times if two flows of traffic are to be merged in the next sector. The effect of this practice is to prevent normal passing from taking place between aircraft with different cruising speeds. There is not room in one Center's airspace to catch up, pass, and get 20 to 40 miles ahead before crossing the next Center boundary, so the flights are slowed and vectored to maintain spacing in the flow behind the slowest aircraft in line. AFR flights would be exempt from this as they are not under IFR control en route and merge with the IFR flights in the destination terminal area using RTA, where available, or a separate

arrival fix elsewhere. It should be noted that AFR flights are sequenced equitably with IFRs in a destination airport delay program, but would be free to meet the arrival time on their own rather than through an imposed takeoff time upstream, thus can fly more optimal routes and altitudes.

In the continental US, "convective activity" (thunderstorms) exists somewhere during at least nine months of the year. It is a common practice for the FAA Command Center to create mass re-routes for flights that would traverse an area of forecast convective activity to prevent flight diversions around cells that increase controller workload. The re-routes can add hundreds of miles to a route of flight, and sometimes the weather either doesn't materialize, or shows up at a different location or time. AFR flights would be exempt from these re-routes and free to fly around the actual weather encountered in real-time using airborne and ground-based radar and "now-cast" products, and dispatch services, when available.

ATC preferred routes abound, especially east of the Mississippi, between all major city pairs. Those routes are established to force traffic into major flow patterns that assist human controllers in managing the traffic. Preferred routes commonly add 10-20 and often up to 50% increases in route mileage over the great circle route between the cities. In addition, there are standard terminal departure routes that add additional miles. Those in the larger metropolitan areas are quite circuitous, adding significant mileage to the flight, and they also contain altitude constraints that prevent the ability to use an efficient (uninterrupted) climb profile. AFR flights are free to find and fly a "wind-optimized" route to destination, again, merging with the IFR flow in the destination terminal area.

## **8.2. Fractional Operator Benefit Mechanisms**

The majority of the flights flown by the fractional operators experience the same sorts of delays and inefficiencies as the airlines, with an increased bias away from benefit number 1 toward benefit number 2. This bias stems from the greater use of the non-hub airports by the fractionals, while still frequenting the largest population centers in the country. Fractionals are particularly hard hit by IFR airspace structural constraints because terminal airspace structures favor the major airport and frequently add additional penalty for those using the satellite airports. But the fractionals take a double hit from structural inefficiency since many of their operations are range-limited and the route penalties can force a fuel stop en route when the same trip could be flown nonstop using AFR without the route penalty.

## **8.3. General Aviation Benefit Mechanisms**

The benefits of AFR for the majority of GA flights come from mechanisms 2 and 3. GA flights have the same route mile penalties as the fractionals when operating from satellite airports in the major terminal areas. They also have an even bigger problem when trying to fly IFR from airports not in the major metropolitan areas - a problem of gaining access to the airspace. At most of these airports, an IFR clearance cannot be received on the ground by radio because there is no radio coverage to the ground. Procedures call for obtaining an IFR clearance from these airports over the telephone from a Flight Service Station. The coordination between the Flight Service Station and the Center takes time, of course, and the Center may be busy with other traffic and place this clearance on a low priority. Once the clearance is finally received, it comes with a void time. "Clearance void if not airborne by...". After the delay in getting the clearance, there is often a rush to get airborne before the void time, which is a situation that does not enhance the safety of the operation. Once in the air on the IFR clearance, the same issues of inefficiency described for the fractional operators hold equally true for GA operators.

There is a high percentage of GA operations that are not point to point transportation. Among them, flight training, sport and recreational flying and a myriad of "surveillance missions" of sorts like real

estate, power line and pipeline patrol, and other surveys of all kinds. These flights do not go from A to B, but return instead to A. Furthermore, they cannot specify the trajectory to be flown because it is not known in advance, and it depends on what is encountered or occurs after takeoff. Most helicopter flights face similar IFR delays. VFR makes these flights possible today but when any portion of such a flight might encounter Instrument Meteorological Conditions (IMC) today, the flight must be scrubbed. With the AFR option available, these flights could continue to operate and provide their benefits with much greater reliability.

#### **8.4. UAS Benefit Mechanisms**

In a similar fashion, many of the proposed UAS civil operations depend on access to the airspace, not from the major airports, but from secondary or even private facilities for launch and recovery. UAS operations will benefit from mechanisms 2 and 3 with an emphasis on 3. The large, unmanned vehicles have the capability to fly using IFR, if necessary, to accomplish their missions. But the IFR constraints are cumbersome, time consuming, wasteful of fuel, and worse for the environment. The ability to perform these missions using AFR would provide very substantial savings, and in many cases, make the mission possible at all.

Civil use of UAS is very small right now, but in the time frame that AFR could be approved, there are solid proposals for a large number of operations that would truly be additional flights in the airspace, not just existing (manned) flights shifting from IFR to AFR. The scalability of AFR supports this projected increase in flights that may occur with regular use of UAS in the NAS. In this sense, AFR not only eases access to the NAS, it actually *enables* access to the NAS when it might otherwise have been denied.

Obtaining access to the airspace is essential, of course, but just as important is the ability to conduct the mission once airborne. The myriad of GA operations that are not point to point transportation is eclipsed by those planned for UAS. From law enforcement to survey to surveillance, fire and disaster relief, communications, environmental monitoring, even tethered power generation - the list is as long as the imaginations of the futurists. The need to operate through periods and locations of IMC during these missions is paramount and AFR provides the practical means for achieving this. AFR, therefore, is not just a financial benefit for these operations, it is truly an enabler of them.

## 9. Considerations for Implementation Strategies

All airspace user classes face a period between first installation and regular, complete use of AFR in their entire fleet. It is important to create a strategy to minimize the costs during implementation while maximizing the operating benefits. Although our proposed implementation is after the effective date of the ADS-B OUT rule, there may be some operators who had not planned on flying in ADS-B airspace who will choose to do AFR and thus will have to implement ADS-B OUT to participate in AFR.

To enable AFR, FAA certification, operational approval, and flight procedures will need to be approved and in place. This will ensure that the mechanisms for individual operational approvals will be in place for applicants to meet the operational, equipment, and training standards. The flight procedures need to include transition to AFR (“after take-off cleared to proceed under AFR”) and integrating the aircraft into the IFR arrival flow at high density airports. For arrivals, the current concept is that the AFR aircraft will be given an arrival fix and a required time of arrival (if needed) to that fix. When the aircraft is flying “direct to” that fix and conflict free (about 10 minutes prior) the pilot will call ATC and ask for an IFR clearance (possibly a FIM clearance). It is assumed that lower traffic density will permit the assigned arrival fix to be closer to the airport. Procedures for equipment failure will also need to be approved. In the vast majority of cases, the aircraft will be conflict free at the time an equipment failure occurs, thus there will be time for the aircraft to call ATC and request an IFR clearance (the aircraft intended route of flight will already be available to the controller).

The equipment to be purchased for AFR will comply with AFR MOPS created in the RTCA, and for airlines, the boxes will have to meet a TSO. The installation of even TSO'd equipment has to be done according to an approved Supplemental Type Certificate (STC). The pilot training requirements will vary by operator type but at a minimum there will likely be a new FAR Part 61 set of rules regarding acceptable training and checking for AFR operations. Airlines will have their AFR training program approved by their Principal Operations Inspector (POI). All of these things must be in place before the transition begins. When it is possible to buy approved equipment for AFR, train pilots to use it and operate it using established AFR rules in the national airspace, then it is time to purchase and install the equipment, train the pilots to use it and begin flying AFR. The implementation strategy is a transition plan from being totally unequipped to participate to a final state of being completely capable of using AFR in all operations. At each stage of the transition, the strategy should ensure maximum payback from the investments made (benefits minus costs). Until the first aircraft is equipped and the first crew trained, there will only be costs, of course, but the strategy is to turn this equation positive in the shortest time and continue to grow it during the transition. What follows are the more detailed implementation strategy considerations by airspace user class.

## 9.1. Airline Strategy Considerations

The strategy for airline implementation of AFR includes these cost considerations:

1. Fleet and sub-fleet size
2. Existing avionics
3. Purchase price
  - Delivery rate, maintenance agreement, favored customer status
4. Installation opportunities
  - Installation vendor
5. Training program and schedule
6. Flight Planning systems
7. Operational feedback

The benefit considerations during implementation are:

1. Aircraft routing
2. Flight planning
3. CDM treatment

An airline fleet is defined by the aircraft type, e.g., B-757. Each fleet may be divided into sub-fleets for many reasons, usually having to do with installed equipment, operating regions (domestic, overwater), or pilot qualification. For AFR, these are all important distinctions. The sub-fleet that has the most required avionics already installed will have the smallest equipment acquisition cost. As this is the largest cost item, it should be used in appraising the starting choice. Next, look at where the fleet spends most of its flying time, as AFR will initially only be available in the US domestic airspace. The first fleet to receive equipment and training should operate domestically and make a preponderance of its departures from major airport terminals where IFR delays and constraints are high. A secondary consideration would be fleets that fly city pairs which currently experience the greatest distance penalty over the great circle distance.

The equipment cost per unit in any given sub-fleet is nearly always subject to negotiation. Things that affect this cost are number of units purchased, the delivery schedule, other revenue connected to the purchase such as additional, unrelated avionics equipment, maintenance agreements for the equipment and perhaps, a favored vendor status that exists prior to the purchase. As long as there is competition in the equipment supplier marketplace, the costs will be in line with other avionics of similar complexity and certification criticality. An exception to this may be the aircraft that have all their electronic functions bundled into a single proprietary "cabinet". This represents more of a monopoly supplier situation that can impact equipment cost significantly since the price may be set according to the expected benefits to be enjoyed by the user rather than production costs plus margin. This has become a common practice in the industry during the last few decades. For an AFR system, the cost impact could be significant because of the high benefits available from its use.

It is common practice among the airlines to install systems while the airplane is "down" for routine scheduled maintenance visits. This prevents adding "out of service" revenue loss to the cost of installation. The maintenance visits in question are normally "heavy maintenance" when much of the airplane's interior is already being removed, creating access for necessary wiring changes. These visits usually occur about once in five years, however, so it could take a very long time to equip a sub-fleet for which the pilots have all been trained but only get a few opportunities to fly the airplanes that have been modified. Thus it is important to find the shortest fleet wide installation time and pair it with more routine maintenance visits in order not to stretch out the transition too long, thus delaying the accumulation of benefits. Sometimes this favors doing the installation in-house as the opportunities are more frequent. On a large fleet, however, the savings in installation cost by outsourcing might outweigh the benefit of a

more rapid conversion. In addition, with all crews trained, each aircraft will receive the full benefit as soon as the aircraft is converted thus enticing airlines to expedite the equipage. This will also accelerate the benefits from other ADS-B IN applications that require a high percentage of equipped aircraft.

Any fleet that shares a common pilot type rating with another fleet has a larger number of pilots assigned to fly it. As the number of pilots that might fly the airplanes is increased, the total training costs go up. This is a cost consideration that will go into the payback equation but will probably not determine which sub-fleet to equip first by itself. Development of the training program will be about the same for each fleet regardless of fleet size, so amortization of that cost favors starting with the largest fleet. However, the training development cost is usually small compared to the pilot pay for training, so it is a minor consideration. Once the installations begin on any sub-fleet, the pilot training to use the equipment for benefit should proceed immediately so that every equipped airplane will have a trained crew on board to use it for benefit. As long as the training can be accomplished by CBT, it can proceed simultaneously among all the effected pilots. All can be trained within a matter of weeks.

The flight planning system used for the chosen initial AFR fleet should be modified as necessary to disregard ATC preferred routes and procedural constraints when calculating a wind-optimized flight plan. This modification should be timed for completion prior to the first AFR-equipped aircraft entering service as the cost will be the same whenever it is done, but it must be accomplished to receive maximum AFR benefits on the first flight. CDM is a term applied to the airlines collaboration with the FAA Command Center during the use of TFM initiatives. These initiatives occur daily in at least some part of the country, so the airlines have created sophisticated automation tools to assist in the handling of their IFR flights to limit the delay impact of TFM initiatives as much as possible. The ground delay programs associated with adverse weather at a destination airport causing a reduced acceptance rate will include both IFR and AFR flights, but the AFRs will be exempt from the other local and enroute initiatives, and the airlines CDM tools should be able to automatically exempt them from participation, from the time of the first AFR flight onward.

The feedback system to let pilots inform management about the AFR experience and any part of the system or procedures that need attention should likewise be in place at the time of the first AFR flight. Any reported AFR incident should be immediately flagged for analysis and lead to remedial action, if necessary. Flight planning and CDM modifications and information feedback systems represent one-time costs, non-recurring, but essential to obtaining the maximum benefits from AFR. These fixed start-up costs argue for making the initial AFR sub-fleet relatively large to begin re-cooping these costs as soon as possible.

## **9.2. Fractional Operator Strategy Considerations**

The primary differences between airlines and fractional operators are: The size of the aircraft is smaller; the operations are not regular nor scheduled far in advance; the costs of avionics are a much higher proportion of the total value of the aircraft; the operating regulations (Part 135 vs. 121) are less stringent; the use of major hub airports is less. The ways in which they are the same include: fairly large fleet size; point to point transportation; use of professional pilots with contractual flight rules and pay; centralized dispatch organizations and flight planning systems. Thus much of what was said above for the airlines holds true of the fractional operators as well.

Most of the fractional companies operate more than one fleet type. The most recently purchased aircraft will likely have the most modern avionics and could integrate the AFR additions with the least cost. Fractionals are caught between the airlines and General Aviation in terms of avionics requirements and costs. They want to have (and be able to advertise) the reliability and safety of airline equipment but the cost of getting an AFR equipment STC for some of these small fleets of aircraft can be prohibitive.

The greater the number of aircraft types, the worse this problem becomes. Large avionics manufacturers will be more likely to obtain STCs for their equipment installations in the large airline fleets than for 20 or so "business jet" sized aircraft. The offerings from Garmin, Bendix/King, and Avidyne could make a lot more sense for AFR retrofit in the fractionals' market.

AFR benefits for the fractionals are often related to exemption from the IFR routings and procedures in place for a major hub airport, that must be flown even when the flight is operating to or from another airport in the same terminal area. These terminal procedures and other parts of the ATC preferred routing structure can spell the difference between a non-stop flight and having to make a fuel stop. Accordingly, other things being equal, the most range-limited fleet should be considered as the first to be equipped for AFR.

Installation costs will again be the second highest category for the fractionals and timing the installation to occur with maintenance visits is common in these companies as well. The correct strategy would be to equip the fleet first that requires the least in upgrades for lower purchase and installation costs so that those aircraft can be producing operating savings while the balance of the fleet gets equipped. The issue of in-house installation versus outsourcing should be decided by the existing capability to perform this work. If such exists, that is likely the best option. If not, it may make the most sense to look for a purchase agreement that includes the installation at a reputable (and capable) avionics mod shop. Like the airlines, the fractionals can negotiate deals that may combine equipment purchase and installation and perhaps even continuing maintenance under one contract.

Also like the airlines, pilot training for those pilots in the chosen first fleet should be accomplished by the time the first airplane is equipped for AFR. CBT should be used if such a program will be approved by the FAA. The company's local FAA oversight office should be included in the installation and training planning from the start so that the rationale behind all decisions is understood going in. This will help prevent costly mistakes and time consuming delay in achieving the operating benefits of AFR.

The flight planning systems used by the fractionals are frequently outside services available under contract. The implementation strategy for fractionals must include consultation with their flight planning service providers to determine whether they are capable of producing a wind-optimized plan for AFR flights, free of the IFR preferred ATC structure. If not, it may require looking for an alternative service provider to obtain the full AFR benefits. In the event that collaboration with the FAA on flow management initiatives is not handled centrally, the pilot training must include information on what types of restrictions exempt AFR flights and how to plan and interact with ATC accordingly.

Fractionals also may not have a formalized pilot feedback mechanism in place. While this is not anticipated to be a regulatory requirement, some form of messaging in an easy to use format should be established, whether by email, SMS messaging or phone call with an established addressee and an internal process for handling the information received.

### **9.3. General Aviation Strategy Considerations**

Because of the extreme diversity of GA operations, the strategy to implement AFR will vary widely by the type of operator and the mission. The biggest disparities are between very large and very small aircraft, and multiple fleet business aviation departments vs. owner/pilot transportation in one airplane for business and pleasure. The strategy for major aviation departments is similar to that of the fractionals, but the larger number of small owner/pilot aircraft will have a strategy of their own, that is given here.

There are many General Aviation pilots that only fly VFR. While this helps the efficiency and flexibility of their flights, the "see and avoid" practice offers less than perfect mid-air collision safety. Many GA pilots have purchased TAS including ADS-B surveillance along with active interrogation on

the transponder frequency to lower the risk. For many of them, AFR offers additional safety advantages and they will want to consider that equipment to get the extra protection.

All the major manufacturers of general aviation ADS-B equipment already have ADS-B IN offerings for traffic awareness and FIS-B weather products. By 2020 when the ADS-B OUT mandate takes effect, these manufacturers expect to include an AFR software upgrade with these offerings, assuming the FAA has approved the system standards and created operational rules for its use. Thus the acquisition strategy for a GA owner /pilot is simply to survey the offerings and decide if the upgrade is worth the price for the operations they either do, or would desire to conduct. It is probable that there will be an upgrade for any of the major GA avionics packages that even now contain ADS-B IN applications, and the owner will look to the supplier of his currently installed avionics for the upgrade.

Many GA operations take a huge penalty when conducting a flight under IFR compared to making the same flight under VFR. Departing a non-towered airport without radio contact availability on the ground can be very frustrating and time consuming doing it over the phone. By contrast, departing AFR in IMC in Class G airspace, with an automatic log-on to an ADS-B ground station once airborne, has no delay at all. The ability to proceed direct to destination after take-off rather than "fly east to go west" as is often required on an IFR departure can also save very significant time and fuel. So the GA strategy consists primarily of understanding and evaluating the benefits of AFR in their particular operation and comparing that to the cost of an AFR upgrade. It is expected that the training for certification will be offered on-line by several of the flight training and re-certification schools that currently provide this for other ratings and certificate renewal. The big question is whether the FAA will require any demonstrated performance in either a simulator or an aircraft if the pilot being trained is already instrument rated, because getting an instruction from the cockpit system that is identical to that given by a controller should not require any simulator or airplane demonstrations. A computer-based test to confirm the pilot knows the rules and how to operate the equipment should suffice.

#### **9.4. UAS Strategy Considerations**

UAS operations in the NAS today are very limited because of the restrictions on access and the onerous requirements for operational approval. AFR could dramatically alter the access picture and make feasible a smorgasbord of UAS domestic missions in civil operations as well as greatly ease the ability of the military to operate their UAS in the NAS. For the military, it not only would ease the flights to and from military operating areas but could help to reduce the need to restrict the airspace for military operations only, thus benefiting all civil users.

The UAS AFR cost categories are fewer than for manned operations because of the absence of a pilot in the cockpit and the expected direct link between the ATU output and the UAS flight control systems. The costs are:

- Equipment Acquisition
- Equipment Installation
- Remote pilot familiarization
- Routine maintenance

AFR avionics for the UAS are considerably simpler than for crewed aircraft because there is no need for flight crew interactions and display. It was assumed in the architecture description in Section 4 that UAS would only use the tactical separation mode, so the surveillance and the output are simplified to the deterministic algorithms. It thus becomes just an upgrade to the DAA system currently under development. The upgrade will include an outer layer of standard IFR separation to the collision

avoidance function already included. Communication of the near term trajectory to both the remote pilot and the ANSP will use existing channels and contain the ATU output to show how separation will be maintained. An additional benefit for UAS is that operations now conducted only in Visual Meteorological Conditions (VMC), to enable the vehicle to remain within the sight of an observer, would not need to be concerned with the VMC requirement. Flights could go in and out of clouds under AFR with no diminution of safety and eliminate the requirement for an observer while still avoiding the restrictions of IFR.

There are so few UAS operations outside of restricted airspace today that it is unlikely there will need to be massive retrofits for AFR use. The capability will be specified at the time of purchase so installation by the operator would not generally be required. It will largely be a forward fit situation. UAS will also benefit from an ability of DAA equipment to detect non-cooperative targets operating under VFR (or IFR) in the lower altitudes of the Class E airspace. Filling this surveillance gap is an important step forward.

As the remote pilot (where used) will not actually control the vehicle through the conflict resolution, his training will only consist of familiarization with the function in order to be completely aware of what is going on. A training bulletin will likely suffice for this need.

Maintenance of the ATU is not an additional cost for the UAS operator who already has a DAA system installed on the vehicle. It will be accomplished with the maintenance of the parent system. Thus the implementation strategy for UAS operators is related solely to the vehicle capability going in. If it is equipped to operate under IFR, the upgrade to AFR will quickly pay for itself. If it is currently restricted to VMC because IFR restrictions won't permit the intended mission, then adding the AFR capability is indicated, and the cost of the system must be justified by the improved utility of the mission. Size, weight, power and cost considerations must be weighed against the ATU avionics offerings available, but when imbedded in the DAA, these are negligible.

## 10. Other Feedback from Outreach Interviews

In the course of information gathering for this study of AFR implementation costs, it was necessary to describe the AFR concept of operations as they pertained to each of the airspace user class representatives. This engendered a discussion of the value of the AFR option and the expected difficulties that might be encountered trying to establish the new operating paradigm.

Interestingly, the value of AFR operations was perceived as very high by all of the user classes. It was not seen as something that "might help out the other guy". Rather, it was described in superlative terms. "This is the most important thing ever to come out of ADS-B", and, "this doesn't sound that complicated to me."

After agreeing that it would work in mixed operations, there was usually a discussion of the integration with IFR flights in the terminal area. Departure was considered uncomplicated, consisting of being released to "proceed under AFR" shortly after takeoff. The arrival scenario depended on the degree of automation in existence at the terminal in the time frame of AFR introduction (post 2020). An automated airport arrival scheduler is assumed by everyone, upgrading the old Traffic Management Advisor system to Time-Based Flow Management (TBFM) or something better with greater sequence adjustment flexibility. "FIM" (Flight Deck Interval Management) was seen to be totally compatible with AFR and it would pick up the guidance function approaching the terminal just as the IFRs would do using this capability. Where FIM is not implemented, a separate arrival fix next to each of those existing for IFR could be established with AFR performing any needed metering to this fix so that conventional human controller techniques could be easily used to merge the arrivals beyond the arrival fixes.

The discussion of obstacles to be overcome generally placed the cultural shift at the top of the list, and potential resistance by the National Air Traffic Controllers Association (NATCA) to mixed operations. While NATCA has not yet been briefed in the AFR outreach, it is planned to do so. The AFR concept includes a number of features to make mixed operations acceptable to controllers. AFR flights will always give right of way to IFR, so that even though they will appear on the controller's display, the controller will not be responsible for them nor have to consider them in the normal course of controlling his/her IFR traffic. A separation buffer is in the concept, so that even if an IFR maneuvers toward an AFR flight, there is time to resolve the conflict without loss of separation. Additionally, the intent of the AFR will be known in almost all cases, beyond the velocity vector to at least the first TCP (trajectory change point). And, the AFR flights will be monitoring the active frequency of the sector they are in so that contact could be made, if the controller so desired. It may also be possible to reduce the redundancy of equipment on the aircraft by implementing procedures where an AFR failure on board an aircraft would require the crew to contact ATC for an IFR clearance. Since the aircraft will most likely be conflict free for at least ten minutes following such a failure, this procedure should not be burdensome for the controller or the crew.

Another frequently raised point is that AFR is not yet in the FAA's NextGen program, even though some aspects of self-separation are (FIM, PTM, corridors). This means formal recognition of AFR and specific funding must be found for standards development and rulemaking. Gaining operational approvals for the airlines and others, once the concept is accepted, was considered to be routine by some, difficult by others. In any case, the FAA's early involvement in bringing about the AFR concept was considered both essential and problematic, because it wasn't part of the ADS-B IN Aviation Rulemaking Committee, and the list of applications coming out of that seems to be the total focus of FAA right now.

The airlines, in particular, thought the big "airframers" Boeing and Airbus should be included in the outreach soon, even though they worried about them taking ownership of the avionics and sending the prices sky high. For those aircraft with a high degree of avionics integration during the initial

manufacture, the addition of the AFR function could be more complex as a re-certification problem because of the number of connected systems and the manner in which those systems would be impacted.

Overall, the feedback was very positive toward AFR, recognizing that it is not just the "ultimate ADS-B IN application, but the way all the airspace users ultimately wished to operate in NextGen.

## 11. Conclusions and Recommendations

This study has estimated the user cost of implementing AFR, and findings indicate the cost to be comparable to navigation system upgrades for all four airspace user classes and therefore generally within reach for most operators. The AFR equipment is very similar to avionics already being purchased, or planned for future purchase by most operators. As the primary element of AFR, the ATU is just a software upgrade using information from inside the aircraft and from external surveillance that is already defined and in increasing use. Neither installation, training nor operations are seen to be major obstacles as they will all follow normal and accepted practices, and the safety of the operations is assumed from the start as pilots will still be following clearances and instructions just as they always have, emanating from a new source.

Typical costs for each of the four classes of airspace user to implement AFR on a "per aircraft" basis were projected to be:

<u>User Class</u>	<u>Average</u>	<u>Range</u>
Airline	\$236,400	\$210,000 to \$603,000
Fractional Operator	\$92,281	\$50,000 to \$200,000
General Aviation	\$15,000	\$10,000 to \$50,000
UAS	\$13,000	\$10,000 to \$45,000

These cost projections include purchase and installation of the necessary avionics equipment, training of the pilots to use it in manned aircraft, and operations and maintenance of the equipment on an on-going basis including optimizing the flight plans for maximum beneficial use (and payback) of AFR. The projected range figures show the difference between expected (hoped for) safety case outcome and a more onerous result. They also reflect the difference between a few upgrades to existing equipment and all new equipment and new wiring on very old aircraft.

For owners of large fleets of aircraft, necessitating an extended period for implementing the capability throughout the entire fleet, there are strategies which can begin producing operating savings very quickly while the investment is still quite low. This result of benefits accruing to the first adopter makes the business case for AFR even stronger.

Recommendations include the following:

- NASA should conduct a comprehensive and quantitative AFR benefit study to complete the necessary information needed in the investment decision equation. It was found in this study that the airspace users intuitive feel for the value of the benefits showed them to be very substantial, supporting a short payback period.
- Perform research on failure modes
- Assist FAA with the AFR safety study
- Test and refine CD&R algorithms - especially tactical
- Investigate simpler pilot interfaces with the system and procedures for its use
- Engage with the UAS research community to integrate DAA with AFR
- Expand the concept to the runway, both departure and arrival

A final, but major, recommendation is to engage in a joint development program for AFR with the FAA so that work on standards and rules can proceed in parallel with the remaining research.

## 12. References

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## Appendix A. AFR End to End Flight Scenarios

### A1. Air Carrier Scenario Example

The year is 2020. Transcon flight 657 is a regularly scheduled flight from Phoenix (PHX) to LaGuardia (LGA). It departs PHX at 1050 PDT and on this day in July is scheduled to arrive at 1745 EDT. The airline's flight planning system has recently been upgraded with optimization logic that can ignore structural route preferences except for the RNP Standard Terminal Arrival Route procedures at major terminals, such as LGA. The winds at altitude are typically light for the summertime but definitely favor flying north of the great circle route today. The flight planning system picks a lateral track that is slightly S-shaped and defined by 15 waypoints between PHX and the LGA arrival fix. The vertical path includes three 1000 foot step climbs between top of climb and top of descent. The cruise speed varies some throughout the flight as fuel is burned but averages about .01 less than standard Mach number because of slightly favorable winds. There is possible thunderstorm activity forecast from the Ohio valley northward through the Great Lakes but cells are expected to be scattered. Nevertheless, the ATCSCC has already begun Severe Weather Avoidance Plan (SWAP) route assignments for most IFR traffic that would otherwise fly through this area. The Transcon dispatcher and pilot assigned to this flight agree with the computer generated plan and add just 800 pounds for possible detours around cells during the final hour before descent into the New York area. The AFR flight plan is transmitted to both the FAA and the aircraft as the pilots go to the airplane to make ready for the flight.

Following a routine cockpit setup which includes verifying the expected route loaded in the FMS, the first officer logs in to the ANSP automation with the flight number, origin and destination for human/automation verification of the flight plan. The aircraft mode S code, Flight ID and the route of flight and initial cruise altitude from the FMS are automatically sent with the log in message to complete the verification process. Because the mode S transponder code is used and communications will be via CPDLC for this AFR flight, no pre-departure clearance is necessary. As soon as the flight indicates "ready" via data link, the route to follow from Terminal 3 to runway 8R is shown on the Electronic Flight Bag (EFB) display of the airport surface. When ready to enter taxiway Charlie from the ramp, the aircraft to follow is also shown on the display. When nearing the end of the departure runway, the taxi route indicates use of the runway intersection at Charlie 2, that is 500 feet from the runway end. This is done to bypass other IFR flights with departure fix restrictions, eliminating a few minutes wait before departure. Takeoff clearance is received as soon as the preceding departure is 6500 feet down the runway with a restriction to remain separated from that aircraft during departure. The IFR intent information available to Flt 657 shows the preceding departure will be turning to a heading of 060 after liftoff climbing to 8000 feet and proceeding direct to DRYHT when out of 4000. The ATU, knowing the two aircraft types will experience a slight overtake directs an initial heading of 045 to our AFR crew which will be used until standard lateral or vertical separation is established. This, and all subsequent flight guidance given to the AFR crew will also be sent to other AFR aircraft and the ANSP for use in the ground system safety monitoring functions.

As Flt 657 is leaving 4300 feet Mean Sea Level, standard lateral separation is achieved when the preceding departure heads direct for DRYHT and the message "Proceed under AFR" is received by our crew. This version of the FMS software continuously adjusts the entered route to begin at present position on the current track while flying in heading or track mode, so the pilots merely engage FMS lateral navigation and are on their way to LGA using the most current optimized trajectory available. The airline's flight planning system runs a new trajectory search from present position to destination right after liftoff and every subsequent half hour using the latest met information and sends a new plan to the airplane if it saves either a minute or 100 pounds of fuel. During the climb, the ATU detects a conflict with an IFR flight descending toward PHX and, because the vertical separation buffer is quite large while neither aircraft is in level flight, creates a slight adjustment to the right to pass behind this aircraft at a

distance of four miles, one more than the current ubiquitous three mile separation from IFR aircraft. At this point in time, even though the three largest US airlines have announced their intentions to go all AFR, only 5% of the fleet is equipped. This results in most conflicts being with IFR aircraft in which the AFR is burdened with the resolution responsibility. However, overall traffic has only grown 15% since 2012 and with the three mile standard, this is the only conflict encountered during the whole flight to the LGA arrival fix. The cold front in the eastern half of the country has progressed southeastward more quickly than forecast altering the winds used during initial flight planning and two flight plan amendments are received by the AFR crew, one resulting in earlier step climbs due to lower temperature and the other because of the shifting wind direction resulting in a trajectory closer to a great circle direct to the arrival fix. Destination fuel is shown increasing from both changes so they are immediately executed by the crew.

Throughout the flight, vectors and speed control instructions given to IFR flights in order to maintain miles in trail at boundary crossings are an amusement to our crew which is exempt from those constraints. Just before entering Indiana, the crew picks up the current convective activity from both their airborne and ground sensed radar, the latter being sent through their broadband connection. The place to be avoided at this point is further south than anticipated and several IFR aircraft are detouring on vectors around the south side of the weather even though this was expected to be clear and on their SWAP routes. The ATU had also chosen to go this way but based on the existing radar and visual observations of the weather, the crew "draws" a new route on the Nav Display just skirting the north side of the weather and then going direct to LIZZY on the Milton 4 arrival. The new touch screen display allowed the pilot to "grab and pull" the route to a new desired location, eliminating a lot of typing. They then Execute and the new plan is sent to other AFR aircraft and the ground. This new trajectory is used by the ground automation to define flight 657's Coded Departure Route to LIZZY, even though it is not on one of the charted transitions. The sent trajectory also contains an estimated LIZZY crossing, which is used in the TBFM automation to merge Flt 657 with the other arrival traffic to LGA. Two of the aircraft that deviated south of the weather in Indiana were also going to LGA and are now slightly behind their previous estimates so the TBFM has altered the sequence and now needs Flt 657 to cross LIZZY 24 seconds earlier than its estimate. This time is entered into the FMS at the fix and a new descent profile is calculated, leaving cruise altitude a little later and using a higher speed in descent. Even though several aircraft are converging at small angles toward LIZZY, their time separation at the fix keeps them separated longitudinally as they lose lateral separation due to the convergence.

Throughout the flight, the AFR crew had received data link messages updating the voice guard frequency for their location and they listened to the IFR communications, but none were required for Flt 657 and none were made. Nearing the LIZZY arrival fix, the ground-based IM software sends a message to Flt 657 containing the aircraft to follow and the desired time interval to use. After confirming this data, the crew accepts it, confirming the plan to the ground and allowing the FMS to provide flight guidance to the autopilot and flight director to establish and maintain the interval to the runway threshold. LIZZY is still 71 miles from LGA and during that arrival, several building cumulus clouds were present on the charted path. The crew of Flt 657 was able to clear the airspace and deviate around the bumpy clouds while still maintaining the interval on the aircraft ahead with a slightly increased speed, taken care of by the autothrottles. Any aircraft following 657 at a prescribed interval simply maintained the time to its abeam position on the common route. The more precise inter-arrival interval made possible by FIM permits an increase of 7 arrivals per hour from 34 to 41 when using the ILS to 4R. This increase has made it possible to eliminate the slot restrictions at LGA during almost the entire day. Flt 657 gets landing clearance on the datalink while just outside the DNNIS final approach fix and crosses the threshold 68 seconds behind the preceding arrival, two seconds early.

The taxi route to the gate is already on the EFB surface map and the "hold short" intersections and aircraft to follow clearly indicated. As the airplane pulls into the gate and sets the parking brake, the flight completion/logoff message is created and sent when the main cabin door is opened.

## **A2. Fractional Ownership Operator Scenario Example**

The year is 2021. YourFlight, Inc. is a fractional ownership operator that uses three types of jets ranging from the five seat successor to the Eclipse called the Penumbra to an eight seat Citation XX and several long range Bombardier 500 Globals. A call has just come in to take a family of three from Manchester New Hampshire to Fort Lauderdale Executive Airport in Florida. The Penumbra is the right fit for the job except that the IFR preferred route is to fly west to Wilkes-Barre, PA before turning south toward Florida. This adds 85 miles to the route and puts the destination just out of non-stop range. Fortunately, YourFlight has just installed the equipment and trained their crews to operate AFR in the Penumbra primarily because of the range limitation. A late autumn nor'easter is moving up the coast and the flight planner shows that a route just off the coast east of the New York metro area saves 35 minutes over going around to the west over Pennsylvania, enabling the flight to proceed non-stop. The AFR flight plan is loaded into the FMS and filed with the FAA for their reference.

After the airplane is loaded with the family and their luggage, the cockpit setup is completed including the AFR login with the FAA, confirmation of the filed flight plan, and initialization of the ATU computer that will manage flight optimization and traffic separation during the flight. Manchester does not yet have CPDLC so routine voice communications are used with the tower for taxi and takeoff clearance. The only difference is that even though the weather is IMC, the takeoff clearance sounds like the flight was VFR. "YourFlight 23, cleared for takeoff on Runway 35, left turn on course, monitor departure on 124.9". No wait is required to get a release from the Center, and no charted departure routing to conform to Boston traffic flows is needed. The flight plan keeps our flight initially at 14,000 feet for the first hour because it is above the mechanical turbulence and below the higher turbulence caused by high altitude wind shear associated with the storm system. It also provides a rare northeast tailwind that further speeds our flight toward Florida.

A conflict is detected by the ATU with a flight westbound to Westchester County airport, and the ATU computes a 10 degree left turn to pass clear behind. Crossing Long Island, the ATU indicates that climbing is not available because of a flight above descending for landing at Kennedy. Even though we had not planned to climb for another 45 minutes anyway, giving way to an occasional IFR flight is more cost effective than flying the additional 85 miles under IFR. Several other flights appear on the display while flying southwestward off the New Jersey coast, but none result in a conflict. Further south the winds aloft gradually shift around to favor the higher altitudes where the true airspeed is also higher. The optimization function of the ATU indicates a gradual climb to FL340 is available and will save fuel. A cruise climb is begun, and the trajectory is broadcast to other AFR's and the FAA over the ADS-B and to the company via the Broadband link .

Over the east coast of South Carolina, the customer gets a call from her sister asking if they could meet in Boca Raton rather than Fort Lauderdale as they had gotten delayed at Grandma's house. Quickly inquiring of our Captain, she is told, "no problem". Entering the Boca Raton airport in the FMS results in a new trajectory, optimized from the present position. Pushing "Execute" sends the new route to the others as before for use in their strategic planning systems. The ATU automatically checks the status of the offshore Warning Areas and, as they are hot, keeps the flight west of that airspace. The CPDLC routinely provides the voice frequency to monitor as the flight progresses through ATC sectors on the way south. No calls from ATC are required, nor made. Just off the Georgia coast, the flight begins to pick up light chop. The meteorological data suggested it would be smooth as high as Flight Level (FL) 330 so

the lower altitude is checked for conflicts and seeing none, FL330 is selected in the FMS and a descent begun.

Since the Boca Raton airport is in Class D airspace, it is not necessary to fly any of the charted arrival routes, thus saving additional miles. The Automatic Terminal Information Service (ATIS) indicates runway 05 is in use so the FMS connects the descent trajectory to a standard left turn into the final approach fix TANAH. This plan is sent to the Terminal Radar Approach Control (TRACON) as soon as it is executed. An idle descent from FL 330 begins 91 miles out as computed by the FMS which had loaded the current winds for the altitudes to be traversed along the way. Slight differences between the forecast winds and those encountered are accommodated by small pitch changes that increase and decrease the speed slightly around the target 260 knot descent speed.

At 35 miles from the airport, a message is received to extend the Final Approach Fix (FAF) out one and a half miles on the final approach course to accommodate another arrival that was a little later than forecast. Pulling the FAF into the scratchpad, "plus 1.5" is typed in, selected and executed. The execute key triggers the return message confirming the new clearance. The 1 degree right turn is almost imperceptible as the aircraft adjusts to the new course. The Approach Descent checklist is completed and, just prior to the turn to final, landing clearance is received. The desired parking area at Signature Flight Support had been sent earlier, prior to descent, so after landing, the taxi route to that location via the ramp taxiway appears on the iPad EFB with no interfering traffic showing to yield to. The welcoming party is standing at the fence outside the Fixed Base Operation (FBO), cheering our passengers as they leave the airplane in the warm sunshine, just three hours, but worlds away from the storm they had left behind in New England. The flight took just 3 hours and 11 minutes. More than an hour of flight time, additional fuel and lots of hassle and turbulence was avoided by going AFR non-stop vs. IFR with an enroute stop.

### **A3. General Aviation Scenario Example**

In 2020 when the ADS-B mandate took effect, AFR flights were allowed for the first time and Clyde Snodgrass was planning a business trip in his Piper Meridian, N280KTS. Mr. Snodgrass understood the value of AFR to his flying and had purchased the equipment a year earlier to be ready. He had taken and passed the FAA's required online training making it legal to fly AFR once the rules were effective. In the interim, he routinely operated the system while in VMC and flying under VFR to take advantage of the extra safety it provided.

Mr. Snodgrass is a marketing executive with a major tractor and farm implement manufacturer in Rock Island Illinois. However, he lives in his hometown of Altamont, TN on the Piney Creek Airpark (88TN) and keeps his airplane in his hanger, which is part of his house. It was Sunday night when Clyde checked the weather for his Monday morning flight to the office and found it was forecast to be clear in Tennessee but with low surface visibilities due to haze. During the flight to the Quad Cities airport (MLI), multiple layers of clouds would be encountered between 4000 and 18,000 feet. MLI was expected to have a ceiling of 4,000 and visibility of 5 miles at the proposed arrival time. The forecast wind increased rapidly out of the west at altitudes above FL240 so he decided to fly over at FL200, to be above all clouds during cruise in smooth air.

Clyde took out his electronic notebook and logged into his favorite third party flight planning provider to create his flight plan and file it with the FAA - as an AFR flight Plan! As his airplane's performance is already stored in the planner, Clyde just put in his preference for FL200 and requested the most fuel efficient route. Because of wind circulation patterns and wind gradient during climb and descent, the best wind route is almost never the great circle from origin to destination. This day was no exception and the flight planner produced a plan with the initial track during climb to the west of the direct track, the cruise portion drifting back across the track to the east and the descent gradually arcing

back in to Moline. Taking advantage of the wind gradient saved two minutes compared to the great circle, resulting in a 1 hour 44 minute flight plan. To go IFR would have meant a route over Nashville and Saint Louis, arriving from the southwest for an increased distance of 62 miles and additional 15 minutes of flight time.

Departing IFR from an uncontrolled airport can be a very time consuming process if the nearest tower can't be contacted by radio while on the ground. The clearance must be received over the telephone, good for a small window of time during which you must take off before the "void time". Sometimes this may only take an extra 10 minutes. Often, especially on busy Monday mornings, it can take a half hour or more. AFR flights are exempt from this process. Thus, the combination of shorter flight time and simplified departure allows Clyde to get an extra hour of sleep before the flight, leaving at 0700 Central time.

Fueling and preflight inspections had been completed the night before, so after pulling the airplane out of the hanger, Clyde gets in, starts the engine, turns on the radios and taxis out for takeoff. The pre-takeoff checklist is completed, his departure at Piney Creek is announced on 122.8 and he is on his way in less than 4 minutes since getting into the airplane. At 700 feet above the ground as he enters the Class E airspace, the ATU has logged in through the nearest ADS-B ground station and its annunciator shows that the initial frequency to monitor is Nashville Approach. During his cruise climb, Clyde can hear two aircraft being worked into the landing pattern at Nashville. They are also displayed on the ND, but are "no factor" as indicated on the ATU, being well below the climb path of N280KTS. The seven waypoints in the flight plan between Piney Creek and Moline that define the S - shaped lateral path are being followed by the autopilot and have also been sent to ATC via the Broadband link. The frequency to monitor has switched to Memphis Center, then Indianapolis Center and back again as the flight track cuts across the boundaries of their respective airspace.

Near the top of the climb, a northeast bound IFR flight is converging from the left at 17,000 feet. The ATU shows that a fifteen degree turn to the left will pass behind the traffic. Clyde turns the heading bug to the left, satisfying the ATU. This information is also sent via ADS-B from his newly purchased transponder unit. Even though the ADS-B mandate does not require sending this information, AFR rules do. As the method for including commanded headings and altitudes is already in the MOPS, some manufacturers have been including it in their new units, along with the next two TCPs, for competitive reasons, even though it is not mandatory. The traffic crossing takes place just 2 minutes after the new heading was established and Clyde redirects his navigation system to proceed direct to the next waypoint.

Clyde is flying in the clouds now and picking up light rime ice. The anti-ice system is keeping most of it off but the residual is costing about 5 knots of indicated airspeed. Upon reaching FL 200, the airplane is still going in and out of the cloud tops so Clyde continues the climb to FL210 and is now in the bright sunshine, where the residual ice will shortly sublimate. Near the Central City VHF Omnidirectional Range (VOR), IFR traffic appears at the edge of the display co-altitude and nearly head-on. The ATU shortly shows a projected conflict 45 miles ahead and indicates that a slight deviation to the right will resolve it. This is accepted and executed, and the conflict is cleared.

Other aircraft appear on the display during cruise, but no conflicts result, as most of them are at higher altitudes. The flight planning service uses more recent wind data and sends an updated plan to Clyde via the Broadband link. There is minimal change to the lateral track but the descent begins earlier, 75 miles from Moline, so it is accepted and executed. During the descent, a south bound airline flight is climbing on a converging course from the right and the ATU instructs that the descent rate should increase to pass well below the traffic. As soon as the vertical speed reaches 2000 feet per minute down, the conflict clears. The rest of the descent is routine and no other conflicts are encountered.

As soon as the communications monitor frequency calls for Quad City Approach, Clyde makes the standard IFR call in, "leaving 8000 feet 30 miles southeast with information Bravo". The AFR flight plan

has triggered an electronic flight strip in the TRACON so the controller has been expecting N280KTS and she responds with, "proceed direct to PCITY and plan an Area Navigation (RNAV) Runway 31 approach. You are number three to land but traffic is no factor". Clyde pulls the speed brakes briefly to get down to the 2,500 foot crossing altitude and sets up for the straight in approach and landing. Not having to fly a pattern to an opposite direction runway saves another five minutes thanks to the wind direction. Clyde is cleared to taxi via runway 23 and Delta to the ramp, where his assistant is waiting with the car. The fifteen minute ride to the office has him at his desk by 0900 Central time, just two hours after leaving his home in rural Tennessee.

# Appendix B. Organization Interviews

## B1. Example presentation

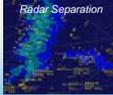
### AFR Implementation for Airlines

NASA investigation of AFR Implementation Issues



### Origins of IFR Flight Restrictions

- *Early IMC navigation limited to a few radio airways*
  - Surveillance by position reports, communications through 3rd party
  - Led to ATC procedural separation by assignment of route/alt/speed
- *By 1960s: radar, direct pilot/controller comm., RNAV*
  - New technologies enabled reduced separation standards
  - But assignment of route/alt/speed still the norm
- *Recent decades: Airspace "sector" controller has become the limiting factor*
  - Limitations of human cognition demands "orderly" traffic flows
  - Airways, "preferred" routes, cardinal altitudes, "pass back" of delays
  - Sectors, human capabilities limit aircraft simultaneously handled
- *Restriction, delay, inflexibility the norm for IFR*
  - Necessary to enable ATC to maintain responsibility for separation
  - Inefficient routing, non-optimum altitudes, reduced speeds
  - Miles-in-trail spacing, ground delay programs due to en route "congestion"
  - En masse rerouting for weather



### Background

- Airline operations are hindered by IFR procedures
  - Human centered separation paradigm requires regimentation, limits numbers of operations
  - TFMI have replaced efforts to expand capacity
  - NextGen no longer transformational
- NASA AFR concept is designed to overcome the limitations of IFR



### Solution – AFR Operations

- Self separation from all other traffic, weather and airspace hazards
- Airborne surveillance and separation algorithms provide safe trajectory guidance
- Pilots follow approved guidance just like following an ATC clearance
- Flights are free to optimize within the constraints of the automated guidance



### Purpose of Discussion

- Explain the Autonomous Flight Rules (AFR) concept for self separation
- Review benefit mechanisms
- Present enabling assumptions
- Discuss avionics architecture issues
- Address airline specific AFR adoption costs



### AFR Benefit Mechanisms

- Exemption from departure fix delays
- Exemption from airspace ground delay programs
- Exemption from Miles-in-Trail passbacks
- Exemption from use of ATC preferred routes
- Exemption from en mass weather re-routes
- Continuous trajectory optimization in accordance with individual business case



## Research & Development History

- Concept of Operations
  - "Distributed Air-Ground Traffic Management" (~2000)
  - "Autonomous Flight Rules" (2011)
- Flight-Deck Technology Development (AOP)
  - Algorithms, displays & procedures, avionics integration (~2000 ongoing)
- Human-in-the-Loop Research
  - Intent information (2002)
  - High-hazard scenarios (2002)
  - Basic mixed operations and scalability (2004)
  - Air vs. ground separation assurance comparison (2010)
  - Mixed operations w/ ground-based NextGen (2012a, 2012b)
    - Controller-focus and pilot-focus experiments
- Batch Research
  - Traffic density (2007)
  - Pilot response time (2008)
  - Wind uncertainty (2009)
  - ADS-B surveillance limitations (2010)
  - Weather/traffic avoidance integration (2010)
  - Intent information (2011)

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## ATU Functional Description

- Trajectory modeling – ownship and nearby traffic
- Conflict detection out to established time horizon
- Calculate conflict resolution(s) and prevention
- Communicate resolution to crew, (UAS Autopilot), to the ANSP and nearby aircraft
- Participate in destination airport TFM
- Perform ownship business trajectory optimization

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## AFR Descriptive Papers

- NASA/TP-2011-217174 "Autonomous Flight Rules – A Concept for Self Separation in U. S. Domestic Airspace"
- AIAA-2011-6865 "For Spacious Skies: Self Separation with 'Autonomous Flight Rules' in U.S. Domestic Airspace"
- AIAA-2012-5417 Paper "Autonomous Operations Planner: A Flexible Platform for Research in Flight Deck Support for Airborne Self-Separation"

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## Required New Enabler Systems

- Air Traffic Unit (ATU) software application
- ADS-B "In and Out" on ownship and ADS-B "Out" on all others
- TIS-B (enhanced) backup surveillance
- Basic Data Comm between ownship and ANSP
- Interfaces with some existing cockpit systems

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## Enabling Assumptions

- User demand for AFR Operations
- Successful completion of safety case for AFR
- FAA approval of mixed AFR, IFR, VFR operations
- FAA approved conflict detection and resolution algorithms publically available
- Liability issues no different than TCAS

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## Automation Technology for AFR

NASA "Autonomous Operations Planner" (AOP)

Integrated avionics system enabling self-separation

- Traffic separation in FMS and MCP flight modes
- Optimization of trajectories (integrated with de-confliction)
- Conformance with trajectory constraints
- Provisional probing for conflict-free trajectory changes
- Implicit coordination with "traffic aircraft" actions



## Why New Flight Rules?

- Permits continuity of service to IFR and VFR
- Gives flexibility in defining AFR and its integration with other operations
- Permits uniquely defined training, equipment and certification requirements
- Clarifies operator responsibility with clearly delineated operating rules

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## Sample AFR Architecture

- Airline Aircraft
- Dual FMS with:
  - intent bus providing own aircraft 4D trajectory to the ATU\*
  - ability to accept 4D trajectories from ATU\*
  - airspace information (sector boundaries, SUAs, ATC frequencies) in the navigation data base, and aircraft performance limitations available
- CDTI on large format Nav Display with AFR and other ADS-B "In" applications
  - ability to display heading, airspeed, and altitude resolutions from ATU\*.
- MCP with status (horizontal and vertical nav modes, heading, airspeed altitude) output to ATU
  - heading, airspeed, and altitude from ATU if that feature is implemented under CPDLC.\*

\* expected to be present in 2020

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## Sample AFR Architecture (cont.)

- TCAS and/or Transponder LRUs which includes:
  - hybrid surveillance\*
  - independent ADS-B "In" system with 1090 and UAT receivers, processes TIS-B and FIS-B, hosts air traffic unit for AFR, IM, closely spaced parallel approaches and other applications
  - receives and outputs to CMU and/or broadband and/or Overlay (weather, SWIM, ownship and other aircraft trajectories, etc.)
  - outputs to FMS (and MCP if implemented) in Data Comm format (or CPDLC or AOC formats)
  - outputs to aural alerting system\*
  - interfaces with MCDU or other I/O device

\*expected to be present in 2020

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## Sample AFR Architecture (concl)

- Upgrade 1090 antennas to 1090/UAT antennas
- Dual VHF Data Radio\*
- Dual MCDU\*
  - ATU status, CD&R information and pilot interface
- Architecture 1: dual TCAS as described above, level B software
- Architecture 2: single TCAS as described above, second Air Traffic Unit in TCAS LRU with independent power source and 2<sup>nd</sup> 1090/UAT receivers (share 1090/UAT antennas), level C software (but without TCAS function)

\* expected to be present in 2020

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## **B2. Interview Questions**

### ***Installation***

1. What fleet types do you operate?
2. How many aircraft in each fleet?
3. What plans are in place for aircraft additions and retirements?
4. Have you made plans to equip for the ADS-B mandate?
5. Do you perform avionics installations in-house?
6. Do you have your own DAS authority for avionics STCs?
7. Do you plan installations to coincide with regular maintenance visits?
8. How are costs allocated for avionics installations?
9. What was your experience with the TCAS change 7.2 upgrade? Did you include hybrid surveillance?
10. On which fleets do you have flat panel NAV Displays, versus CRTs? Do you have plans for replacing CRTs?
11. How are simulator modifications made to reflect aircraft changes?

### ***Training***

5. To what extent do you train your pilots using individualized CBT techniques?
6. What training programs have you had approved by your POI using CBT?
7. What costs are associated with CBT?
  - Course development?
  - Pilot pay for training time?
8. What costs are involved in incorporating new procedures into:
  - Recurrent training?
  - Initial/Transition training?

### ***Operations***

1. What do you see as obstacles to obtaining operational approval?
2. What formalized procedures do you have to receive operational feedback from pilots?
3. What costs are associated with administering feedback programs?
4. Is your flight planning system capable of ignoring ATC constraints while optimizing plans? If not, how hard would it be to modify for this capability?
5. Do you optimize flight plans of airborne aircraft?

### ***Maintenance***

1. Do you perform your own avionics maintenance?
2. If avionics maintenance is outsourced, to whom?
3. What are typical costs to maintain TCAS and Transponders?

### **B3. Organizations and companies interviewed**

Name

Airlines for America  
Aircraft Owners and Pilots Association  
Air Line Pilots Association  
National Business Aircraft Association  
General Aviation Manufacturers Association  
American Airlines  
Delta Airlines  
JetBlue Airlines  
Southwest Airlines  
United Airlines  
VirginAmerica Airlines  
General Atomics  
Northrop/Grumman  
Honeywell/Bendix/King  
ACSS  
Garmin  
Rockwell Collins  
ITT/Excellis  
Federal Aviation Administration

## Appendix C. Abbreviations

1090ES	1090 Megahertz Extended Squitter
4D	Four Dimensional
ADS-B	Automatic Dependent Surveillance Broadcast
AFR	Autonomous Flight Rules
ANSP	Air Navigation Service Provider
AOC	Airline Operational Control
AOP	Autonomous Operations Planner
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
ATU	Air Traffic Unit
CBT	Computer Based Training
CD&R	Conflict Detection and Resolution
CDM	Collaborative Decision Making
CDTI	Cockpit Display of Traffic Information
CMU	Communication Management Unit
CPDLC	Controller Pilot Data Link Communications
CRT	Cathode Ray Tube
DAA	Detect And Avoid (also referred to as Sense And Avoid, SAA)
EDT	Eastern Daylight Time
EFB	Electronic Flight Bag
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAR	Federal Aviation Regulations
FBO	Fixed Base Operator
FIM	Flight-deck Interval Management
FIS-B	Flight Information Service Broadcast
FL	Flight Level
FMS	Flight Management System
GA	General Aviation
GPS	Global Positioning System
I/O	Input/Output
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
ITP	In-Trail Procedures
LRU	Line Replacement Unit
MASPS	Minimum Aviation System Performance Standards
MCDU	Multifunction Control Display Unit
MCP	Mode Control Panel
MFD	Multi-Function Display
MOPS	Minimum Operational Performance Standards
NAS	National Airspace System
NATCA	National Air Traffic Controllers Association
ND	Navigation Display
NextGen	Next Generation Air Transportation System
PDT	Pacific Daylight Time
PFD	Primary Flight Display
POI	Principal Operations Inspector
PTM	Pairwise Traffic Management
RNP	Required Navigation Performance
SARPS	Standards and Recommended Practices
SNAPI	Status Notification and Planning Information

STC	Supplemental Type Certificate
SUA	Special Use Airspace
SWAP	Severe Weather Avoidance Plan
SWIM	System Wide Information Management
TAS	Traffic Advisory System
TASAR	Traffic Aware Strategic Aircrew Requests
TBFM	Time-Based Flow Management
TCAS	Traffic Alert and Collision Avoidance System
TCP	Trajectory Change Points
TFM	Traffic Flow Management
TIS-B	Traffic Information Service Broadcast
TRACON	Terminal Radar Approach Control
TSO	Technical Standard Order
UAS	Unmanned Aircraft Systems
UAT	Universal Access Transceiver
US	United States
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
WAAS	Wide Area Augmentation System

## Author Biographies

### William B. Cotton

Captain Cotton is known worldwide as the “Father of Free Flight”, the ATM operating concept for the future that would simultaneously increase safety, capacity, and operating efficiency in the air traffic system. As the chief technical pilot at United Airlines, he directed all of their air traffic control and flight systems related efforts. Mr. Cotton managed numerous projects from concept through development and implementation and has been a key innovative participant in many aviation industry activities to bring new technologies to fruition, such as TCAS and FANS-1. After retiring from United, Captain Cotton was President of Flight Safety Technologies, Inc. creating and managing the company’s strategy for developing its air safety technologies. This included creation of the concepts of operation and the operational design of its safety systems including the patented Unicorn ground proximity and collision alerting system, and the Aircraft Wake Safety Management system for increasing airport capacity. Mr. Cotton is currently a consultant working with NASA, the JPDO and FAA on several NextGen development efforts, including the investigation of self separation concepts for NASA under their Airspace Systems Program. He received a BS in Aeronautical and Astronautical Engineering from the University of Illinois and an MS in Aeronautical and Astronautical Engineering from MIT. He is still an active pilot and engineer.

### Robert Hilb

Captain Bob Hilb is retired from UPS where he headed the Advanced Flight Systems Department which recommended and implemented new technologies and systems for UPS aircraft and operations. Among the successful programs were a number of industry firsts: GPS autolands, an ASDE-X surface management system, CDAs (OPDs), and ADS-B certification and operational approvals. He also participated in numerous aircraft acquisitions. Prior to UPS he was a 737 Captain and headed the Operations Computer Department at People Express Airlines and he served in the Air Force and Air Force Reserve in various operational and staff assignments. Capt. Hilb has a BS degree in Astronautical Engineering, Engineering Sciences, and Computer Science from the United States Air Force Academy and a MS degree in Computer Science from Auburn University. He was an airline Captain for over 26 years. He participated and chaired various industry groups on ADS-B, Controller Pilot Data Link Communications, Flight Management Systems, and Airborne Separation Assurance. He has been a member of a number of aviation advisory groups such as the Gore Commission, the National Academies study on NASA, and the FAA’s Free Flight Steering and Air Traffic Management Advisory Committees. Bob holds patents on a number of aviation technologies and received numerous awards. Since retiring he has been a consultant to airlines, avionics companies, the FAA, and NASA.

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