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Digital Flight:
A New Cooperative Operating Mode to Complement VFR and IFR

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Abstract

Digital Flight is a proposed new operating mode for all airspace users, complementing and adding to the existing operating modes of visual and instrument flight rules (VFR and IFR) and providing for cooperative integration in controlled airspace. Under new regulations (Digital Flight Rules, DFR) that set requirements for its sustained use, qualified operators employ Digital Flight to enhance their airspace access and operational flexibility in all visibility conditions and eventually all airspace classes without requiring segregation from incumbent operations. Enabled by connected digital information and technologies, Digital Flight operators employ cooperative practices and self-separation to ensure flight path safety in lieu of visual procedures or receiving separation services from Air Traffic Control. Its distributed structure and automated functions enable traffic densities and operational tempos not achievable with the existing operating modes. Various ongoing and emerging industry initiatives for enabling new entrants (e.g., unmanned aircraft systems, urban air taxis) and enhanced use of underserved airspace (e.g., ultra-high altitude) are pursuing various alternative operating modes with significant similarities, creating a unique and time-limited opportunity for harmonization and convergence. Digital Flight is proposed to serve that harmonizing role, creating a common new paradigm for airspace operations. Such convergence would not only bring together these emerging market segments but will also bolster the existing operators with access to this new operating mode and its advantages. Digital Flight provides an opportunity to focus regulatory development and benefit the aviation industry. This paper describes Digital Flight in sufficient detail to initiate community engagement and deliberation on a common new operating mode. It describes the essential elements, principal capabilities, and operational integration of DFR in shared airspace. It describes the value proposition from multiple perspectives and presents initial thoughts on the path forward.

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Executive Summary

Aviation is on the threshold of tremendous change, with new technologies and new aircraft types driving diverse proposals for new operational missions. Advancements include remotely piloted aircraft; electric, hybrid, and other propulsion technologies; new vertical and short takeoff-and-landing aircraft; and increasingly autonomous operations. At an accelerating pace, as new entrant operators drive technology forward and lean on connected digital information and automation technologies, they are creating a new age of aviation. The Federal Aviation Administration has responded to the needs of new entrants by developing concepts of operation to accommodate the specialized needs for air traffic management and traffic deconfliction. New concepts include Unmanned Aircraft System Traffic Management (UTM) for operations near the surface, Urban Air Mobility (UAM) for operations in and around urban centers, and Upper Class E Traffic Management (ETM) for operations in airspace above 60,000 feet. Recognizing the risk of divergence and yet the commonality among these efforts, this paper proposes a mechanism to harmonize these various concepts and to empower all operators – new entrants *and* incumbents – with a new digitally enabled operating mode called **Digital Flight**.

> ***Digital Flight*** *is an operating mode in which flight operations are conducted by reference to digital information, with the operator ensuring flight-path safety through cooperative practices and self-separation enabled by connected digital technologies and automated information exchange.*

Formalizing Digital Flight under a set of *flight rules* is a natural progression in airspace operations, building on the historical progression that expanded operations from only visual flight the early period of aviation to enable the addition of instrument flight. In the same manner in which, in the last century, Instrument Flight Rules (IFR) enabled a dramatic expansion of aviation services and airspace use that Visual Flight Rules (VFR) alone could not support, introducing **Digital Flight Rules (DFR)** will accommodate the public need emergent in this century.

> ***Digital Flight Rules*** *are a set of regulations authorizing sustained Digital Flight as an alternative means of separation in VMC and IMC, in lieu of employing visual procedures (i.e., VFR) or receiving Air Traffic Control separation services (i.e., IFR).*

DFR is principally motivated by five drivers, the needs for: (1) **traffic scalability** as new entrants fulfill a public need for new aviation-based services; (2) **procedural compatibility with self-piloted aircraft** where there is no pilot onboard to operate with visual reference to the ground or manipulate flight controls in response to Air Traffic Control (ATC) instructions; (3) **operational predictability** particularly for emergent electric aircraft that cannot readily increase onboard energy stores; (4) **operational flexibility** enabling advanced air mobility in varying weather and airspace classes; and (5) **regional growth** via runway-independent operations and operations at non-towered airports.

The principal operational benefits of DFR to new entrants and incumbent operators will be combined **airspace access** and **operational flexibility** without the tradeoff required under VFR and IFR. Airspace access is the ability to operate in all airspace classes without outside visual reference (i.e., all weather conditions) and without specific ATC clearance/permissions for access to Classes A, B, C, and D airspace. Operational flexibility is the ability to dynamically change flight path intent without outside visual reference and without specific ATC clearance/permissions. By design, DFR operators will share the airspace with VFR and IFR operators without requiring segregation. They will proactively manage conflicts through self-separation automation with embedded cooperative practices. As with VFR and IFR, prerequisite qualifications will be established for DFR operators, including equipment, training, currency, and other requirements determined by Federal regulators in consultation with the industry.

Digital Flight is predicated on employing four essential elements: **digital information connectivity and services** (for maintaining a digital model of the operating environment for decision making); **shared traffic awareness** (for maintaining awareness of relevant traffic for use in conflict management); **cooperative practices** (for governing the behavior of DFR operations to ensure harmonized use of the airspace); and **separation automation** (for automating the separation function in flight path management). During flight, the DFR operator interacts with the separation automation in much the same way an IFR pilot interacts with ATC. Serving as the DFR operator's tool for conflict management, the separation automation also ensures conformance to the constraints of the operating environment and aircraft performance. Embedding cooperative practices into the automation's logic ensures they are consistently and reliably applied by all DFR aircraft in the presence of other DFR aircraft, non-DFR aircraft, and ATC, resulting in highly predictable behavior and seamless airspace integration.

The purpose of this document is to provide a description of Digital Flight at a sufficient level of detail to facilitate deliberation and debate by the aviation community as it explores the desirability, viability, and feasibility of a third common operating mode. Implementing a new operating mode for the airspace user community at large is a substantial undertaking and will require a broad community effort to see it through. Among the challenges will be establishing sufficient evidence of safety, performance, and maturity of DFR's enabling technologies, supporting data and infrastructure, and cooperative practices. Enabling limited Digital Flight applications to first emerge under VFR and IFR will provide opportunities to gather that evidence. Laying out a detailed path for implementation is a complex task and beyond the intended purpose of this document. However, several key activities relevant to the path forward are briefly described. These activities are based on pursuing an incremental implementation of Digital Flight capabilities that provide increasing benefits with time, while generating the required operational data and other artifacts for the eventual regulatory approvals and wide-scale adoption of Digital Flight and DFR.

The prospect of introducing Digital Flight, and ultimately DFR, offers the potential for significant value to the aviation industry, the airspace user communities, individual performers such as pilots, controllers, and dispatchers, and the ultimate beneficiary of aviation: the general public. The value to the aviation industry overall is the mechanism Digital Flight provides to safely advance the industry in a collective manner, enabling a significant expansion to the diversity of aviation operations while reducing friction for new entrants and their growth. Regulatory implementation of DFR that focuses on optimizing the benefit to the broad user population is a rare generational opportunity for the industry to embrace and empower aviation's growth in the 21st century.

1. Introduction

The history of aviation is a history of innovation and evolution. Advances in aircraft technology required a natural progression of policies, procedures, and infrastructure to enable the benefits of an innovative aviation sector. As early aircraft evolved, the need for standard operating practices to ensure safety became necessary. It was only two decades from the first flight at Kitty Hawk to the need for Airport Traffic Control to accommodate competing demand. In six decades, aviation went from first flight to supersonic travel. Aircraft technology was driven by military innovation that quickly became available for civil application and created a need for clearly defined regulatory frameworks.

Early navigation relied on visual reference to the ground, and aircraft avoided each other visually as well. Over time, Visual Flight Rules (VFR) created organized operating practices that supported pilots' ability to see and avoid other aircraft and anticipate each other's actions. The dependence on visual means for navigation and traffic deconfliction restricted operations under VFR to periods of Visual Meteorological Conditions (VMC). As aircraft technology continued to evolve, and as the services provided by air transportation demonstrated increasing value to society, the dependance on visual means impeded growth, innovation, and safety improvement.

Navigation and traffic deconfliction using information derived from sensors and instruments was enabled by the development of Instrument Flight Rules (IFR) that are available to pilots in either Instrument Meteorological Conditions (IMC) or VMC. The development of IFR led to the expansion of Air Traffic Control (ATC) from airports to airspace, and it fostered continually evolving standards, technologies, and procedures to accommodate increasing demand and complexity. With each major innovation in aircraft, there were corresponding innovations in infrastructure to support navigation, communication, surveillance, and other ground-based services provided to aircraft.

Today, the innovation in digital technology creates the opportunity for dramatically new operations in the airspace. Uncrewed flight, autonomous operations, and flights untethered to an airport infrastructure have captured the imagination of the industry. Just as technological improvements enabling operators to expand from visual flight to instrument flight required an appropriate set of flight rules, IFR, the improvements enabling a natural progress to "digital flight" call for an appropriate set of flight rules, proposed in this paper as Digital Flight Rules.

1.1. Digital Flight and Digital Flight Rules (DFR)

The capability of Digital Flight introduced and described herein aligns with and builds upon the concepts addressing the needs of many of the new entrants and emerging operations in the National Airspace System (NAS). The Federal Aviation Administration (FAA) describes Unmanned Aircraft System Traffic Management (UTM) [1] as being predicated on layers of digital information sharing to achieve safe operations. Operators under UTM share flight intent with each other and coordinate to deconflict and safely separate trajectories, without reliance on visual procedures or ATC separation services. As will be described in detail, Digital Flight shares the same principles of information sharing and operator managed separation, though on a much larger scale. Similarly, in the FAA's description of Urban Air Mobility (UAM) [2], strategic deconfliction of trajectories and tactical separation of aircraft occur without direct ATC involvement within UAM airspace constructs; these functions are instead allocated to UAM operators, pilots, or UAM service providers. In the emerging concept for Upper Class E Traffic Management (ETM) [3], operators are provided a choice between ATC separation services or cooperative community-based separation, where operators are ultimately responsible for maintaining separation from other vehicles. A common thread among these three emerging concepts is *operator responsibility for separation*. They also share common foundations of *cooperative practices*, *information sharing*, and *digital technology*, illustrating the emerging opportunity for a common operating mode. These foundations support the proposal for Digital Flight to be the common operating mode that can harmonize these otherwise disparate operations.

Neither IFR nor VFR are static rulesets. As technology evolved, new provisions emerged to allow its use. The evolution of aircraft navigation from visual reference to the ground, to radio beacons, to area navigation, to performance-based satellite navigation demanded an evolution of flight rules, regulations, and technical standards. However, enabling Digital Flight requires going beyond additions or modifications to existing flight rule sets that govern the IFR and VFR operating modes. Neither are designed to accommodate aircraft without an onboard pilot. The existing rules also do not take advantage of the advanced sensors, connectivity, and onboard computing power that are inherent to a digital operating mode. Technological advances have the potential to fundamentally alter or replace the human role in operating an aircraft. Growth in new markets with greater numbers of aircraft and diverse aircraft performance is limited by the existing IFR and VFR modes. The publication "*New Flight Rules to Enable the Era of Aerial Mobility in the National Airspace System*" [4] proposes and justifies the development of a third operating mode for digitally enabled operations.

Digital Flight Rules (DFR) are proposed as the regulatory implementation of the new cooperative operating mode of Digital Flight, thereby creating a formal complement to IFR and VFR. The result is three commonly available operating modes available to *any* airspace user – new entrant or incumbent – able to meet the appropriate performance requirements. For flights conducted in this new mode, the *aircraft operator* holds responsibility for flight path safety, including traffic separation, in VMC and IMC.[i] In lieu of VFR's visual procedures and IFR's ATC separation services, DFR operators meet this safety responsibility through the application of cooperative practices, self-separation, connected digital technologies and automated information exchange.

Just as IFR and VFR operations can coexist in the same airspace, DFR is envisioned to share the airspace with IFR and VFR without disrupting these operations, eliminating the need to segregate airspace for DFR flights. This integration is enabled by cooperative practices embedded directly in the automation and procedures. Incumbent airspace users will have the choice among these three operating modes to select which is most appropriate for their purposes, just as they are able to select between IFR and VFR today.

1.2. Document Purpose and Structure

The purpose of this document is to provide a description of Digital Flight at a sufficient level of detail to facilitate deliberation and debate by the aviation community as it explores the desirability,

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[i] The aircraft operator is the entity that uses, causes to use, or authorizes the use of the aircraft for purposes of flight. While 14 CFR (Code of Federal Regulations) 1.1 does not formally define operator, it defines *operate*: "With respect to aircraft, means use, cause to use or authorize to use aircraft, for the purpose (except as provided in § 91.13 of this chapter) of air navigation including the piloting of aircraft, with or without the right of legal control (as owner, lessee, or otherwise)."

viability, and feasibility of a third common operating mode. It is intended to serve as a reference frame for discussion, enabling the community to assess its merits and propose refinements and modifications. The description focuses on the essential elements and high-level capabilities to help in the future identification of specific functions, technologies, data sources, architectures, procedures, and performance requirements that are suitable for Digital Flight. The document also addresses the merits and anticipated impacts of Digital Flight from various stakeholder perspectives.

The remainder of the document is organized as follows.

- Section 2 presents the motivation for a new operating mode within the context of the existing modes and emerging challenges.
- Section 3 presents a technical description of Digital Flight, including its relationship to the existing modes and the airspace environment. The section presents four Essential Elements, six Principal Capabilities, and system safety considerations of Digital Flight.
- Section 4 presents the value proposition from the perspectives of aviation overall, airspace user communities, and individual stakeholders.
- Section 5 presents thoughts on the path forward toward achieving Digital Flight.
- Section 6 concludes the paper with thoughts on regulatory implementation of DFR.

2. Motivation

The motivation behind proposing a new operating mode begins with understanding the fundamental characteristics, advantages, and limitations of the existing operating modes, VFR and IFR. It is within this context that DFR brings distinctive value, including the enablement of new kinds of operations and improvements in operational capacity, efficiency, and safety (e.g., large scale operations of aircraft without onboard pilots). This section explores the characteristics and limitations of the existing modes relative to emergent needs and why now is the time to initiate the natural progression to a new operating mode.

2.1. Existing Operating Modes

2.1.1. VFR

VFR is characterized by distributed decision-making among VFR pilots. The option or requirement for coordinating actions through a centralized party such as ATC is dictated by airspace class:

- Class G, ATC services are not available.
- Class E, ATC advisory services are available on request, controller workload permitting.
- Class D, ATC separation is provided only for runway operations.
- Class C, ATC provides separation services to VFR aircraft from IFR aircraft.
- Class B, ATC provides separation between VFR and both IFR and VFR aircraft.
- Class A, VFR flight is not permitted.

The airspace classification system provides increasing levels of service based on potential airspace congestion and complexity, with higher levels of service closer to airports. VFR flights are otherwise self-managed by the pilot, and traffic deconfliction depends on the pilot onboard the aircraft to visually "see and avoid" other aircraft, supported by increasing levels of air traffic services as the airspace demands. Clear regulatory frameworks and licensing requirements ensure common understanding among all participants. Procedures are established through various regulations (e.g., 14 Code of Federal Regulations (CFR) Part 91 [5]) and non-regulatory guidance material (e.g., Aeronautical Information Manual [6]) such that VFR pilots know what to expect of each other and can anticipate each other's actions without formal coordination. Some examples of such procedures are yielding right-of-way, flying at cruising levels based on direction of flight, and following traffic patterns at uncontrolled airports. VFR is limited to verbal declarations of intent in the vicinity of certain airports via UNICOM or Common Traffic Advisory Frequency (CTAF) radio communications. [6]

VFR has inherent advantages and limitations. VFR provides operators with operational flexibility and scalability. Under VFR, pilots have the flexibility to replan their flight path at will, and without external coordination. Path changes are bounded only by operational restrictions established in the regulations for safety and airspace access (e.g., minimum safe altitudes, minimum weather conditions, special activity airspace). Scalability is an outcome of VFR's distributed structure, with the number of decision-makers scaling with the number of aircraft operating. The requirement for traffic deconfliction is for the VFR pilot to "remain well clear" of conflicting traffic, relying on the judgement of the individual pilot as decision maker to determine appropriate distance.

The primary limitations of the VFR operating mode are density of operations and airspace access. VFR safety derives benefits from the "big sky," and basic weather minimums are applied to make visual separation viable (i.e., flight visibility and distance from clouds). VFR operations are also prohibited in some classes of airspace (e.g., Class A). VFR poses a challenge to commercial business models that require on-demand airspace access, notwithstanding the weather or airspace class, as well as operations into congested areas that could result in unpredictable flight delays. Additionally, VFR suffers from a reduced level of safety compared to IFR because of the limitations of the "see-and-avoid" practice, which are particularly pronounced in higher traffic densities, faster speeds, and lower visibilities.

2.1.2. IFR

For flights conducted under IFR, the pilot and the air traffic controller have joint responsibility to manage flight path safety in a traffic environment. While the pilot retains final responsibility for collision and weather avoidance, IFR does not allow for deviation from the assigned course, route, or altitude without ATC approval (with the exception of an emergency maneuver). ATC is structured as a delegated system of centralized control. Airspace is divided into sectors, with one executive controller responsible for traffic in that sector, supported by other sector team members as workload demands. The services provided in each sector are dictated by the communication and surveillance capabilities in the designated airspace. Airspace is delegated to individual ATC facilities appropriate to the provision of services, including airport traffic control towers (ATCT), terminal radar approach control facilities (TRACON), and air route traffic control centers (ARTCC). Airspace and traffic planning and coordination is managed by the centralized Air Traffic Control System Command Center (ATCSCC) and its subordinate units located at air traffic facilities.

IFR flights are typically characterized as centrally managed. An operator-submitted flight plan is approved by ATC before IFR flight is permitted, and a controller issues route and altitude clearances, including flight path changes for IFR aircraft within their sector. [7] The sharing of flight path intent is formalized under IFR through flight plans and clearances, but intent is not specifically shared among individual aircraft. IFR flight path intent is used by ATC to facilitate strategic conflict management and provision of separation services, ensuring aircraft are kept apart by the application of an established separation standard. The appropriate minimum distance to be maintained between aircraft is established through a prescriptive standard developed through a formal safety management system. The sharing of IFR intent also enables the prediction of demand for airspace and airport resources, facilitating resource scheduling and demand-capacity balancing, and providing an increased degree of system-level predictability (if not individual flight predictability). It also enables tactical conflicts to be identified with longer lead times and therefore less significant modifications of the intended flight path.

Advantages of IFR relative to VFR are increased airspace access and system-level predictability. IFR access is not restricted by visibility conditions, and IFR flight is permitted in all airspace classes. IFR has the benefit of services provided by ATC in controlled airspace for the safe, orderly, and expeditious flow of air traffic. These services reduce or eliminate conflicts with other IFR flights, and they enable strategic operational management including demand-capacity balancing.

Limitations of the IFR operating mode include reduced operational flexibility for the operator, and sector capacity. Sector capacity is limited by frequency congestion from controller-pilot interactions, ATC workload, and airspace availability. Each of these is affected by external events, particularly weather or priority operations. The surface capacity (runways, taxiways, and gates) constrains arrival/departure capacity at many airports and surrounding airspace. Airspace capacity limitations not related to surface capacity are cyclically overcome through the adoption of new technologies and procedures like reduced vertical separation minima (RVSM), Performance Based Navigation (PBN), and Required Navigation Performance (RNP). These capacity enhancing technologies and procedures demonstrate that system limitations can be overcome through the regulatory acceptance of new technologies. While some capacity enhancements, like RVSM, increased system capacity through certification of avionics and adoption of a new separation standard, more complex opportunities required comprehensive change to communications, navigation, and surveillance (CNS) systems both on the aircraft and in the ATC system infrastructure. IFR could be adapted to permit remotely piloted flights, where the remote pilot has similar capabilities and responsibilities as a pilot onboard the aircraft. However, IFR is unsuitable for serving automatic or autonomous flight operations in the NAS.

2.1.3. Other Modes

While IFR and VFR are the operating modes used by most aircraft and are detailed in 14 CFR Part 91, General Operating and Flight Rules, there are other operating modes available to specific types of aircraft and missions that have very limited applicability. These other operating modes support the following types of aircraft:

- Moored balloons, kites, amateur rockets, and unmanned free balloons, 14 CFR Part 101 [8]
- Ultralights, 14 CFR Part 103 [9] [i]
- Small Unmanned Aircraft Systems (UAS), 14 CFR Part 107 [10]

Conflict management for aircraft operating under these specialized operating modes is accomplished through operating limitations (e.g., limiting the airspace in which they may operate) and specific operating procedures (e.g., small UAS must remain within visual line of sight of the remote pilot on the ground). These limitations and procedures are restrictive from both flexibility and airspace access perspectives.

2.2. Natural Progression to DFR

IFR and VFR modes are robust and effective, but they do not fully enable many of the evolving operational needs of this century, including the accommodation of various classes of new entrants. The increasing numbers of unmanned aircraft and the many different concepts associated with Advanced Air Mobility (AAM), to include urban air taxis, autonomous regional cargo delivery, unmanned parcel delivery, Beyond Visual Line of Sight (BVLOS) UAS operations, and unmanned High Altitude Platform Systems (HAPS) flights, are not readily accommodated by the current operational modes. As public demand for new airspace utilization emerges along with the enabling

[i] Ultralights are exempt from certain requirements in 14 CFR Part 61 and the altitude limits in 14 CFR Part 91, but use standard VFR for separation in all their operations.

technologies (as was the case leading to IFR), it is natural to progress to a new operating mode to accommodate the emergent public need.

2.2.1. Principal Motivations

Five principal motivations for a new operating mode are highlighted:

Scalability: Proponents of many of the new-entrant concepts envision 100s or potentially 1000s of simultaneous flights in a geographic region. The physical separation requirements and controller workload limitations associated with IFR operations are limiting factors in the number of simultaneous operations that can occur in a geographic region. As an example, in most terminal areas, a requirement exists for IFR flights to be separated by at least three nautical miles laterally or 1000 feet vertically.[7] Traffic volumes in individual ATC sectors are typically limited to one to two dozen aircraft to prevent controller overload.[11][12] These factors would significantly limit the number of short-duration, UAS/UAM/AAM flight operations under IFR, especially in airspace with already dense traffic.

Procedural Compatibility with Self-Piloted Aircraft: Many of the new entrants are envisioning a future without onboard pilots and potentially with aircraft that are effectively self-piloted, with the human's role reduced to one of monitoring and oversight. The operator may not have the ability to manipulate flight controls and may only be able to offer high-level guidance to the automation controlling the flight path. Self-piloted aircraft also cannot directly conform to current VFR and IFR requirements and procedures. There is no pilot to operate with visual reference to the ground, see and avoid obstacles and other aircraft, follow visual procedures, communicate with ATC, accept clearances, or monitor CTAF/UNICOM frequencies.

Operational Predictability: Most electric powered aircraft will not have the option that conventionally powered aircraft have of increasing their energy stores (i.e., adding extra fuel) prior to takeoff to account for operational uncertainties such as vectoring, holding, speed controls, and other delays enroute and at the destination. These aircraft will often be operating close to their maximum endurance (accounting for required safety reserves), which will generally be much smaller than conventionally powered aircraft. For some operations, an unexpected delay may constitute a large percentage of the entire planned flight duration. Operational predictability provides that, when the flight departs, the operator can be reasonably certain that it will encounter minimal changes to its overall enroute flight time.

Operational Flexibility: AAM operations depend on VFR-like flexibility to operate at scale in all classes of airspace and in varying weather conditions including IMC. Flexibility means not being restricted to specific route structures, altitudes, or airspace volumes and not requiring ATC permission for changes in route and altitude.

Regional Growth: The growth of runway-independent operations and operations at non-towered regional and rural airports in IMC could be constrained by current one-in, one-out ATC procedures. Operators under IFR departing non-towered airports into controlled airspace must request an ATC clearance to enter controlled airspace, the receipt of which can be time-consuming. Also, congestion at major airports occasionally creates airspace bottlenecks that impact flights that do not have the congested airport as a destination.

2.2.2. Respecting the Existing Modes

Over time, VFR and IFR have evolved to address new challenges. However, the degree of adaptation required to accommodate the capabilities and envisioned operational tempos of the new entrants is likely beyond the ability to be addressed through modification to the existing operating modes. Changes to VFR and IFR regulations could also adversely impact incumbent operators, requiring them to modify their procedures and potentially requiring new equipment and performance capabilities. A new operating mode respects the needs and stability of users under existing modes.

While motivated by the needs of new entrants, Digital Flight also creates opportunities for existing users. All incumbent airspace users may benefit from operating under DFR if they choose to satisfy the operational performance requirements and adhere to the cooperative procedures. In the same manner that the introduction of IFR created a new option for existing users without precluding the VFR option, DFR would expand the options even further without imposing new equipage requirements or procedure changes on VFR and IFR operators.

2.2.3. Time for a New Operating Mode

Aviation is on the threshold of tremendous change, with new technologies and new aircraft types driving diverse proposals for new operational missions. Advancements include remotely piloted aircraft; electric, hybrid, and other propulsion technologies; new electric vertical takeoff and landing (eVTOL) aircraft using lift-plus-cruise and tiltrotor/wing configurations; and increasingly autonomous operations. Examples of new operational missions include high-altitude, long endurance flights (e.g., HAPS) and runway-independent UAM operations, with tempos envisioned to be orders of magnitude greater than today's rotorcraft operations. Many of these new entrants will not be able to fully integrate in the NAS at scale using current operational regulations, processes, and procedures.

Digital Flight addresses many of the underlying mechanisms and approaches included in the FAA's current efforts to address the needs of this diverse group of new entrants. The aviation community, with leadership from the FAA and NASA, is exploring a variety of new conflict management approaches, referred to collectively as eXtensible Traffic Management (xTM).[13] For the most part, these concepts are being proposed independently for different operational domains. They include UTM (focused on small UAS operating below 400 feet), UAM (focused on urban operations at several thousand feet), and ETM (focused on high altitude operations above 60,000 feet).[1][2][3] These different concepts have commonalities: increased connectivity to information and data sharing, cooperative operating practices, the operator leveraging automation for conflict management, and third-party service providers[i], all of which align with the Digital Flight concept described here. This creates an opportunity to introduce a single operating mode that satisfies the

[i] A third-party service provider can assist the operator in meeting operational requirements that enable safe and efficient use of airspace without direct ATC involvement. Third-party service providers can (1) act as a communications bridge between participants, (2) provide operators with information about planned operations in and around a volume of airspace so that they can ascertain the ability to conduct their mission safely and efficiently, and (3) archive operational data in historical databases for analytics, regulatory, and operator accountability purposes. Third-party services can also support operations planning, intent sharing, vehicle deconfliction, conformance monitoring, and other airspace management functions. Adopted from [3].

requirements of all the xTM concepts, instead of implementing several new operating modes that would add significant complexity to rulemaking and airspace management.

While the FAA's xTM concepts all allude to a new operating mode, others have been more explicit. Airbus and Boeing together called for "*new ATM (Air Traffic Management) concepts for all airspace users that facilitate the safe integration of new vehicles and technology.*" [14] Their joint paper described taking the mechanisms and underlying philosophy of UTM and applying them broadly to address the needs of a range of new entrants and current users of the airspace. The MITRE Corporation called for the creation of "*Augmented Visual Flight Rules*" [15] which are very similar to the DFR operating mode described here. In a draft concept paper, the International Civil Aviation Organization (ICAO) discusses "*additional or adapted set of flight rules for new entrant*s."[16] In their comprehensive report on AAM, a National Academy of Sciences panel indicated that ultimately new capabilities and new flight rules are likely going to be needed to enable routine AAM operations.[17] It is clear that NASA is joined by many respected experts on aviation operations, including Airbus, Boeing, MITRE, ICAO, and the National Academies, saying in various ways that the time for a new operating mode is now. DFR is proposed to be that new operating mode.

Making operational changes to the NAS is time consuming. Many of the proponents for the new entrants are expecting initial operations within the next three to five years, with operational tempos increasing rapidly over the next decade or two. Initial operations will take place largely under the existing operating modes of VFR and IFR, but the industry must look to the future. To have a new operating mode in place to serve the aviation community in the next 10-20 years, planning, testing, and implementation needs to start now. History has demonstrated that NAS paradigm changes, like the Next Generation Air Transportation System (NextGen) initiative, can take well over a decade to realize.[18] Thus, there is little time to spare in starting to develop DFR to ensure that the "*airspace is ready when the aircraft are*."[19]

3. **Description**

The following definition of **Digital Flight** is the basis for the description herein:

> ***Digital Flight*** *is an operating mode in which flight operations are conducted by reference to digital information, with the operator ensuring flight-path safety through cooperative practices and self-separation enabled by connected digital technologies and automated information exchange.*

The term "digital" is chosen to represent the conduct of flight operations *by reference to digital elements* (i.e., information, connectivity, and computing automation). The naming parallels visual flight codified as VFR (flight operations *by visual reference*) and instrument flight codified as IFR (flight operations *by reference to instruments*). It is proposed that Digital Flight be formally enacted in regulation as a new operating mode, codified as new flight rules, referred to here as **Digital Flight Rules (DFR)**.

> ***Digital Flight Rules*** *are a set of regulations authorizing sustained Digital Flight as an alternative means of separation in VMC and IMC, in lieu of employing visual procedures (i.e., VFR) or receiving ATC separation services (i.e., IFR).*

Prior to DFR enactment, it is envisioned that some Digital Flight capabilities will be authorized for use under VFR or IFR on an advisory or assistive basis. This will establish an incremental path to full DFR while providing early and ongoing operational benefits. Some Digital Flight capabilities are anticipated to be of benefit to airspace users who choose to operate under VFR and IFR even after full DFR enactment.

In this paper, the term Digital Flight is used to encompass the capabilities under the proposed regulatory operating mode of DFR, as well as the supplemental use of Digital Flight capabilities at any point under VFR or IFR. The acronym DFR is used where the context is formally established *flight rules*. The intention is to emphasize the operating mode rather than the specific regulations that would authorize it. If Digital Flight or a similar concept is ultimately adopted, the regulator will determine the form and naming of its authorization.

3.1. ICAO Foundation

This new operating mode proposal is intentionally consistent with the ICAO Global Air Traffic Management (ATM) Operational Concept, First Edition.[20] Digital Flight aligns with this concept's guiding principles of *Safety, Humans, Technology, Information, Collaboration,* and *Continuity*. These principles highlight safety as the highest priority, recognize the essential role of humans in managing operations, and focus on functional needs rather than specific technologies. They also emphasize the importance of quality-assured information sharing to enable dynamic and flexible decision-making, and of contingency management to ensure continuity of service. In addition, a set of guiding principles for defining new flight rules, proffered in [4] and applied here, are that new flight rules should preserve and be distinct from VFR and IFR; should formally establish operator responsibility for separation; should increase airspace access and flexibility; should be available to all operators that meet the requirements; should not require segregation from VFR and IFR operations; should be scalable and resilient to disruption; and should be capable of incremental introduction.

The ICAO Global ATM Operation Concept provides a structure through which Digital Flight can be established as a unique operating mode, defined by its approach to *conflict management*. The ICAO structure consists of three layers of conflict management:

1. ***Strategic conflict management*** is the first layer of conflict management and is achieved through the airspace organization and management, demand and capacity balancing, and traffic synchronization components.
2. ***Separation provision*** is the second layer of conflict management and is the tactical process of keeping aircraft away from hazards by at least the appropriate separation minima.
3. ***Collision avoidance*** is the third layer of conflict management and must activate when the separation mode has been compromised.

While Digital Flight associates with all three layers, it is primarily distinguished from the other operating modes by its means for accomplishing the second layer, *separation provision*. The ICAO Concept defines the *separator* as "the agent responsible for separation provision for a conflict and can be either the airspace user or a separation provision service provider." According to the ICAO Concept, to avoid ambiguity, a *predetermined separator* must be defined a priori for all hazards, though the role may be assigned to different agents for different hazards (e.g., the airspace user for weather, a service provider for traffic). Whereas the role of separator may be delegated, the predetermined separator is the agent to whom responsibility returns after the delegation terminates.[20]

The ICAO Concept states that "*the predetermined separator will be the airspace user, unless safety or ATM system design requires a separation provision service*." Consistent with this statement, DFR is defined as an operating mode in which the airspace user is the predetermined separator, accomplishing this role through means (i.e., digital elements) that ensure safety in a manner compatible with ATM system design. Specifically, Digital Flight establishes the *aircraft operator as the accountable party for separation provision*, and it applies automation as the responsible tool of the separator. The DFR operator therefore delegates the role of "traffic separator" to automation that is certified for the traffic separation function, while the operator remains accountable for the proper installation, maintenance, and use of the automation. A pilot, as the operator's agent, may interact with the automation, but the *operator* remains accountable. As a result, the DFR operator is now responsible for *all hazard separation, including traffic separation* (distinguishing DFR from IFR, for which traffic separation is provided by ATC). Furthermore, DFR operators must apply appropriate quantified separation minima, i.e., minimum allowed displacement between an aircraft and a hazard (distinguishing DFR from VFR, which specifies an unquantified subjective requirement to "remain well clear").

Digital Flight can also be viewed in terms of the first and third layers of conflict management. The *strategic conflict management* layer, according to the ICAO Concept, aims "to reduce the need to apply the second layer – separation provision – to an appropriate level as determined by the ATM system design and operation." In the context of IFR, separation provision is primarily a human-centric and occasionally workload-intensive task, and thus strategic conflict management for IFR aims to reduce the workload of controllers to ensure separation services can be readily provided within their limitations. In the context of DFR, however, separation provision is automated and thus does not present the same limitations as the human-centric method. Strategic conflict management will still be employed for DFR, but not those aspects designed to manage controller workload in separation provision. For instance, it will include traffic synchronization elements related to ensuring efficient use of capacity-limited physical resources shared with IFR flights, such as runways, to which DFR operators may contribute valuable functionality to enhance efficiency. DFR operators will also contribute to their own strategic conflict management in various ways to ensure the self-separation functions perform to an acceptable level of risk as traffic density or complexity increase.

The *collision avoidance* layer for Digital Flight will be similar to today's airborne collision avoidance capability, with more uniform application and resolutions potentially enacted by automation rather than issued as an advisory for a pilot to execute. It may employ new collision avoidance technologies that use lateral and speed maneuvering dimensions in addition to the vertical dimension.

3.2. Principal Benefits

As a new operating mode, Digital Flight provides specific operator benefits aligned with the new operator responsibilities. Different types of operators (e.g., private, commercial operators, air carriers) and new-entrant operational concepts (e.g., UAM, ETM, Regional Air Mobility) will be able to deploy these benefits in innovative and potentially diverse ways to gain specific value (discussed further in Section 4, Value Proposition). The principal operator benefits proposed for Digital Flight are:

- **Airspace Access** – the ability to operate in all airspace classes without outside visual reference (i.e., all weather conditions) and without specific ATC clearance/permissions for access to Classes A, B, C, and D airspace.
- **Operational Flexibility** – the ability to dynamically change flight path intent without outside visual reference and without specific ATC clearance/permissions.

"Outside visual reference" refers to the flight visibility and cloud clearance requirements of VFR. Like IFR operators, DFR operators would not be subject to these requirements and thus can operate equally under VMC and IMC. "Specific ATC clearance" refers to the authorization given by ATC to specific flights to perform specific actions. Like VFR operators, DFR operators do not rely on ATC separation services and therefore do not require specific clearance in most situations. (Exceptions are addressed in Section 3.4 Applicable Environment.)

These two principal benefits to the DFR operator (described further in Section 4.3.1 Value Proposition: Operators) are enabled by the operator taking responsibility for applying cooperative practices in conjunction with self-separation. Detailed in Section 3.5 Essential Elements, cooperative practices are the set of expected, complementary, operational behaviors that promote effective and equitable sharing of the airspace and its resources. These practices are encoded into separation automation to ensure they are applied reliably and consistently. The intended result is for Digital Flight to be recognized and accepted by all as a safe, cooperative, and performance-based operation that is welcome in the airspace.

3.3. Operational Integration

DFR operations are intended to share the airspace with VFR and IFR operations without requiring new airspace classes or segregated airspace. Several mechanisms will enable harmonized operational integration with the incumbent operating modes, while still accommodating future technology advancements.

Operational compatibility: Even before DFR is formalized as a new set of flight rules, Digital Flight capabilities will be introduced and begin to be exercised under VFR and IFR (with exemptions, deviations, waivers, or authorizations, as appropriate[21]), thereby developing compatibility with these operating modes from the beginning. Compatibility means VFR and IFR traffic information is incorporated into the DFR technology and procedures such that DFR operations will not inhibit or disrupt non-DFR operations. Given this compatibility, the regulatory transition to DFR should largely be transparent to VFR and IFR operators, which would continue to have the same levels of airspace access and operational flexibility they have today. Key to this transparent transition is the DFR cooperative practice to "respect" these non-DFR operations, meaning to proactively manage conflicts in their presence and ensure new burdens are not added to the pilots and controllers conducting these operations. Further requirements to ensure compatible integration will be developed collaboratively by the broader community to ensure the desired equity among operating modes is achieved.

Predictable behavior: More so than the existing operating modes, DFR operations will exhibit highly cooperative and predictable behavior, essentially ensuring DFR operations are seen as a "good neighbor." Cooperative practices encoded in the separation automation should yield expected and predictable actions that are viewed as amenable to those sharing the airspace. While DFR operations remain flexible (i.e., flight path intent may be changed at will), their predictable behavior lies in the active sharing of intent, and changes are made in a manner compatible with established rules (e.g., providing advanced notice, creating no new conflicts).

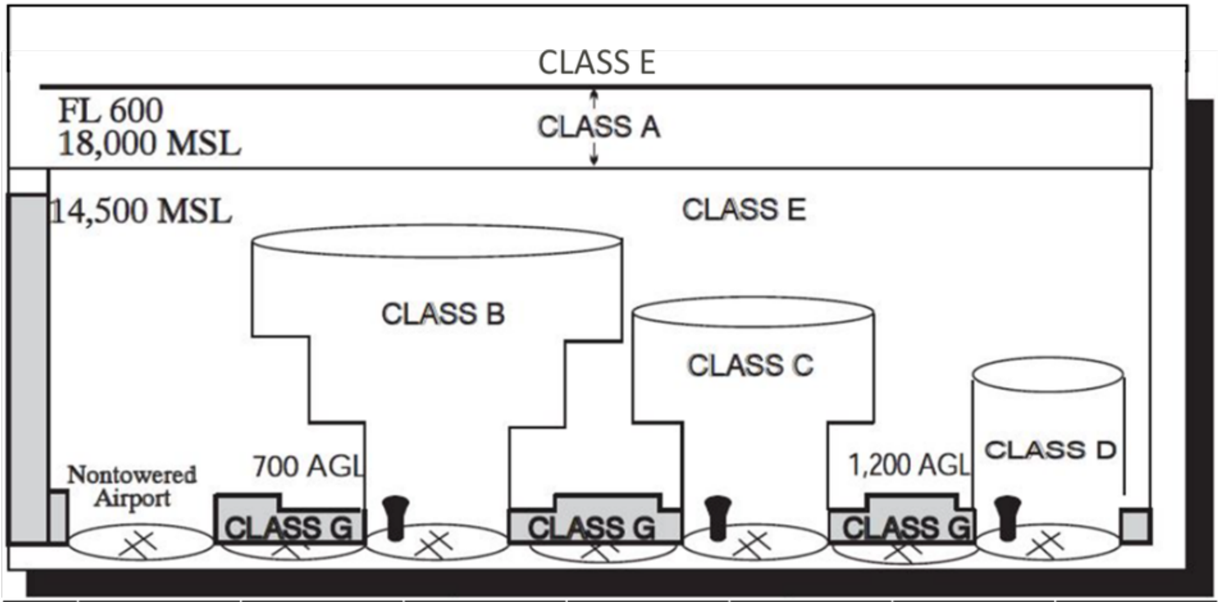
Reliable performance: Digital Flight will be developed as a performance-based operation. As such, it will yield operational benefits not only to the DFR operators but also to the airspace system. For instance, a high-performing DFR operator will be able to apply separation standards tailorable to individual encounters, factoring in such considerations as the flight rules of the traffic, the shared intent, and the performance of the aircraft involved. Precision separation standards increase airspace access and flight efficiency, increasing overall airspace capacity. As a performance-based operation, Digital Flight will allow incorporation of continuing advances in technology, adding new features and improved capabilities. Digital Flight will not be a static capability, but will serve as a foundation for long-term innovation as technology advancements enable new Digital Flight capabilities.

3.4. Applicable Environment

DFR operations are intended to be permissible in all airspace classes. As specified, it does not require segregated airspace or the need to create new airspace classes. While DFR operations will eventually be occurring in every airspace class, as shown in Figure 1, they may be first introduced in some classes and for specific types of operations and later expanded to those with less risk tolerance.

3.4.1. Airspace Entry

Airspace class entry and two-way communication requirements, currently defined in regulations, would be modified to accommodate DFR operations in such a way to minimize the burden on ATC. Even though ATC is not providing separation services to DFR aircraft, some situations, like those for VFR, may warrant DFR aircraft operating under an ATC clearance. A distinction is



	Class A	Class B	Class C	Class D	Class E	Class G	Class E Above A
VFR	Not Permitted	ATC Clearance	2-Way Comm	2-Way Comm	Transponder[1]	Transponder[1]	Transponder[2]
IFR	ATC Clearance	ATC Clearance	ATC Clearance	ATC Clearance	ATC Clearance	Limited	ATC Clearance
DFR	Cooperative Practices and Required System Performance						

1. Required in the Mode C veil or ≥ 10,000 feet with some exceptions.
2. Must meet Class A requirements to transit.

Figure 1 – Airspace class entry requirements vary by operating mode. Graphic above table by FAA.

introduced between clearances as they are issued today (i.e., a specific clearance, current practice) and a regulatory approval (proposed addition).

Specific Clearance – A specific clearance is issued by an air traffic controller to a specific flight, by call sign, at the time of the operation as controllers do today. Such clearances may be issued by voice or by data communications. Situations that may warrant a specific clearance to DFR aircraft include clearances to taxi, takeoff, and land at towered airports within Classes B, C, and D airspace. Here, ATC is managing the flow of arrivals and departures, regardless of the flight rules under which flights are conducted. Similarly, DFR aircraft that benefit from ATC arrival sequencing should expect to operate under a clearance and be treated like any other arrival. However, DFR capabilities for collaborating with Traffic Flow Management (TFM) automation will permit merging into a traffic flow without the need for ATC vectoring and speed control. Similarly, DFR capabilities for precise interval spacing may be leveraged to increase runway throughput. After takeoff, a DFR aircraft can expect to be "cleared to proceed DFR" which implies the operator should begin exercising responsibility for self-separation from that point forward.

Regulatory Approval – A regulatory approval enables an aircraft to enter controlled airspace based on meeting the regulatory requirements for entry but does not require a route and altitude clearance. For example, Class A airspace, currently reserved for only IFR flights, would therefore include both IFR and DFR flights based on a regulatory approval for DFR flights to enter the airspace without a specific clearance. While in controlled airspace, cooperative practices codified under DFR would require DFR aircraft to resolve all conflicts with IFR aircraft prior to a controller's decision time horizon, thus minimizing disruption of ATC-IFR operations. Class B airspace, which currently accommodates VFR and IFR aircraft and with both subject to positive control, would now also accommodate DFR flights, also subject to positive control when landing at the primary airport. However, DFR aircraft *transiting* Class B airspace (i.e., not landing at an ATC controlled airport) will be permitted without specific clearance, rather just regulatory approval. Cooperative practices again would require DFR aircraft to remain clear of the major arrival/departure flows, potentially through geo-fencing, to avoid disruption. All aircraft will be in communication with ATC (DFR included) either by voice or data communications and able to follow ATC instructions if needed. However, the cooperative behaviors of DFR that facilitate airspace integration will minimize the need for ATC instructions.

No Clearance Required – Situations that are not expected to warrant a DFR aircraft requiring an ATC clearance are entering and operating within airspace classes C, D, E, and G[i] (although landing clearance would still be required at Class C and D airports). These airspace classes currently do not require ATC clearance for entry. DFR aircraft would be permitted to operate without clearance in both IMC and VMC.

Two-Way Communications – An important requirement of airspace entry (for Classes A, B, C, and D) is establishing two-way communications with ATC prior to entry. DFR aircraft are always performing at least one-way communications through their automatic sharing of intent. ATC must have access to intent for all DFR aircraft operating within or planned to enter their airspace. While early DFR operations can begin with two-way voice communications, it is proposed that an automatic acknowledgement mechanism be eventually employed, similar to automated transfer of communications for IFR flights via data communications, thereby effectively establishing two-way data communications between DFR operators and ATC prior to entry of these airspace classes. It is further proposed that DFR operators be reachable by ATC at all times while operating within these airspace classes, such that ATC instructions can be received when needed.

3.4.2. Flight Visibility

As separation provision under DFR is based on automated flight path management informed by cooperatively transmitted telemetry and intent data, and augmented where feasible by non-cooperative sensors, flight visibility has no bearing on separation performance and therefore is not relevant to this aspect of DFR operations (similar to IFR). Flight visibility requirements would still apply for DFR aircraft using standard instrument approach and takeoff procedures when being flown manually. Otherwise, DFR operations will be equally permitted in VMC and IMC.

3.4.3. Hazards Proximity

Avoidance of weather hazards, obstacles, and terrain is an operator/pilot responsibility that is not specific to Digital Flight. It is proposed that conventional mechanisms for their avoidance be acceptable for DFR operations (e.g., visual avoidance, adhering to charted minimum altitudes). The Digital Flight community could also pursue alternate means of compliance, such as sensor technologies and incorporating all such hazards into the self-separation logic. At its core, however, the essence of Digital Flight is the self-provision of services otherwise provided by ATC under IFR, in particular, traffic separation and avoidance of active special activity airspace. Other

[i] Class F airspace is not used in the United States of America.

hazards should be considered separately when formalizing the scope of DFR in the regulatory process.

3.4.4. Shared Airspace and Altitudes

Digital Flight is designed for DFR operators to share the airspace with VFR and IFR operations. DFR aircraft will proactively avoid conflicts with VFR and IFR through automated application of codified cooperative practices. Action to avoid or resolve conflicts will be taken prior to the normal decision horizons of VFR pilots and ATC to minimize disruption, and the resolution plan (i.e., revised intent) will be automatically shared. Though VFR and IFR aircraft are typically separated by staggered altitudes when in level cruising flight, they still share the same airspace. DFR aircraft will also share the same airspace, but it is not expected that DFR operations would require separate altitudes, as DFR separation automation should not require it.

3.5. Essential Elements

As with VFR and IFR, prerequisite qualifications will be established for DFR operators, including equipment, training, currency, and other requirements determined by Federal regulators in consultation with the industry. For this general description, qualifications are focused on the DFR operator needing to employ four *Digital Flight Essential Elements* shown in Table 1.

Table 1. Digital Flight Essential Elements

Digital Flight Essential Element	Purpose
Digital Information Connectivity and Services	Maintaining a digital model of the operating environment for use by decision-making automation
Shared Traffic Awareness	Maintaining awareness of relevant traffic for use in conflict management
Cooperative Practices	Governing the behavior of DFR operations to ensure harmonized use of the airspace
Separation Automation	Automating the separation function in flight path management

Taken together, these elements serve as the foundation for enabling the Principal Capabilities of Digital Flight, described in Section 3.6. Each of these elements will require formal community-based definition, requirements research, and performance-based standards for certification and/or operational approval. A high-level description of each element is provided here.

3.5.1. Digital Information Connectivity and Services

In Digital Flight, the aircraft operator uses automation to plan, monitor, evaluate, revise, and coordinate the aircraft's flight path within the operating environment. To perform these functions, the automation must maintain or access a *digital model* of the operating environment, tailored to the aircraft's particular operation. Distributed and maintained by the operators and their service provider networks, each model consists of appropriately current information received from reliable, verified, and authorized sources. It must include all relevant conditions, weather, hazards, and constraints that DFR operators are required to consider in their decision-making. Because Digital Flight requires forward planning, the digital model will need to include both current and forecast information to the extent available, (i.e., a digital model of the operating environment projected forward in time). In addition, all such information must be in a form processable by automation, as compared to information designed only for human consumption and interpretation. For instance, maps of raw convective weather radar returns may need additional processing to convert the data into polygons or contours that automation can use for flight path analysis and revision.

Information requirements for the digital model are derived from Digital Flight's unique capabilities. Of highest priority are those related to the separation function, including the state vectors and intent data (discussed below) of relevant traffic aircraft, and airspace and environment data that directly affect trajectory predictions (e.g., atmospheric and wind models). To the extent that Digital Flight also requires automated avoidance of non-traffic hazards (e.g., hazardous weather, terrain, obstacles), these must also be included in the digital model either as specific objects or minimum operating altitudes that ensure hazard avoidance. It must also include any airspace restrictions (e.g., special activity airspace, other airspace constructs) that bound or otherwise impact flight path planning. The digital model should also include flow constraints of either a general nature (e.g., delay predictions) or specific to the flight (e.g., scheduled time of arrival), as well as terminal arrival information (e.g., runway configurations, approaches in use) for required airports. Additional information that operators typically use in flight operations, regardless of operating mode, would also be contained in the digital model for convenience and efficiency.

Because the digital model will be used for safety-critical decision-making, the data it contains must meet certain criteria, e.g., relevant, timely, and secure. The digital model can be populated with data from a mix of government and regulator-approved commercial services, and traceability of the data will be important to ensure authenticity and compatibility. There may also be a need to customize the data to specific operator needs and aircraft location. Because data tailoring requirements will vary among types of operations, and even among different operators within a given type, it is not expected that a single, common digital model will be used by all. For most data elements, this degree of shared situation awareness is not necessary. For instance, a weather element considered a hazard to one operator may be non-hazardous to another operator.

Some areas of shared situation awareness will be important to maintain in the digital model, specifically those related to Digital Flight's separation function. (Shared traffic awareness is the second Essential Element; its specific information requirements are discussed in the next section.) To ensure a shared view of conflicts, the digital model must include data elements important to both the interpretation of the shared traffic data (e.g., a common position-navigation-timing reference) and the accurate prediction of trajectories (e.g., a common wind field model). Some elements may be impractical for sharing due to their vast diversity or proprietary concerns (e.g., aircraft performance models).

Of particular importance to separation automation hosted onboard are the connectivity mechanisms between the separation automation and the digital information services. Information to be used for traffic separation require minimum latency and minimum potential for corruption. For time-critical information, such as traffic aircraft state data and intent changes, vehicle-to-vehicle communications may be the most direct way to ensure these qualities. Other data that change far less frequently, such as wind field model data, can likely sustain some latency without adverse impact. Generally, the data in the digital model may be loaded just prior to flight, and then updated in flight through air-ground connectivity mechanisms on a periodic and asynchronous basis. More detailed analysis will be required to determine performance requirements for connectivity systems in terms of availability, integrity, security, bandwidth, and reachability (e.g., geographic and altitude coverage).

3.5.2. Shared Traffic Awareness

Digital Flight provides self-separation from traffic, which in turn requires that the separation automation be aware of all traffic within the domain of relevance. In a mixed operations environment, this generally includes all VFR, IFR, and DFR aircraft in the vicinity of the DFR operator's aircraft, including those potentially operating under other rules (e.g., UAS under 14 CFR Part 107).[i]

Because Digital Flight distributes the separation function among DFR operators and their aircraft, there must be a shared awareness of traffic information among DFR operators, ensuring that all separation automation systems involved in a given conflict situation have essentially the same interpretation of the conflict and will make compatible decisions. This shared traffic awareness can be achieved by DFR aircraft sharing three sets of information directly with each other: aircraft state, flight path intent, and intended navigation performance.

Aircraft State – The first and most safety critical contribution to traffic awareness is the aircraft identification and current state vector of traffic aircraft, i.e., the current location, altitude, flight track, ground speed, and vertical speed, akin to the state vector report of Automatic Dependent Surveillance Broadcast (ADS-B). At least this minimum information is needed by the separation automation to perform its intended function. Cooperative transmission of aircraft state will be the preferred mechanism to ensure that surveillance performance meets established standards. Current regulations regarding ADS-B OUT equipage provide a foundation for establishing this cooperative surveillance environment supportive of Digital Flight. Additional requirements for performance and certification may be derived from this document and others to ensure adequacy for the intended function.

For DFR operations in airspace where cooperative surveillance is not required, alternate means of non-cooperative surveillance through either ground-based or airborne technologies would be required.

Flight Path Intent – The second contribution to traffic awareness is flight path intent information. DFR is proposed as a cooperative operating mode, and fundamental to cooperation is the sharing of intent between DFR operators. Intent sharing also enables more effective and reliable planning by ATC, and therefore promotes better airspace harmonization. It facilitates more effective strategic conflict management, and it reduces unnecessary separation provision actions. Three domains of intent are relevant: destination intent, near-term intent, and intermediate intent.

<u>Destination Intent</u> – Sharing destination intent, including estimated time of arrival (ETA), enables arrival flow managers to better estimate demand and to accommodate the DFR aircraft into the arrival flow. Failing to share destination intent may jeopardize this accommodation.

[i] This does not impose a new requirement on State aircraft operating under a due regard standard that are not required to participate in cooperative surveillance systems.

However, similar to VFR operations, the requirement for DFR operators to share destination intent would be limited to their use of capacity constrained airports.

Near-Term Intent – Sharing near-term intent will generally be expected of DFR aircraft to improve the performance of separation provision, especially in conflicts with other DFR aircraft. The degree of near-term intent available to share may necessarily vary by the type of operation and the tactical situation. The minimum near-term intent for a straight-and-level aircraft would be its state vector, and in many cases, this would be sufficient for separation provision to the time horizons established in standards. For a maneuvering aircraft, sharing the target state, e.g., the intended new heading or altitude, may constitute sufficient near-term intent that achieves adequate separation provision performance. For aircraft with future intentions to maneuver, sharing one or more trajectory-change points would be appropriate.

Intermediate Intent – Intermediate intent extends beyond the immediate time horizons for separation provision. The requirement for sharing intermediate intent, if any, would need to be defined based on the operational environment. Generally, the Digital Flight concept supports a range of intent sharing, with additional privileges potentially afforded to those who share the greater amount (e.g., receiving priority in a conflict).

Non-DFR Intent Sharing – Digital Flight does not propose a requirement for intent sharing nor any related penalty to non-DFR operators. However, any available intent of non-DFR aircraft, e.g., as may be available on IFR aircraft through an ATC information service, would be used by DFR aircraft in separation provision. This will enable better harmonization with ATC plans for IFR aircraft, thus reducing controller workload.

Intended Navigation Performance – The third contribution to traffic awareness is intended navigation performance. Sharing intended navigation performance is particularly germane for DFR aircraft encounters with other DFR aircraft in that it provides information needed to safely apply reduced separation standards. An analog to intended navigation performance is RNP, a construct under IFR which bounds the allowable lateral deviation from a specified nominal path. DFR's intended navigation performance can be similarly constructed to bound the DFR aircraft's lateral conformance to its shared trajectory intent. Digital Flight would take this a step further, extending the two-dimensional construct (i.e., lateral performance) to include vertical and along-path dimensions, thereby providing a complete four-dimensional (4D) uncertainty bounding of the shared intent.

Sharing intended navigation performance is essentially a DFR operator's commitment to other DFR aircraft they may encounter, who will also be sharing their navigation performance commitment. Taken together, these commitments enable the application of separation criteria tailored to that specific encounter, resulting in potentially much smaller separation for an equivalent level of safety. Smaller separation criteria can yield several significant benefits: fewer conflicts, greater flight efficiency, and significantly higher traffic density for operations in which the separation function is automated.

Additional Considerations – In addition to these three contributions to traffic awareness, sharing of maneuverability or performance limits may be needed to ensure that a feasible resolution of conflicts can be identified. For instance, a DFR aircraft with limited control response (e.g., limited climb/descent rate) may require either higher priority in a conflict or more time if it is burdened to resolve it. These issues become particularly important for encounters between vehicles of vastly different performance envelopes, and standards development will need to account for them. Similarly, an aircraft in a critical or emergency state (e.g., reaching critical energy levels) would need to share their situation to be afforded priority, though such situations should be rare.

3.5.3. Cooperative Practices

For distributed decision-making to occur in a manner that is safe, organized, and effective, there must be a set of shared cooperative practices that all DFR operators follow. The mechanism for formalizing these cooperative practices may vary. For instance, they may be specified in regulations or industry standards, or included in recommended practices or community guidance (e.g., Aeronautical Information Manual). In contrast to how VFR operators typically follow cooperative practices through interpretation and judgment, Digital Flight cooperative practices will be more rigorously applied, with most practices encoded in automation.

The set of candidate cooperative practices shown in Table 2 and described below should be viewed as a starting point for industry deliberation. Some have been previously discussed in this paper. Modeling and simulation will help refine and verify that these practices are both necessary and effective in ensuring the safe, orderly, and expeditious operations of DFR aircraft in a mixed environment. Aviation community engagement in the refinement and establishment of these cooperative practices will ensure that they are broadly equitable and acceptable.

Table 2. Candidate Cooperative Practices for Digital Flight

ID	Cooperative Practice	Purpose
CP-A	Share and Update Intent	Increase predictability, efficiency, stability, and safety
CP-B	Take Timely Action	
CP-C	Respect Intent When Changing Intent	Minimize disruption to existing operations
CP-D	Respect VFR and IFR Aircraft	
CP-E	Navigate with Intended Precision	Increase airspace capacity; reduce actionable conflicts
CP-F	Apply Pair-Appropriate Separation	
CP-G	Respect Right-of-Way Among DFR Aircraft	Distribute separation burden; increase safety
CP-H	Coordinate Maneuvering Among DFR Aircraft	
CP-I	Coordinate with ATC in Controlled Airspace	Facilitate airspace integration; minimize controller workload; minimize disruptions
CP-J	Join in Appropriate Flow Management	
CP-K	Avoid Active Protected Airspace	
CP-L	Respect Established Operating Procedures	

Each cooperative practice proposed here specifies the practice (an action or behavior of the DFR operator or system) and the intended effect (one or more resulting benefits that promote harmonized use of airspace resources or other positive attributes). These should be considered notional hypotheses that require validation and, in many cases, further specification.

CP-A. Share and Update Intent

Cooperative Practice: The DFR operator will share and update their flight path intent, enabling other actors to predict the DFR aircraft's future state to an appropriate time horizon (which may vary among types of operations). Intent updates will be shared at or before the first change maneuver. Intent sharing beyond the basic level is not compulsory, nor is continued adherence to shared intent. However, all else being equal in a DFR-DFR conflict, the cost to the DFR aircraft sharing the lesser intent may be to assume the separation burden between them.

Intended effects: Increased stability and efficiency of flight paths; earlier detection of conflicts; improved predictability of resource demand; improved safety.

CP-B. Take Timely Action

Cooperative Practice: The DFR operator, when burdened, will resolve conflicts at a sufficiently early time frame such that the other party is not also burdened to act to resolve the same conflict. The conflict is declared resolved when an intent change that clears the conflict is shared, even if the initial maneuver is delayed.

Intended effects: Reduced occurrences of multiple actors resolving the same conflict; increased effectiveness of right-of-way implementation; reduced workload due to high confidence in encounter outcomes.

CP-C. Respect Intent When Changing Intent

Cooperative Practice: The DFR operator will not maneuver so as to create a conflict with another aircraft's shared intent within an established time horizon. This time horizon for preventing new conflicts may vary based on the performance of the aircraft involved. Every encounter between two aircraft should invoke a single separation standard and decision time horizon appropriate for that encounter.

Intended effects: Reduction of conflicts; reduction or elimination of follow-on conflicts; improved safety and equity.

CP-D. Respect VFR and IFR Aircraft

Cooperative Practice: The DFR operator will take action to separate from other VFR and IFR aircraft prior to the time when their pilots or controllers would normally take action. A DFR operator will remain at least "well clear" of VFR aircraft, maneuvering in a manner consistent with the VFR right-of-way rules in 14 CFR 91.113. A DFR operator will maintain at least standard IFR separation from IFR aircraft, sharing their intent with ATC in sufficient time to provide assurance that separation will be maintained.

Intended effects: Minimized changes to existing "see-and-avoid" and ATC separation procedures; minimized impacts to the trajectories of VFR and IFR aircraft; minimized workload for non-DFR pilots and controllers.

CP-E. Navigate with Intended Precision

Cooperative Practice: The DFR operator will determine their intended 4D navigation precision performance, share it as part of their flight path intent, and conform to the shared precision.

Intended effect: Basis for smaller pairwise separation criteria.

CP-F. Apply Pair-Appropriate Separation

Cooperative Practice: The DFR operator will apply separation criteria appropriate to each pairwise encounter, based only on information electronically exchanged or accepted defaults. Relevant factors include states, intents, navigation precision, performance limitations, and flight rules of the encounter aircraft. See Figure 2.

Intended effects: Reduction in actionable conflicts; reduction in different interpretations of the mutual conflict; enabling the smallest separation without compromising safety.

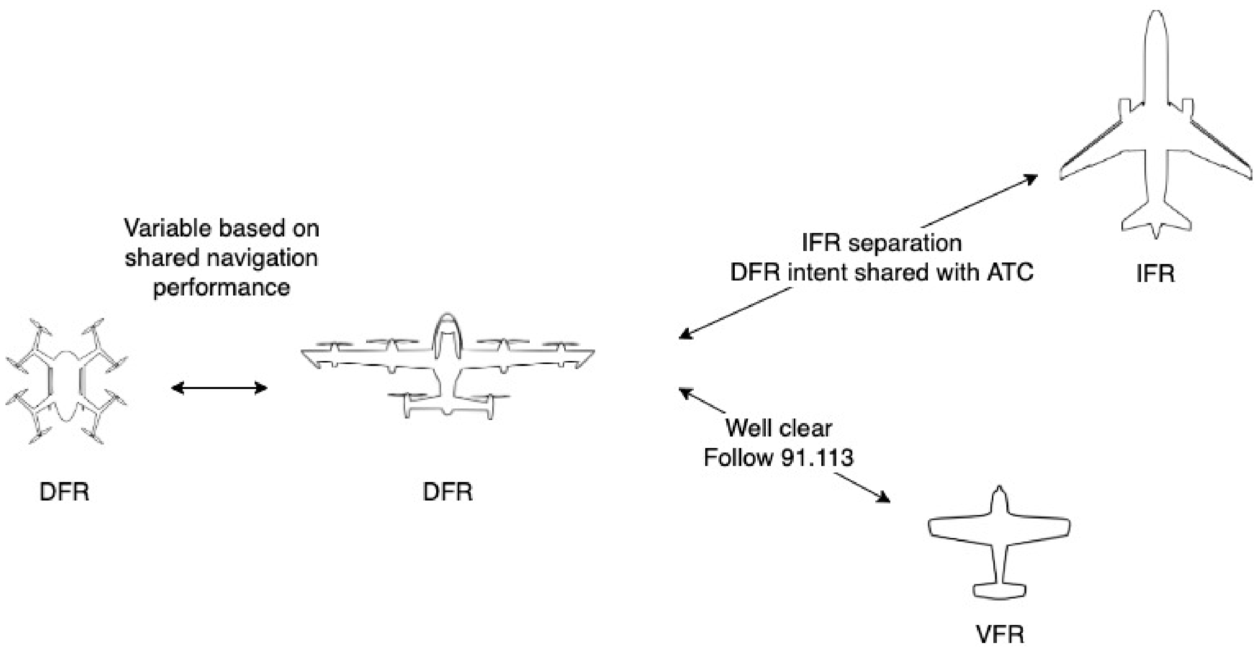


Figure 2 – Pair-appropriate separation criteria are defined by the specific encounter.

CP-G. Respect Right-of-Way Among DFR Aircraft

Cooperative Practice: The DFR operator will yield right-of-way to other conflicting DFR aircraft as determined by established, electronically applied, right-of-way rules for DFR-DFR encounters. Yielding right-of-way means assuming the burden of resolving a detected conflict or otherwise preventing conflict formation.

Intended effects: Increased safety; reduction in unnecessary maneuvering; accommodation of inherent performance differences between DFR aircraft; establishment of a transparent basis for equity in shouldering the separation provision burden.

CP-H. Coordinate Maneuvering Among DFR Aircraft

Cooperative Practice: An unburdened DFR operator, when their aircraft is sufficiently close to risking separation loss with another (burdened) DFR aircraft, will apply automated coordination (implicitly or explicitly) to ensure mutual maneuvering occurs in complementary directions.

Intended effects: Increased safety for encounter time frames within which right-of-way burden assignment is no longer appropriate; ensuring additive separation in a two-actor encounter; reduced occurrence of collision avoidance maneuvers.

CP-I. Coordinate with ATC in Controlled Airspace

Cooperative Practice: The DFR operator will operate under an ATC clearance for taxi, takeoff, approach, and landing at primary airports in Classes B, C, and D airspace. For transiting Classes A and B airspace, the DFR operator will share intent and in turn will operate under regulatory authorization in lieu of a specific clearance.

Intended effects: Minimized impact on ATC arrival/departure traffic flow procedures; reduced controller and operator workload for transiting airspace; reduced frequency congestion.

CP-J. Join in Appropriate Flow Management

Cooperative Practice: The DFR operator, when intending to use ATC-managed, capacity-limited resources of the airspace system, will participate equitably in associated traffic management initiatives (TMI). Contributions that enhance traffic flow performance, such as meeting a Required Time of Arrival (RTA) or employing Interval Management (IM)[22] procedures, may be used to the DFR operator's and ATC's mutual advantage.

Intended effects: Preservation of equity among DFR and non-DFR operators; establishment and maintenance of stable, predictable traffic flows into a constrained resource; increased TMI performance in reducing traffic delays.

CP-K. Avoid Active Protected Airspace

Cooperative Practice: The DFR operator will remain clear of published protected airspace during their active periods, unless having precoordinated their entry with the controlling authority. This includes not only special activity airspace but potentially the arrival and departure corridors of larger airports.

Intended effects: Increased safety; reduced workload of the controlling authority.

CP-L. Respect Established Operating Procedures

Cooperative Practice: The DFR operator will conform to established operating procedures when departing from and arriving at controlled and uncontrolled airports.

Intended effect: Smooth integration with IFR and VFR traffic patterns.

3.5.4. Separation Automation

The confluence of the first three Essential Elements (digital information connectivity and services, shared traffic awareness, and cooperative practices), occurs in the fourth Essential Element, separation automation and its role in flight path management. The DFR operator uses separation automation to establish and maintain a safe flight path to be flown in a constrained traffic and hazard environment. This automation system is the actuator of Digital Flight's cooperative, self-separation capability. During flight, the DFR operator interacts with the separation automation in much the same way an IFR pilot interacts with ATC. The automation serves as the DFR operator's tool for detecting traffic conflicts, determining maneuver burden, and computing flight path changes to resolve conflicts as required, while conforming to the constraints of the operating environment and the performance limitations of the aircraft. The cooperative practices are embedded into the separation automation's logic to ensure they are applied consistently and to unburden the human operator from remembering or interpreting them. Until conditions are reached in which the DFR operator/pilot can visually or procedurally avoid hazards, the automation determines any maneuvering to be done (or not done). The operator ensures maneuver implementation either through pilot action or designated auto-flight execution function. The separation automation also evaluates any user-proposed changes to the flight path (e.g., a desired course or altitude change) to ensure separation is maintained. The separation automation also provides constraint conformance, such as respecting an airspace construct or meeting an RTA. These functions interact with the separation function and therefore must be integrated in the automation functional design.

The primary functions of the separation automation during a flight are four-fold: to *monitor* the flight path relative to mission objectives, the operating environment, constraints, and other factors; to *evaluate* ongoing operational acceptability of the flight path; to *revise* it as needed to sustain a set of desired qualities; and to *coordinate* flight path changes with other airspace users and service providers. The desired qualities of a flight path are for it to be operationally *feasible*, *deconflicted*, *harmonized*, *flexible*, and *optimal*. Feasible flight paths are within the aircraft's performance and range, and are conformant to airspace restrictions, fixed obstacles and terrain, and time constraints. Deconflicted flight paths are conflict-free to appropriate time horizons and separation standards with respect to traffic, hazardous weather, and other dynamic constraints. Harmonized flight paths meet the requirements of the cooperative practices. Flexible flight paths have sufficient adjustability to enable future changes if necessary (e.g., to resolve later conflicts). Optimal flight paths meet the business objectives of the operator as best possible within all other constraints, including system-level optimization considerations. Ref. [23] presents a formalized system concept description of separation automation supporting dynamic, in-flight, path planning.

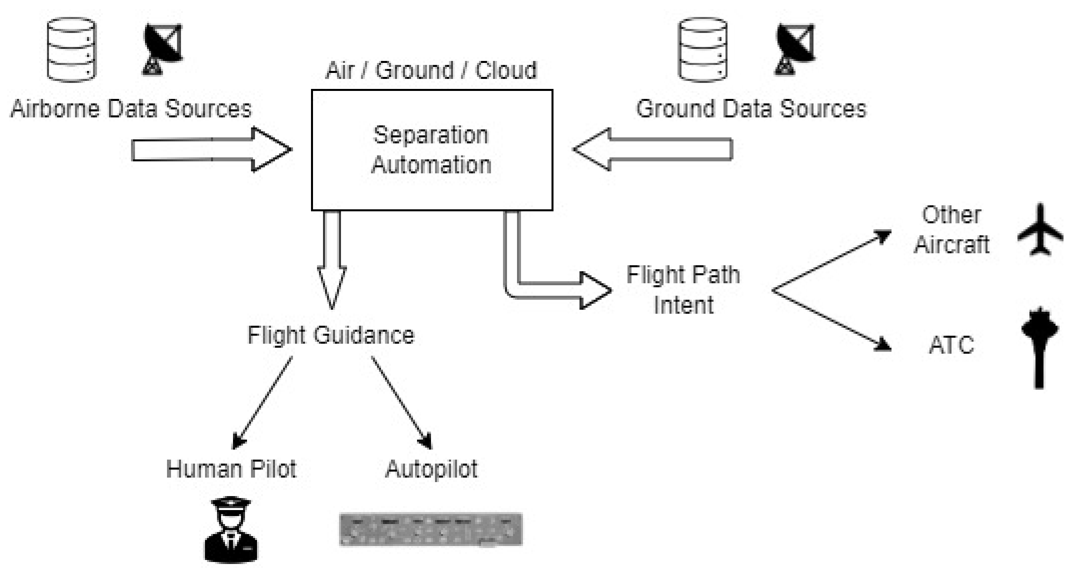


Figure 3. Separation automation may include airborne and/or ground components connected to various data sources.

In Digital Flight, the hosting location of the separation automation will be the operator's decision. This flexibility is intentional to suit a diversity of candidate system architectures appropriate to the operator or type of operation (see Figure 3). For instance, the operator may host the automation onboard the aircraft, or in an operator's ground control facility, or even in a cloud service. Regardless of the chosen architecture, it will be critical that end-to-end system integrity meet established performance standards, given the time and safety criticality of the separation function. Non-aircraft hosting locations, for example, would be dependent on a highly reliable air-ground communications link for uninterrupted, secure, and low-latency connectivity to the aircraft flight control system. Depending on cost and other factors, the performance requirements may be better met with the automation hosted in multiple locations.

Furthering Digital Flight's intentional flexibility in system architecture is the operator's choice to either *self-provision* the Essential Elements or *acquire* some portions of these elements through governmental or commercial service providers. While the DFR operator retains ultimate accountability for the safety of the operation, including traffic separation, it may be economically advantageous for some DFR operators to meet this responsibility through acquired services. An analogy is aircraft maintenance, repair, and overhaul (MRO), where some operators host MRO functions in house, while others use regulated commercial providers. In both cases, the operator remains accountable for the airworthiness of their aircraft. In Digital Flight, the accountability is set to a higher standard, given the real-time operational and safety impact of flight path decision making. Thus, the role of service providers in Digital Flight may focus on information and

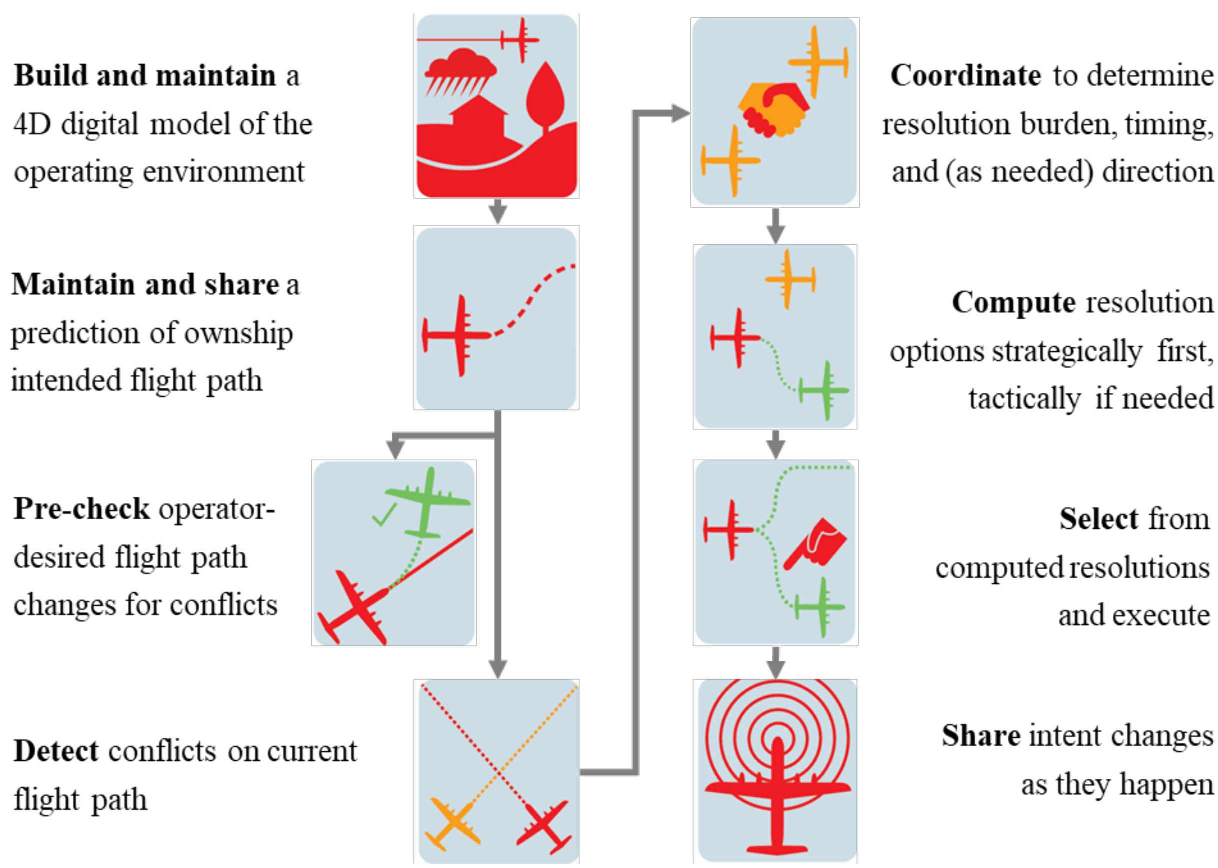


Figure 4. Representative process for cooperative self-separation in Digital Flight.

coordination services, while operators manage decision-making related to cooperative separation provision. Regardless, Digital Flight allows for a spectrum of self-provisioning and acquired services.

A representation of the cooperative self-separation process is shown in Figure 4. All four Essential Elements are included in this notional process, from maintaining a digital model of the operating environment and sharing operational intent, to applying cooperative practices to the management of conflicts. Not all aspects of DFR operations are illustrated here, such as the collaborative interactions with ATC and conformance to operational constraints.

3.6. Principal Capabilities

Leveraging the four Essential Elements described in the previous section, Digital Flight brings forth a set of candidate operational capabilities that collectively enable DFR to provide unique operational value relative to other optional modes. This section introduces an initial set of six *Principal Capabilities* of Digital Flight, with recognition that additional capabilities may yet emerge as operational experience with DFR is gained and further innovative applications of Digital Flight are devised. The six Principal Capabilities, detailed below, are summarized in Table 3.

The first three listed capabilities are considered essential to Digital Flight and therefore are proposed to be required of all DFR operators. The fourth listed capability is applicable to operators intending to use ATC-managed airport resources and may be required of those DFR operators. The remaining two listed capabilities are speculative capabilities (i.e., likely requiring additional research and thus taking longer to be realized) but are considered instrumental in achieving the full scalability benefits of DFR operations.

Table 3. Principal Capabilities of Digital Flight

Capability	Operation Enabled
Operator Self-Separation	Enables DFR operators to provide their own separation from VFR, IFR, and other DFR aircraft in lieu of visual procedures and ATC separation services
Cooperative Conflict Management	Enables DFR operators to coordinate with each other to equitably and safely share or distribute the separation burden
Adaptive Pairwise Separation	Enables DFR operators to tailor the separation criteria to each encounter, creating the potential for significantly reduced separation between DFR aircraft without compromising safety
Collaborative Utilization of Constrained Resources	Enables DFR operators to collaborate with ATC in arrival traffic synchronization and demand-capacity balancing at controlled airports
Self-Organization & Sequencing	Enables DFR operators to arrive and depart non-towered airports in IMC in an orderly, self-organized fashion
Self-Regulation of Density & Operational Complexity	Enables DFR operators to sustain safe operations while scaling to increasingly complex environments

3.6.1. Operator Self-Separation

The capability of a DFR operator to directly ensure at least a minimum quantifiable displacement is maintained from known traffic and hazards, in VMC or IMC, and in shared airspace with VFR, IFR, and other DFR aircraft.

This capability, illustrated in Figure 5, is the primary mechanism by which DFR operations are conducted safely and forego the need for segregation from VFR and IFR operations. The capability distinguishes DFR from VFR's subjective "see and avoid" capability and IFR's separation service provided through mandatory ATC positive control. Traffic separation is the focus of this capability, but all physical and operational hazards such as terrain, obstructions, weather, and protected airspace, can be included in its construct. Separation provision is performed generally through dynamic, computational techniques involving flight path modeling, conflict-free maneuvering, detection of conflicts, and computing resolution maneuvers.

The four Essential Elements described in Section 3.5 establish the required information, functions, and behavioral rules for this capability (and for the remaining capabilities). In particular, the cooperative practices in Section 3.5.3 play a significant role throughout. For instance, Cooperative Practice B (CP-B) requires the DFR operator to "*Take Timely Action*." Thus, the self-separation capability applies appropriate time horizons and prediction uncertainty buffers to ensure timely and definitive conflict management. CP-D requires the DFR operator to "*Respect VFR and IFR Aircraft*." A DFR operator will therefore remain at least "well clear" of VFR aircraft (by digital rather than visual means), maneuvering in a manner consistent with the VFR right-of-way rules in 14 CFR 91.113. Similarly, a DFR operator will maintain at least standard IFR separation from IFR aircraft, sharing their intent to ATC in sufficient time to provide assurance that separation will be maintained.

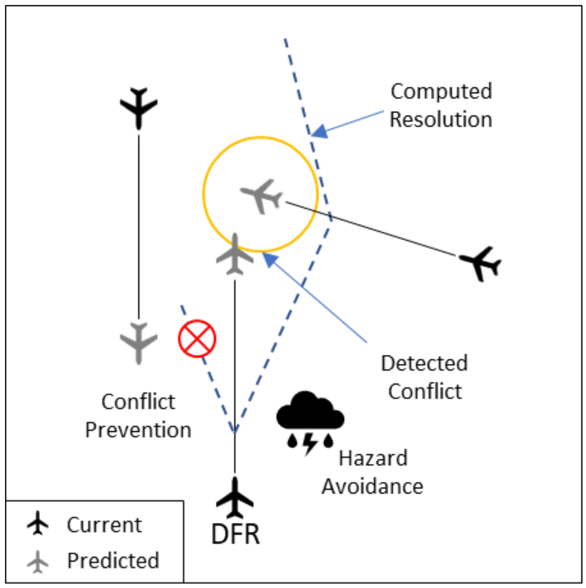


Figure 5. Digital Flight capability of operator self-separation ensures adequate displacement from traffic and other hazards.

The self-separation capability is applied at all times when the DFR operator is <u>not</u> operating under a specific clearance (i.e., issued by a controller to a specific flight, by call sign, at the time of the operation, as described in Section 3.4). For operations from non-towered airports, self-separation begins at runway (or pad) occupancy and proceeds through departure. At towered airports, it begins at the termination of the ATC departure clearance. Similar periods of responsibility apply for arrivals, dependent on whether operating under a specific clearance.

To self-separate from non-traffic hazards, DFR operators may choose to apply non-digital techniques. These could include procedural methods, such as complying with regulator-published minimum altitudes and instrument arrival/departure procedures for terrain and obstacle avoidance, or by applying visual separation if operating in VMC. Alternatively, the operator may employ the same digital (i.e., dynamic, computational) technique used in traffic separation, thus integrating all hazard avoidance into a common mechanism. This flexibility of different acceptable means of compliance is intended to support a wider array of DFR operations, given that not all hazards apply equally to all types of operations. For example, CP-K "*Avoid Active Protected Airspace*" ensures that the DFR operator incorporates this requirement, where applicable, into their flight path planning and monitoring functions.

The authority of DFR, enabled by the self-separation capability, also affords the operator the flexibility to dynamically self-optimize to achieve a business objective, such as fuel or time savings, on a non-interfering basis (i.e., within the degrees of freedom defined by traffic, hazards, and other applicable airspace system and flow management constraints). Similar self-optimizing capabilities exist in VFR and IFR but are limited to VMC under VFR and requires ATC approval under IFR. Under DFR, the operator has the capability to self-optimize without these constraints.

3.6.2. Cooperative Conflict Management

The capability of DFR operators to equitably share or distribute the burden of separation provision among themselves, thereby sharing the airspace with minimal mutual impact.

This capability, illustrated in Figure 6, enhances the operator self-separation capability by adding common procedures that DFR operators can mutually apply to cooperatively increase their operational efficiency, minimize duplicative efforts or other unnecessary actions, and enhance safety when operating in close proximity to one another. These common procedures are captured in the cooperative practices described in Section 3.5.3.

CP-A requires DFR operators to "*Share and Update Intent*." This practice establishes the basis for cooperation by making intentions transparent among the cooperating parties, which in turn allows better planning. For instance, sharing an upcoming turn with nearby DFR aircraft increases a recipient's digital situation awareness and enables their automation to assess the impact of that turn on their own flight. It may allow an earlier detection of a conflict, thereby enabling a more efficient solution, or it may eliminate a conflict and its required action entirely. Among large numbers of proximate DFR aircraft, intent sharing can increase stability and reduce unnecessary maneuvers in the airspace.

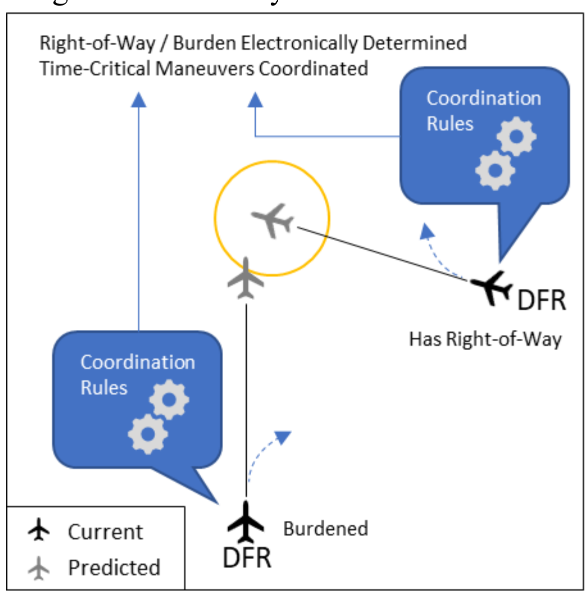


Figure 6. Digital Flight operators cooperate in conflict management to share burdens equitably and safely.

CP-C instructs DFR operators to "*Respect Intent when Changing Intent*." Aligning well with the previous cooperative practice, this manner of cooperation establishes that intent sharing affords an aircraft some level of priority while conforming to that shared intent. Accordingly, other DFR aircraft cooperate by not maneuvering into conflict with that flight path. Preventing conflicts is as much a part of separation provision as is resolving conflicts, and by cooperating in this fashion, the burden of separation provision is shared in a manner that creates equity.

Further enhancing equity and increasing stability is the application of CP-G, "*Respect Right-of-Way Among DFR Aircraft*." While there is no intention that DFR would alter the right-of-way rules established in 14 CFR 91.113 for VFR and IFR aircraft, there may be merit to establish right-of-way rules specifically applicable to the interactions between aircraft operating under DFR. The primary purpose of such rules would be to unambiguously assign the separation burden for a given DFR-DFR encounter. Cooperating in this respect enables the unburdened aircraft to maintain their preferred flight path, while establishing a mechanism for equity (i.e., in another encounter, the roles may be reversed). It also reduces the safety risk of mutual dependency if the maneuver burden is shared but one aircraft fails or delays their maneuver. Right-of-way rules also provide a mechanism for incorporating other factors into assigning priority, such as aircraft performance. With digital application of these rules, diverse and complex factors may be readily incorporated.

For highly proximate conflict encounters, CP-H dictates that DFR operators "*Coordinate Maneuvering Among DFR Aircraft*." For conflicts that are sufficiently close to separation loss, this requirement presumes that both aircraft must now maneuver to ensure the required separation is achieved. The cooperative element here is the coordination of each aircraft's maneuver direction to ensure their maneuvers are complementary (i.e., additive toward the separation goal and not inadvertently subtractive). The coordination is automatic and may take either implicit or explicit form. Implicit maneuver coordination is achieved through regulator-approved logic in each aircraft's separation automation that selects complementary maneuver directions based on already shared information (e.g., state vectors shared as regular telemetry). Explicit maneuver coordination includes additional pairwise communication specific to reaching agreement on that encounter.

3.6.3. Adaptive Pairwise Separation

> The capability of DFR automation to tailor separation criteria to specific pairwise factors, enabling safely reduced separation to increase operational efficiency and airspace capacity.

This capability of safely operating with smaller separation criteria than used for IFR separation is one of the key mechanisms by which Digital Flight is envisioned to enable operations at significantly higher traffic density. Rather than using a small number of fixed separation criteria for all encounters, as is done for IFR, this Digital Flight capability uses cooperative sharing of intent and navigation precision to derive separation criteria specific to and appropriate for each encounter, as illustrated in Figure 7. This cooperative information sharing enables CP-F, "*Apply Pair-Appropriate Separation*." Due to its cooperative requirement, this DFR capability is applicable to encounters between DFR aircraft. Through cooperative practices CP-A "*Share and Update Intent*" and CP-E "*Navigate with Intended Precision*," DFR aircraft communicate their planned flight paths with each other and how precisely they intend to conform to these paths.

Intended navigation conformance is analogous to RNP, but with two distinctions. First, there is no "required" navigation performance for Digital Flight. Instead, DFR operators determine their own aircraft's navigation performance capability and share this information as part of their intent message, essentially serving as a self-proclaimed commitment to other proximate DFR aircraft. Second, navigation conformance must be specified in more dimensions than just RNP's lateral dimension, as this information will determine separation criteria for encounters with arbitrary geometries. DFR aircraft with tighter 4D conformance commitment are candidates for applying smaller separation criteria, though the actual values would depend on the navigation performance of both aircraft. In addition, since separation risk tolerance may vary among operators or types of operations, regardless of navigation performance, this risk tolerance can be incorporated into the intended navigation performance message. As a result, each encounter would have its own separation criteria, adapted to the pairwise performance and separation risk tolerance of the aircraft involved.

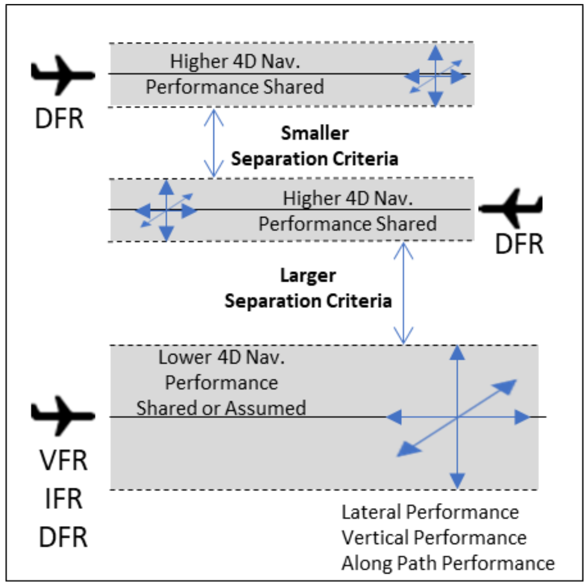


Figure 7. Digital Flight enables the capability to adapt separation criteria to the unique properties of each encounter.

3.6.4. Collaborative Utilization of Constrained Resources

> The capability of DFR operators to collaborate with arrival flow management by contributing dependable future states of their aircraft to enable more efficient use of capacity-limited airspace resources.

This capability engages the DFR operator directly in the strategic conflict management functions of traffic synchronization and demand-capacity balancing, benefiting both the efficiency of arrival operations and the workload of the personnel involved. Any airport with arrival demand exceeding the landing rate capacity merits the use of TFM to regulate the arriving flows to an appropriate level that maximizes throughput and minimizes delay. As the use of dynamic scheduling methods in TFM becomes more widespread, DFR operators will bring collaborative capabilities to augment these methods through precise, conflict-free arrival performance, as illustrated in Figure 8.

The cooperative practice CP-J "*Join in Appropriate Flow Management*" aligns with this capability. The cooperation begins well in advance of arrival, and in some cases before departure, with DFR operators sharing their intended destination, ETA, and preferred arrival fix/runway/pad. This information allows more accurate demand estimates by TFM and therefore better scheduling. ETA updates from the DFR operator enroute will enable schedule refinement as uncertainties diminish. The DFR operator applies its 4D conformance capabilities and commits to a precise and dependable arrival state, thereby collaboratively enhancing TFM performance.

The schedule times can either be specified in absolute terms (i.e., an RTA at a specified location, altitude, velocity, and alignment with an applicable arrival path) or relative to a leading aircraft (e.g., invoking IM procedures). Given that DFR aircraft are self-separating up to this point, the separation automation is computing all flight path adjustments necessary (e.g., speed, path, and altitude changes) to deliver the aircraft safely and independently to that future state. Relative to IFR procedures, this collaboration has the potential for significantly lower workload for controllers, pilots, and traffic flow managers. As the DFR aircraft proceeds into the terminal airspace, it invokes CP-I "*Coordinate with ATC in Controlled Airspace*" by receiving and operating under an ATC clearance, as appropriate. Operations henceforth are analogous to a VFR aircraft following ATC instructions for arrival.

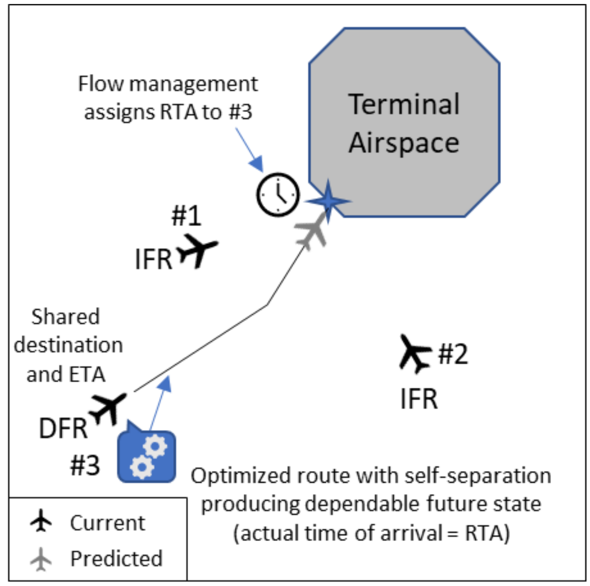


Figure 8. Digital Flight operators collaborate with flow managers by providing dependable states such as RTA meeting and Interval Management.

3.6.5. Self-Organization & Sequencing

The capability of DFR operators to perform distributed local interactions that create order among aircraft to meet a shared operational objective, usually, sequencing and spacing to land.

This speculative Digital Flight capability enables DFR operators to share a capacity limited resource without a central authority providing scheduling or sequencing for that resource. While not a fundamental requirement for Digital Flight like the first three listed capabilities, the capability to self-organize and self-sequence will enhance operations at non-towered airports. Analogous to VFR operations at a popular uncontrolled field, where self-organizing and self-sequencing is performed regularly through established procedures, traffic patterns, voice-radio procedures, and visual acquisition, this Digital Flight capability complies with those procedures and extends the operation into IMC while relying primarily on automated digital exchanges. Separation automation algorithms process information on the dynamic operating environment and local traffic, and they determine their aircrafts' appropriate positions in the arrival sequence. Intent sharing removes ambiguity, including potentially

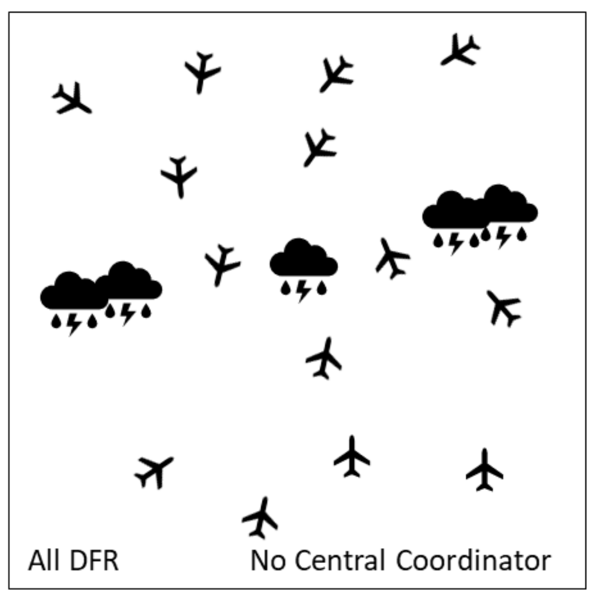


Figure 9. Digital Flight may be developed to produce self-organizing behaviors.

declaring the traffic aircraft being followed. Sequence conflicts are resolved automatically through preestablished priority rules. Interactions with arriving VFR and IFR aircraft are similarly handled, applying CP-D "*Respect VFR and IFR Aircraft*" and CP-L "*Respect Established Operating Procedures*" to ensure compatibility with their operations.

The capability to self-organize and self-sequence may be applicable also in environments apart from uncontrolled airports. For instance, as illustrated in Figure 9, DFR operators that encounter convective weather may use this capability to organize and sequence themselves through weather gaps. Whether separate automation functionality is needed to manage this scenario would depend on the emergent behavior of the self-separation capability, where deconfliction creates a natural ordering of traffic as one aircraft gives way to another.

3.6.6. Self-Regulation of Density & Operational Complexity

> The capability of DFR operators in a distributed, automated fashion to apply appropriate mitigations, as traffic volume increases, to ensure safe operations are maintained at scale.

This Digital Flight capability, also speculative, is attributable to the collective ability of DFR operators to ensure their self-separation capabilities remain feasible as the density of aircraft or the complexity of their interactions grow. The capability is analogous to the static implementation of capacity limits for each ATC sector but has important differences. Rather than applying a static cap on aircraft count or density, the capability is dynamic and tailored to the Digital Flight mechanism for separation provision (i.e., distributed, cooperative, automated, and trajectory-based). Unlike under IFR, human workload is unlikely to be a consideration in how many DFR aircraft can share the airspace and in what configuration, nor is frequency congestion. Rather, it is the flexibility preserved for future flight path changes to perform self-separation that matters. Illustrated in Figure 10, as long as DFR procedures ensure sufficient maneuvering room and decision-making time, the performance of self-separation should be sustainable to significantly higher levels of traffic density and complexity than are common today.

In the early stages of DFR operations, before this capability is mature, it may be appropriate to apply simple capacity limits that are empirically shown to be manageable by self-separation. However, applying techniques that are appropriate for human-centric ATC will in the long term be self-defeating to Digital Flight. Therefore, developing this Digital Flight capability will be important to achieving Digital Flight's inherent scalability benefits.

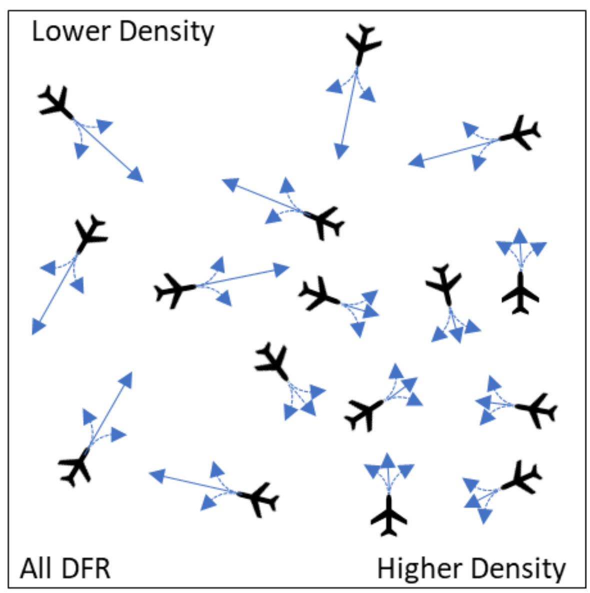


Figure 10. Digital Flights may apply longer lead times and conflict-free maneuver preservation to self-regulate traffic density and complexity.

3.7. System Safety Considerations

System safety is an essential aspect of Digital Flight implementation, both for receiving operational credit under VFR and IFR, and for operations under DFR once it is established as a regulated operating mode. This section addresses considerations for future Functional Hazard Assessments (FHA) and Preliminary System Safety Assessments (PSSA) that will be required for the certification and approval of systems, equipment, and procedures that enable operations under DFR.

The principal safety requirements considered here are captured in consensus standard 14 CFR 23.2510 and corresponding Parts 23.1309 and 25.1309 (Equipment, systems, and installations). The relevant guidance material, such as Advisory Circular (AC) 23.1309-1E (System safety analysis and assessment for Part 23 Airplanes) invokes, in turn, Aviation Recommended Practice (ARP) 4761 (Guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment).

The following sections describes elements of the system safety assessment process as would be applicable to an assessment of DFR. The process entails the identification and classification of hazards, their mitigations, and their associated probability. Collectively, these factors define the risks associated with DFR, which, in-turn, define the design assurance levels (DAL) and certification path for required equipment, as well as the required nominal and non-normal operating procedures associated with its use. As with all operating modes, DFR has dependencies on humans and technologies, both of which are fallible. The analysis therefore should entail a combination of technical, human factors, and operational considerations, which give rise to the following identified DFR hazards and potential mitigations.

3.7.1. System Failure

In most scenarios, existing operating modes (e.g. VFR, IFR) could be leveraged as fallbacks for DFR in the rare event of critical system failures leading to a loss of the separation function. The most critical case arises when the Digital Flight system fails in IMC, when ATC would otherwise be providing separation (were the aircraft to be operating under IFR). In the worst case, such failures could be latent (un-annunciated), precluding their detection by the operator. This case has similarities to the lost communications state for IFR, or to VFR aircraft when it is not known that communications are lost, until there is an attempt to issue a control instruction or transfer communications.

Several mitigations reduce the risk associated with this hazard, including the establishment of an adequate DAL, system redundancy, and, as a last recourse, the issuance to the DFR flight of a collision avoidance system action, which must be functionally independent of the DFR separation provision system and its computations. The hazard is significantly reduced when the DFR system is *not* the sole means for providing the separation function in lieu of ATC, such as DFR with a pilot onboard during VMC. In these cases, the operator can immediately intervene and reassume responsibility for visual separation while remaining in visual conditions.

Just as there are procedures to manage in-flight emergencies and system failures for IFR and VFR flights, DFR may require additional provisions that take advantage of Digital Flight capabilities. For various DFR encounters and operations, several scenarios in which separation provision system failure could occur can be considered: (1) DFR-DFR encounters; (2) DFR-VFR encounters; (3) DFR-IFR encounters; and (4) DFR approaching to land. Each of these cases would result in different consequences to the primary DFR aircraft and other affected aircraft. In case (1), if the primary aircraft's DFR system failed, the other DFR aircraft's system would ensure separation from the failed-DFR aircraft, treating it essentially as "non-cooperative" traffic that is not performing as required. In case (2), the VFR traffic never loses responsibility to see and avoid traffic, and the failed-DFR aircraft would simply revert to VFR procedures. Case (3) is more critical but is exactly analogous to an aircraft losing RNP or RVSM capability: the operator would be obliged to immediately inform ATC and would obtain a clearance to continue operations under IFR. ATC would take up the separation responsibility for the IFR aircraft and the failed-DFR / newly-IFR aircraft. Case (4) is a combination of the others and would likely only cause problems if the DFR aircraft is providing in-trail separation from preceding traffic. In this case, separation could be achieved by procedural means (e.g., groundspeed control via verbal coordination) or by reversion to ATC control or VFR operation, as appropriate. The use of procedures to mitigate in-flight emergencies is a well-established practice in ATC, IFR, and VFR standards, and would be a consistent approach for DFR.

3.7.2. Surveillance Failures

DFR surveillance failure would lead to a loss of the DFR aircraft's shared traffic awareness, which would disable the separation function as discussed above. The effects could be mitigated by system redundancy and the use of dissimilar data sources (e.g., ADS-B and broadband). Redundancy of data sources and redundancy in the capability-enabling technologies are key to their resilient functionality and to minimizing the need to exercise fallback measures. Even with redundancy, a system-wide surveillance failure would have far-reaching consequences for all affected aircraft, DFR and non-DFR. Cataclysmic failures of this nature are already addressed in the structure of the NAS and are mitigated to a suitably remote probability.

3.7.3. Display and Alerting Failures

DFR system display and alerting failures may lead to an effective loss of the separation function, as discussed above, or a loss of pilot/operator situational awareness, which increases the chances of human error when interacting with the system. The failures fall into two broad categories: loss of function, and display of hazardously misleading information. Following the loss of function that affects a single DFR aircraft, the operation would (barring redundant systems) revert to an alternative operating mode (VFR or IFR), with minimal impact to ATC or other users. The hazardously misleading case is more serious, because of the potential of the DFR system or DFR operator to make incorrect decisions that could compromise safety. This will once again be addressed by achieving the appropriate DAL and system redundancy, and by the incorporation of proven mitigations, such as independent built-in checks and electronic "heartbeat" monitors that shut down the affected system in the event of a freeze. The residual risk of such failures should be comparable to those affecting sole-source Global Positioning System (GPS) navigators, which are fully accepted for preforming safety-critical functions such as approach operations to minima in IMC.

3.7.4. Communication Failures

Digital Flight is not reliant on verbal communications and would likely be more robust than traditional systems in the event of a communications loss. DFR will require some degree of datalink communications, and the impact of its loss would depend on the extent and duration of the outage. The effect would be mitigated by on-board system redundancy and by the multiple paths for receiving the required data. In addition, the separation automation could be designed to maintain a minimum separation time horizon, which would ensure deconfliction from known traffic for a specified time following a failure. This would provide time for the DFR operator to transition to an alternative operating mode once a failure has occurred without jeopardizing separation. A similar concept is currently applied to the loss of Receiver Autonomous Integrity Monitoring (RAIM) during a GPS approach: if a RAIM failure occurs after the final approach waypoint, the receiver is allowed to continue operating without an annunciation for up to five minutes to allow completion of the approach. [24][25]

3.7.5. Human Error

Human errors have been categorized into slips, lapses, fumbles, mistakes, and procedural violations.[26] DFR operators could be subject to each of these error types. When Digital Flight systems are operating autonomously (i.e., without direct operator interaction), the human operator assumes a supervisory role while performing a vigilance task. Humans are not well-suited to this role, which promotes lapses, and so the separation automation will be engineered to keep the pilot or operator engaged with high situational awareness in case rapid intervention is called for. Nevertheless, a properly engineered Digital Flight system will not suffer from the typical human errors, resulting in greater overall safety for the combined operator/ Digital Flight system.

In summary, conventional methods for risk mitigation, such as establishment of suitable DALs, system redundancy, resilient architectures, reversion to VFR and IFR, and existing NAS robustness, will enable DFR operations to be conducted safely and with robustness. In most cases, DFR operations would be *less* susceptible to failures than non-DFR operations, given its reduced reliance on the human element for separation provision.

4. Value Proposition

Introducing Digital Flight, and ultimately DFR, offers the potential for significant value to be received from practically every perspective: from the industry level to airspace user communities to individual stakeholders. For most of aviation's history, the industry has conducted operations with just two primary operating modes, VFR and IFR. Expanding this set to include a third mode, DFR, and giving it the same widespread applicability throughout the airspace and user communities, may be as consequential to aviation as was the emergence of radio navigation that enabled IFR operations to proliferate. The value proposition of DFR is to empower all operators with 21st century capabilities that enable the safety and airspace access benefits of IFR without sacrificing the operator flexibility of VFR. The immediate result will be the opportunity to integrate operations like uncrewed aircraft that are not well supported by VFR and IFR. In time, all segments of the community can explore the value this new operating mode has to offer. Three perspectives are considered here: the value proposition of Digital Flight to the aviation industry as a whole, to segments of the airspace user community, and to individual stakeholders.

4.1. Aviation Industry

The value of Digital Flight to the aviation industry overall is the mechanism it provides to advance the industry in a collective manner, enabling an expansion of diverse operations while reducing friction for new entrants and their growth. The benefits to aviation are expected to be far reaching and has the potential to be among the defining elements of the second century of aviation.

4.1.1. Safety

Foremost among any other proffered value toward industry-wide advancement is safety. In addition to the safety benefits to new entrants, Digital Flight offers safety benefits to existing operators. Digital Flight's application of digital information exchange and automated, cooperative conflict management provides a clear safety benefit to VFR's "see-and-be-seen" foundation by providing traffic advisories on a predictable basis, whether or not a flight is receiving ATC services. Digital Flight also provides a clear safety benefit to IFR flights in non-surveillance airspace by adding another safety layer to the procedural separation practices.

The safety benefit for interactions among DFR aircraft is further enhanced by their redundancy, their mutually cooperative procedures, and the potential for performance-based traffic deconfliction. This benefit is especially pertinent to energy-constrained electric aircraft, for which the separation automation will take into account performance margins to best preserve remaining energy among the aircraft in conflict. As an ancillary safety benefit, Digital Flight provides to all operators an increased availability of information services that will supply weather and traffic information even beyond the DFR market. These services, bolstered by a growing Digital Flight industry, yield a more accurate situational picture at the planning horizon, resulting in safer decision-making for all operators that access them.

4.1.2. Industry-Wide Advancement

As a common new operating mode, Digital Flight benefits the aviation industry in its ability to advance broadly and concurrently. All segments of the airspace user community will have the opportunity to benefit from adopting Digital Flight in their operations, though this hypothesis must still be borne out. However, without a unifying operating mode like DFR, several operator communities will likely pursue their own new operating modes within their own domains (e.g., UTM, UAM, ETM), each waiting their turn for regulatory approval and each encumbered by accommodating the precedent of another's previous rulemaking. Establishing many such new modes may generate serious interoperability issues, leading to segregation or other restrictions that detract from operator benefits and add significant complexity to rulemaking and oversight. Digital Flight directly addresses this issue by providing a single common operating mode with all operator communities taken into account in its design.

The opportunity for a common operating mode is realistic, given that most of the emerging communities are seeking to employ similar attributes in their concepts: digital information connectivity and services, shared traffic awareness, cooperative practices, and separation automation. For this reason, the Digital Flight concept invokes these as Essential Elements. This approach also has the potential to generate a critical mass of industry support for significant change by uniting the disparate operator communities to a common cause. Even if Digital Flight is adopted at different times and for different purposes within the community, it would still have cross-community support because all members will have a voice in Digital Flight's definition to ensure their needs will be met.

4.1.3. Operational Diversity

Digital Flight represents a new tool in the toolbox of aviation operating paradigms. The existing tools, VFR and IFR, limit the diversity of vehicle types and the operational applications they fulfill, leading potentially to a proliferation of tailored regulation. UAS is a prime example. VFR and IFR were not designed for either remotely-piloted or self-piloted aircraft; 14 CFR Part 107 provides a limited solution but under strict limitations (segregated flights and line of sight) that now must be overcome by waiver. More general use of UAS will require a new operating mode for their business case viability.

Once DFR is available to the user community at large, it will be a template for innovation, leading to greater efficiencies, new mission capabilities, and emergent markets. Rather than creating a new operating mode for a very specific application (e.g., UAM) that limits creative application, DFR offers a flexible operating mode embodying generalized capabilities (self-separation, self-optimization, self-organization, etc.) that can inspire a diversity of potential new applications. This will result in proliferation of the diverse ways in which aviation benefits the public, without requiring substantial rulemaking each time.

4.1.4. Reduced Friction for Entry and Growth

Aviation is more valuable to society when it is built on the ability for new entrants to easily join the industry and for new markets to rapidly emerge and grow. In broad terms, new entrants range from individuals seeking to participate in aviation to new or existing companies looking to join or create a market of aviation services. Reducing barriers to entry creates opportunities that can stimulate economic activity and spawn new innovation. Enacting regulation for DFR may prove to be as transformative to society as was the decision to make the military GPS signal available for civil use.

4.2. Airspace User Community

The airspace user community is highly diverse, comprised of numerous user categories that are differentiated by factors such as the types of aircraft they fly, the regions of airspace they predominantly use, their mission objectives, the markets they serve, and their risk tolerance. ICAO categorizes civil aviation as commercial air transport, general aviation, and aerial work.[27] Complementing these categories are emerging/future operations and military operations. The introduction of Digital Flight unlocks potential new pathways for each category to advance and grow.

4.2.1. Commercial Air Transport

Air carriers, commuters, air taxis, and commercial business aviation provide scheduled and on-demand passenger and freight operations using large, medium, and small piloted jet aircraft, as well as large propeller driven aircraft (turbo-props). Applications of Digital Flight to air carriers and air taxis are highlighted here as examples of Digital Flight's value to commercial air transport.

Air Carrier

The ATC system has been designed primarily to accommodate the needs of the air carriers. Conducted predominately under IFR, these operations relinquish the route and altitude flexibility of VFR in favor of the increased safety performance of IFR. Given the volume of air carrier operations, airspace capacity under IFR is constrained by factors including frequency congestion and ATC workload. Digital Flight could bypass both factors, allowing for continually optimized routing, flexible changes to route and altitude in response to dynamic conditions, and increased airspace capacity overall. Under DFR, air carriers could also collaborate with ATC's time-based flow management automation, providing conflict-free delivery of their aircraft to a scheduled arrival waypoint and/or apply IM capabilities for merging and spacing to improve efficiency for airport and terminal operations.

Air carriers and other IFR operators can begin employing Digital Flight capabilities today. NASA's TASAR (Traffic Aware Strategic Aircrew Requests) enables operators to request more optimal routing that Digital Flight-like automation has predetermined to be clear of traffic, thereby reducing controller and pilot workload while achieving immediate operational benefits.[28]

Air Taxi

Current air taxi operators (pre-UAM) use conventional, piloted aircraft to provide air transportation to smaller communities that may only be served by a non-towered airport. Flights are often conducted under VFR when the weather permits, and under IFR when required. At non-towered airports, IFR flights are subject to procedural separation standards, limiting access in IMC to one aircraft at a time. Digital Flight could increase the scale of access and reduce delays to these non-towered airports by eliminating the need for an ATC clearance. Digital Flight would also enable these flights to upgrade their VFR operations to achieve IFR-like safety from collision hazards rather than relying upon "see-and-avoid" procedures.

4.2.2. General Aviation and Aerial Work

General Aviation (GA) and Aerial Work represent aircraft of all types and a wide diversity of flight missions. GA includes non-commercial business aviation, instructional flying, and recreational / personal aviation, while Aerial Work uses aircraft for specialized services such as agriculture, construction, photography, surveying, aerial advertisement, observation and patrol, search and rescue, and other emergency air services. Digital Flight would provide value to these segments of the user community through several mechanisms: improving safety, efficiency, airspace access, and simplification of piloting and ATC procedures. Some examples of potential Digital Flight value to these users are highlighted here.

Aerial Work for Emergency Services

These operations include police and emergency medical services, aerial fire spotting and fighting, authorized surveillance flights over disaster scenes, and other similar aerial activities for the public good. Current operations are frequently limited to established helicopter routes, limited to VMC, have a high collision risk, and require rapid deployment without advance notice.

Digital Flight would enable emergency air services to immediately depart on their missions in VMC or IMC with the ability to independently mitigate collision risk from other airborne aircraft. DFR operations would be more responsive to public service missions than operations under VFR or IFR. In addition, they would be free to choose and dynamically update routing, speeds, and altitudes that are optimal for mission performance based on real-time, local conditions.

Business Aviation

Business aviation operators commonly use high performance jet aircraft and fly at higher altitudes than air carrier operations. Flights intending to cruise above Flight Level (FL) 450 are frequently constrained by traffic flows in the climb to altitude. Digital Flight would allow operators to derive full benefit of the performance capabilities of their aircraft by offsetting from major flows during climb without impacting controller workload. In addition, business aviation often relies on executive or secondary airports, but are still subject to terminal arrival and departure flow restrictions. These operators could see early benefits from the introduction of Digital Flight capability to expand capacity at these airports and nearby satellite airports and avoid flow restrictions.

Recreational / Personal Aviation

Digital Flight would demonstrably increase the safety of VFR operations over "see-and-avoid" procedures. Separation automation will be far more capable than the pilot's eyes at locating and tracking targets and will exceed the alerting function now built into ADS-B IN systems by providing reliable guidance for the resolution of conflicts. Using Digital Flight, safety from collision risk would equal or exceed that available through IFR, without compromising the operational flexibility available under VFR. Under DFR, GA flight efficiency would be improved by making flights between uncontrolled airports free of routine verbal contact with ATC, even if IMC is encountered enroute. When using secondary airports within and under Class B airspace, Digital Flight could facilitate GA access and transit across this constrained airspace while minimizing pilot and controller workload.

4.2.3. Emerging/Future Operations

The civil aviation categories above will soon have new members, with Digital Flight potentially being the most viable path to operational approval. Digital Flight increases the opportunities for future uncrewed operations, currently only permitted under restrictive rules, individual waiver, and/or in segregated airspace. DFR enactment would provide regulatory certainty for new entrants, a critical factor for enabling the development of new operational models.

Small UAS

Small UAS operations, limited to vehicles weighing 55 pounds or less, are primarily surveillance or small package transport. These operations are governed by 14 CFR Part 107 which restrict operations to within 400 feet of the surface and within visual line of sight. Waivers are required for other activities, often requiring some degree of segregation from non-UAS operations. These limitations can pose a significant challenge to the business case for many potential small UAS operators. Digital Flight would eliminate the need for restrictions to visual conditions and low altitude, thereby expanding access and competition. It would also allow vehicles to operate with routing, speeds, and altitudes that are more energy efficient, expanding the useful range of the small UAS aircraft.

Regional UAS

This emerging user category will consist primarily of operators of conventional airplanes converted for remotely piloted use, carrying freight and ultimately passengers on regional flights of roughly 50 to 350 nautical mile stage lengths. Digital Flight would enable safe regional UAS operations regardless of size, cloud presence, and prevailing visibility. Regional UAS will also gain value from Digital Flight through the significant simplification of UAS procedures.

Urban Air Mobility

Urban Air Mobility is expected to consist of eVTOL multi-fan vehicles, including some that employ wing lift during forward flight. While many will initially have onboard pilots, some are being designed for semi-autonomous flight. UAM is generally focused on intra-urban passenger and cargo missions, including shuttle service between major airports and various locations around a metroplex. Digital Flight could enable access to these low-altitude urban environments without dependence on ATC. DFR could serve as the primary operating mode within the early-stage UAM volumes and corridor constructs and enable a rapid transition beyond these constructs as market conditions require. In addition, Digital Flight’s capability for adaptive separation will provide for the closely spaced operations necessary to establish capacity sufficient for market formation.

High Altitude Platform Systems

HAPS are uncrewed, long-endurance aircraft designed to operate above FL600. Typically solar or hydrogen powered, they can remain airborne for months, providing telecommunications or earth observation services to customers on the Earth. Unlike commercial air transport where the service is to transport goods or people through the airspace, HAPS are designed to provide services from the airspace. Current operating modes are not structured for persistent operations, and the FAA is exploring the concept of “cooperative separation” in its ETM Concept of Operations.[3] Currently, HAPS operations are restricted to segregated airspace allocated by the Central Altitude Reservation Function as an altitude reservation. The FAA recognizes this approach as temporary and not scalable to meet the needs of an emerging industry. Digital Flight could enable flexible operations in Upper Class E airspace without expanding the responsibilities of the ATC system or segregating the operations with special activity airspace.

4.2.4. Military

Digital Flight can provide both direct and indirect benefits for military operators. The direct benefits would be similar to their civilian counterparts for equivalent operations.

4.3. Stakeholders

In addition to providing value to the aviation industry and its user communities, Digital Flight also provides value to direct stakeholders, including the operator companies and the individual performers such as pilots, controllers, and dispatchers.

4.3.1. Operators

Beyond the benefit of improved safety, a DFR operator stands to gain operational value in three important areas: access to airspace, flexibility in flight path planning and execution, and as a result of the first two, increased predictability of their operation. Different operators may leverage these benefits in different ways, and some benefits will be more important to some DFR operators than to others, but all will benefit to some degree from the three mechanisms.

Access

Access refers to the ability to use desired airspace for the mission at desired times without restriction or delay. Operators of VFR flights have no access to Class A airspace, and they must obtain an ATC clearance before entering Class B airspace. Radio communications must be established before entering Class C and D airspace, and in-flight visibility and distance-from-cloud limitations must be observed in all airspace classes while operating under VFR.

IFR operators may use any class of airspace but may not operate without first filing a flight plan of complete intent, receiving a pre-departure ATC clearance that may include predetermined restrictions to routes, and conforming to the clearance until an amended clearance is received. Some new entrant operators, especially those of aircraft without a pilot onboard, may not be able to meet the requirements for VFR or IFR flight, restricting their operations to uncontrolled or segregated airspace, or requiring a waiver.

Digital Flight could provide access to all airspace classes without segregation. Under DFR, operators could operate in IMC without forfeiting the flexibility of route and altitude choice allowed by VFR, while benefiting from superior collision safety. DFR operators of new entrant aircraft will have routine access to airspace that otherwise would require approval through a waiver process.

Flexibility

Flexibility refers to the authority to plan and replan one's flight promptly, with minimal restrictions on route, altitude, and timing, and without requesting permission. VFR exemplifies significant flexibility, with operators generally free to plan and replan at will in nearly all the domestic airspace available to them. VFR restrictions to flexibility are primarily related to weather conditions requiring minimum flight visibility and distance from clouds. Otherwise, flexibility is so foundational to VFR that a pilot can literally take off and then decide where to fly and how to get there.

IFR, by contrast, limits flexibility in exchange for access to the airspace in all weather conditions. Using IFR rules and procedures, ATC approves or modifies the original, filed plan, as well as any subsequent changes either prior to or during flight. The airspace is structured into primary flows to deconflict arriving and departing traffic, limiting the flexibility given to an individual flight. Practical limits also exist on both the nature and frequency of changes permissible by ATC in a busy control sector, due traffic volume and congested radio frequencies. The result is that IFR permits airspace access in IMC, but operator flexibility in timing, routing, and re-routing while airborne can be limited.

DFR has VFR-like flexibility in both VMC and IMC and all airspace classes, and is further enhanced by the ability to plan "over the horizon" without regard to meteorological condition or airspace class.

Self-Predictability

Self-Predictability refers to the increased confidence an operator has in achieving a desired operational outcome on any given flight. This benefit is a derivative of the combined benefits of access and flexibility. The ability to access the airspace when and where desired, and flexibility to replan in response to dynamic conditions, provides control and confidence over accomplishing the mission objectives in a predictable manner.

Under VFR, self-predictability is degraded by unexpected weather changes. VFR flight into IMC is a common hazard that can be hard to predict. Commercial operators (both scheduled and on-demand operations) rely on self-predictability to provide commercial value to customers, and reliability of service is diminished when it is restricted to VMC. Under IFR, self-predictability can also be degraded by unexpected events including hazardous weather, capacity restrictions, and ATC availability.

Under DF, the operator may use its freedom of access and flexibility to enact self-optimizing mitigations to disruptions in real time, thereby greatly increasing self-predictability of operational outcomes.

4.3.2. Pilots

Digital Flight may have impacts on the daily activities of existing operational actors, depending on their existing and future roles.

IFR Pilots

IFR pilots can expect no change in equipage, procedures, or ATC services, once DFR is enacted. However, they may take advantage of Digital Flight capabilities under IFR. The NASA-developed TASAR application is an example of an advisory Digital Flight capability intended for use in IFR.[28] TASAR provides pilots with a tool that identifies a conflict-free optimized trajectory, which the IFR pilot uses in making a request to ATC. Since the requested change is already deconflicted based on real-time traffic awareness, ATC approval is expedited.

VFR Pilots

Pilots flying conventional aircraft under VFR will treat DFR flights in the same manner as any other air traffic, applying "see-and-avoid" and other standard procedures in 14 CFR 91.113. With DFR flights proactively remaining well clear of VFR flights, the frequency of traffic encounters prompting the VFR pilot to alter course would be low. Some position and intent messages heard in the traffic pattern may be synthetic (for self-piloted DFR aircraft), but the behavior of visually-acquired traffic will not be altered.

VFR pilots may also benefit from the emergence of Digital Flight technologies and information services, both prior to and after the formalization of DFR in the regulations. Digital Flight capabilities may be commercially available to VFR operators as advisory tools that enhance their situation awareness and operating efficiency.

DFR Pilots (Onboard)

DFR pilots of conventional airplanes will experience the simultaneous benefits of IFR-like access and VFR-like flexibility. For operations they would otherwise have conducted under VFR, pilots operating under DFR will fly with greater confidence in the traffic environment, knowing that separation is provided through automation without relying solely on their ability to visually see and avoid the traffic. Having access to digital information services and dynamic flight path planning automation, they will also be able to plan more effectively beyond the visual horizon. Confidence will also be increased regarding the potential impacts of deteriorating visibility, as Digital Flight capabilities persist independent of visibility.

For operations that would have otherwise been conducted under IFR, the DFR pilot will enjoy simplified procedures and greater autonomy. Departing at non-towered airports will be as easy as VFR, though with greater confidence in the traffic environment. While enroute, the pilot will interact with their automation like they would with ATC if operating under IFR. Flight path changes are pre-checked by the separation automation for conflicts, and resolutions are provided, often giving the pilot a choice of multiple acceptable maneuvers (e.g., a new altitude vs. a lateral path change). Arrival to airports in VMC will also be similar to VFR procedures, though again with greater confidence in the traffic environment. Separation automation will continue to provide guidance to enter the traffic pattern safely, taking into account other aircraft in the traffic pattern and local area. DFR arrivals to controlled airports in IMC will use IFR-like procedures conducted under an ATC clearance. DFR surface operations are not expected to differ significantly from IFR or VFR procedures.

DFR Pilots (Remote)

Remote pilots of UAS aircraft will find that DFR greatly simplifies their processes for planning and initiating their remotely operated flights. The advance coordination and approval process for gaining access to the airspace would be eliminated. The need for segregated airspace and strict avoidance of Classes B, C, D and E airspace (for small UAS) would also be eliminated, making flight planning much easier and enabling new mission types.

The remote operator of UAS under DFR would supervise the mission but allow separation automation to manage the flight path. The remote pilot would use Digital Flight capabilities to accomplish many of their tasks, enabling more vehicles to be managed per remote operator. The remote operator would focus primarily on facets of the operations such as systems health, weather conditions, mission execution, and arrival coordination.

4.3.3. Air Traffic Controllers

Flights operating under DFR provide the controller with more information than VFR and a lower workload than IFR, and therefore DFR flights are expected to increase controller situation awareness and decrease controller workload. For flights under VFR or IFR, Digital Flight capabilities will be available and deliver benefits similar to NASA's TASAR technology that enables controllers to approve flight-optimizing route change requests with reduced workload. Similarly, VFR pilots using Digital Flight capabilities will also be better able to remain well clear of traffic, reducing the need for ATC traffic advisories. Unlike VFR using the subjective "see and avoid" requirement, DFR flights are subject to validated separation standards that consider the complete traffic situation, making alerts less likely than from VFR flights.

ATCT Controllers

Local (tower) controllers will manage DFR flights similar to VFR flights. For departure, on the first call to ground control, the flight would identify itself as DFR and provide the direction of flight. A normal taxi and takeoff clearance would be given, and the controller would clear the flight to proceed DFR, at which point the flight will begin self-separation procedures, making the need for further controller instructions uncommon. Local controllers will generally not need to distinguish DFR arrivals from IFR arrivals in IMC, or DFR arrivals from VFR arrivals in VMC, as the DFR arrivals will not require any additional handling.

TRACON Controllers

Terminal controllers would handle DFR flights in the same manner as VFR flights during departures from controlled airports, and as IFR flights during arrivals to controlled airports. DFR flights will be self-separating as soon as they are released to DFR on departure. DFR flights will be aware of the major arrival flows and will avoid them as they navigate through and beyond the terminal airspace. On arrival, terminal controllers will manage DFR flights by providing arrival instructions or approach clearances as appropriate, and separation services to the extent required. DFR capabilities to self-merge and/or self-space at a specified interval can be leveraged by the terminal controller at their option to improve throughput and reduce workload.

ARTCC Controllers

Center controllers will generally have the least interaction with DFR aircraft that are self-separating. DFR flights would be managed the same as VFR aircraft but behave predictably given their shared intent, not require advisory services, and not interfere with IFR aircraft in the sector. In conflict situations, DFR flights will share their intended resolution, enabling the controller to have advance notice and a predictable outcome.

Traffic Flow Managers

To traffic flow managers, the DFR aircraft are engaged only when their destination airport is impacted with a TMI. DFR aircraft will appear in the metering lists created for the terminal arrival fixes, and they will be able to accept RTA assignments for fix crossing times.

4.3.4. Flight Dispatchers

An airline dispatcher that plans a DFR flight will have more flexibility to create optimal routes, not subject to the constraints of ATC preferred routes and enroute TMIs. They will be able to select optimal climb profiles, cruising altitudes, and wind- and weather-optimized routes to the terminal boundary arrival fix. Dispatchers will be able to leverage greater arrival-time predictability to reduce excess fuel load. Enroute changes created by the separation automation would be coordinated automatically between onboard and operations center computers, facilitating the dispatcher flight-following responsibility with reduced workload.

Dispatchers of UAS flights would have predictable access to more airspace without the need for approvals, waivers, or airspace reservations.

5. Path Forward

Implementing a new operating mode for the airspace user community at large is a substantial undertaking and will require a broad community effort to see it through. A major challenge will be establishing sufficient evidence of safety, performance, and maturity of the enabling technologies, the supporting data and infrastructure, and the cooperative practices, while enabling early applications to emerge in order to gather that evidence. Laying out a detailed path for implementation is a complex task and beyond the intended purpose of this document. However, several key activities relevant to the path forward are briefly described. These activities are based on pursuing an incremental implementation of Digital Flight capabilities that provide increasing benefits with time, while generating the required operational data and other artifacts for the eventual regulatory approvals and wide-scale adoption of Digital Flight and DFR.

5.1. Community Building

Digital Flight represents a novel approach to ensuring the safe separation of aircraft in that it applies automation in the performance of that function. Proving the safety case of cooperative, automated self-separation to the satisfaction of regulators will be a significant undertaking and therefore requires substantial focus by both the broader industry and the regulator. Digital Flight can uniquely provide this opportunity, given its intent to support all airspace user categories, from new entrants to established operators. To capitalize on this opportunity, the different user categories would benefit by coalescing as a *unified Digital Flight user community* in seeking this new operating mode. The alternative of individual or piecemeal requests for rulemaking by uncoordinated user groups focused on their own needs will likely produce competing proposals that strain the regulator's resources. In addition to delaying progress, it may have other unfortunate effects. Rulemaking for early applicants may impose precedents that later applicants must accept. Also, proliferation of inconsistent new operating modes may require segregation, with added complexities at the boundaries. It is therefore imperative that all user categories, even late adopters, have the opportunity to understand Digital Flight and to contribute to its formal specification and implementation. A unified approach from the industry will not only increase the likelihood that a change this significant will be realized in a reasonable time frame, but it will ensure that the next major new operating mode will meet the diverse needs of all airspace users and not just those of the first applicants.

Accordingly, a concerted educational campaign is needed to ensure broad understanding of the capabilities and benefits of Digital Flight and the benefits of a joint effort towards implementation. NASA initiated this educational process on Digital Flight through technical interchange meetings with members of industry in 2021 and 2022, and continues with the publication of this paper. Further engagements with industry will occur in various forums, both targeted and broad. These engagements will expand on the coordination that occurs regularly between NASA, the FAA, and the industry. NASA will work with the FAA to focus on the airspace user community as a whole, and building community consensus is the first important step in that process.

5.2. Early Applications & Capability Maturation

New aviation capabilities follow a repeatable process that typically involves first deployment with advisory, low-risk applications. These early applications provide an indispensable opportunity to incrementally exercise and mature new capabilities prior to substantial policy changes taking place. Policy and regulation typically are only changed after a new capability has shown operational viability in real use cases. Digital Flight capabilities are likely to follow this same process, premised on two assumptions: (1) that DF-like operations can be implemented under VFR (with its applicable regulatory restrictions), as long as the pilot remains the final arbiter of flight path safety via visual deconfliction; and (2) that DF-like capabilities can be exercised and provide benefits under IFR in controlled airspace, provided that an ATC clearance is obtained for any flight path changes. NASA's TASAR application exemplifies the latter concept.[28]

An historical view of past capability maturation paths illustrates several parallels to the implementation of existing technologies that were also "blue sky" when first implemented. These include GPS approaches, approach credit for EVS (Enhanced Vision Systems), RVSM, and ETOPS (Extended-range Twin-engine Operations Performance Standards). In each case, the associated technologies were implemented long before complete operational approval was established in regulation, but operational benefits still resulted from early use of the equipment. Their capability maturity was dependent upon three achievements: (1) their functions being proven reliable to the expected level for the intended use and operation (often assistive prior to being safety critical), (2) the technologies enabling the new functions being mature enough for their intended use, and (3) the sources of required data having the integrity, accuracy, reliability, and availability to feed the core enabling technologies. Figure 11 is a simple illustration of the typical relationship between these elements. Like other historical improvements, Digital Flight will be dependent upon this relationship. Data sources and technologies must be proven to be mature enough to enable the envisioned capabilities and be approved for operational use.

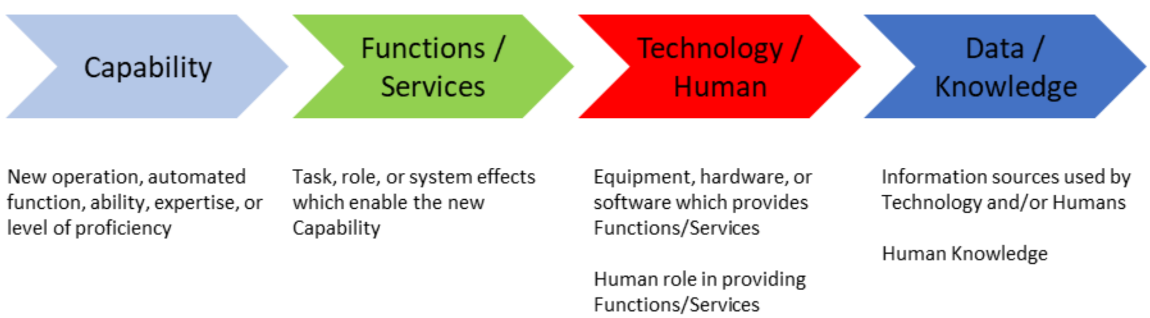


Figure 11. Capability maturity model showing the relationship between capabilities, their associated functions, the enabling technologies, and their associated input data.

GPS: Most GPS approaches were first instituted via "GPS overlay" approaches, where aircrew were required to monitor the underlying navaid in order to conduct the GPS approach. Once adequate operational and safety data were recorded, the system evolved into today's extensive network of thousands of stand-alone GPS approaches, including LPV (Localizer Performance with Vertical Guidance) approaches to Category I minima. In addition, GPS-only airports are now eligible as IFR destinations, increasing their value to the local community.

EVS: In a similar vein, EVS equipment is now cleared for use on approach through touchdown, with reduced approach minima for suitably-equipped aircraft when flown by trained crews. This evolution also required several years of confidence-building, and ultimately the introduction of a newly defined *Enhanced Flight Visibility* in 14 CFR § 1.1 General Definitions.

RVSM: Instituted incrementally, both geographically and by vertical extent, RVSM starting in 1997 with the North Atlantic Track system between FL330 and FL370. By 2005, RVSM airspace had been expanded to encompass the entire western hemisphere between FL290 and FL410, with adoption in Africa, the People's Republic of China, and the Russian Federation achieved by 2011. RVSM doubles the airspace capacity and allows closer access to flight levels optimized for fuel economy, while non-RVSM users are constrained to altitudes outside the RVSM band, with obvious operational repercussions.

ETOPS: Twin-engine, overwater, passenger operations were previously barred due to a 60-minute flight time limitation from a suitable alternate airport. In 1978, ICAO implemented 90-minute ETOPS over the North Atlantic, and the procedure was successively expanded through ETOPS 120, 180, through to ETOPS 370 for approved users. ETOPS 240 essentially enabled worldwide twin-engine oceanic operations, giving clear advantages to approved users, while others cannot operate without a suitable alternate within an hour’s flight time from the proposed track.

In the examples listed above, requirements had to be addressed to achieve FAA certification of the aircraft technology, approval of operational procedures to use the technology by FAA Flight Standards, and approval for the operational integration of the new capability by ATC. In each case, the initial capabilities were implemented in advisory use cases to prove their viability before they were accepted as safety critical capabilities. The same methodology for capability maturity and technology deployment can, and should, be applied to the deployment of Digital Flight. A path to certification would entail the parallel development of Digital Flight’s Essential Elements and Principal Capabilities and the generation of operationally-derived artifacts establishing their maturity and readiness, thereby setting the stage for the development of the necessary technology and regulatory amendments to enable DFR. Such a path would yield early benefits to Digital Flight capable operators and ATC while the regulatory process for full DFR implementation takes place.

5.3. Service Providers and Critical Infrastructure

A cornerstone of Digital Flight is the use of automation and information services, both of which are established as part of the critical infrastructure supporting Digital Flight. These information and CNS capabilities will be diverse and may be developed, deployed, and operated by third parties, i.e., parties other than the DFR operators and the Air Navigation Service Provider (ANSP).

A third-party service provider can assist the DFR operator in meeting operational requirements that enable safe and efficient use of airspace without direct ANSP involvement. Third-party service providers can assist in multiple ways, such as (1) acting as a communications bridge between operators, (2) providing DFR operators with information about planned operations in and around a volume of airspace so that they can ascertain the ability to conduct their mission safely and efficiently, and (3) archiving operational data for analytics, regulatory, and operator accountability purposes. Third-party service providers can also support operations planning, intent sharing, vehicle de-confliction, conformance monitoring, and other airspace management functions (adopted from [3]).

Examples of infrastructure implementation include current initiatives to develop UTM capabilities. For instance, almost a dozen companies are providing public Low Altitude Authorization and Notification Capability (LAANC) services which is an early step towards operationalizing UTM.[29] Other initiatives include several efforts to deploy a shared non-cooperative surveillance capability to detect non-participating aircraft in an airspace volume and share this information among operators. Two examples are NuAIR's 50 mile corridor from Rome to Syracuse in New York and VANTIS statewide network in North Dakota.[30][31]

Additional capabilities potentially provided by third-party service providers may include navigation and augmentation services, obstruction and obstacle data, information exchange, weather sensor deployment and forecasting, and value-added services supporting cooperative conflict management.[32]

5.4. Performance Basis

Instantiating Digital Flight as a performance-based operation will unlock its potential to serve a wide variety of user categories and operational domains. Each may have unique requirements in terms of traffic density, operational tempo, aircraft performance, command-and-control structures (e.g., onboard pilot, offboard pilot, self-piloted), and airspace region. A prescriptive specification of Digital Flight is unlikely to support this diversity, whereas a performance-based specification will enable significant design flexibility and innovative solutions that can continually adopt ongoing technology advancements. As such, a performance basis for Digital Flight will need to be defined, whether it is based on levels of separation tolerance (analogous to RNP) or some other metric related to aggregate performance.

Like any system, the total-system performance of Digital Flight will be a function of its components and their integration, and thus each will require focused research and development (R&D) to establish and validate their performance role. In this paper, the components of Digital Flight are described in the broad terms of the four Essential Elements (Section 3.5). The following are examples of potentially relevant research questions associated with each of these elements.

Digital Information Connectivity and Services (Section 3.5.1) produces a digital model of the operating environment, but what is the performance impact of operating with an incomplete model? VFR specifies a minimum required flight visibility, and so is there a Digital Flight analog for *digital flight domain awareness*?[33] If so, how should it be defined and sized, and what performance implications should be expected as domain awareness is reduced? The digital model is refreshed by connectivity to data sources and services. How does the performance of connectivity systems impact total Digital Flight system performance? How long an interruption can Digital Flight endure without degrading performance, and what mitigations can be implemented to minimize the impact of substantial interruptions?

Shared Traffic Awareness (Section 3.5.2) is clearly critical to separation performance in a distributed construct like Digital Flight. Research will need to establish what constitutes sufficient "awareness" and what minimum information needs to be "shared." For instance, the importance of intent sharing has been highlighted throughout this document, but what are the *minimum* requirements to ensure adequate separation performance and how do they vary by circumstance? What information sharing contributes to the safe practice of smaller separation values? How does differing aircraft performance (e.g., speed range, maneuverability) affect separation performance, and how can this be factored into accomplishing adaptive pairwise separation that enables safely increasing traffic density? What surveillance is required of non-cooperative traffic (e.g., VFR traffic without ADS-B OUT)?

The set of *Cooperative Practices* (Section 3.5.3) postulated in this document are a starting point, but are they necessary and sufficient and will they achieve their intended effects? Research will need to assess their adequacy, determine how to automate their application, and measure their performance in a variety of applications (e.g., user categories, operating domains). Some practices relate to DFR aircraft interacting with each other, and others focus on interactions of DFR aircraft with VFR and IFR aircraft and with ATC. In the former category, what cooperative practices are critical to scalability? In the latter, how can cooperative practices best be applied to minimize impact on incumbent operations? For both categories, what parameters govern the interoperability of aircraft with wide differences in performance, and how can the need for segregation be eliminated beyond that which naturally occurs? How will the regulator monitor the operator's compliance with cooperative practices?

R&D on *Separation Automation* (Section 3.5.4) involves determining the necessary and sufficient set of automation functions required for Digital Flight, novel approaches to certification of the automated separation function, and the impact of different levels of functionality on total DFR system performance. For instance, what are the performance tradeoffs of tactical detect-and-avoid functionality vs. strategic trajectory-based separation functionality (also: onboard, offboard, or via service provision), and how do they vary based on aircraft performance and its operating domain? What are the appropriate time horizons for detecting and resolving conflicts, and how do they relate to encounters between aircraft of varying performance? What functionality is needed to enable the more advanced Digital Flight capabilities of self-organization & sequencing (Section 3.6.5) and self-regulation of density & operational complexity (Section 3.6.6), and how is performance measured for these operations?

These research questions are just examples of many that require study in order to establish a performance basis for Digital Flight. Not only will they inform the development of standards for the Essential Elements, but they will also help to establish a performance structure by which Digital Flight Principal Capabilities can be rolled out incrementally and judiciously based on established risk tolerances of the user categories that choose to employ Digital Flight and the airspace classes in which it is used. Having R&D focus on DFR system performance rather than general feasibility (the subject of decades of past research programs internationally) will lend both purpose and closure to the R&D activities such that actual implementation of DFR is the end result.

5.5. Safety Analysis

A critical enabler for the certification and deployment of Digital Flight is the generation of adequate data to support the safety case for their implementation. Historically, this has been accomplished using a combination of formal methods (e.g., RTCA DO-178C processes), analyses (e.g., FHA and PSSA), and service history. The latter is crucial as it embodies and demonstrates the integrity that is claimed as a result of the other processes. Accordingly, the collection of extensive operational data will be a vital enabler for the wide-scale deployment of the system. Fortunately, Digital Flight has an extensive and comprehensive data component which will make the collection of the required data feasible, without adding excessive overhead to the system. The data collection would continue as the Digital Flight implementation matures, thereby providing an ongoing and integral quality assurance function for DFR operations.

5.6. Standards Development and Means of Compliance

The full deployment of Digital Flight will follow the benchmark path for all disruptive aviation technology changes, inevitably requiring rulemaking and the development of standards for DFR equipment certification, operational approvals, and training requirements. Meanwhile, stakeholders will experience continuously increasing utility from their Digital Flight capabilities serving in advisory and assistive roles under VFR and IFR, while developing operational experience and performance artifacts that will help establish DFR as a new operating mode.

Performance-based R&D will inform the areas in which aviation standards will need to be developed, but one can consider as a starting point the four Essential Elements of Digital Flight (Section 3.5). Total system performance will be determined by the performance of these elements and their integration. By establishing performance-based standards in each element and tracing their performance effects through the integrated system, Digital Flight will exhibit total performance levels agreed upon by the community and appropriate to the risk tolerances of particular user categories and operational domains. While not comprehensive, the following are some examples of areas that may be the focus of standards development for Digital Flight.

Standards for digital information will relate to data sources, aggregation, processing, and delivery. They will address various quality attributes that may include such factors as accuracy, precision, timeliness, resolution in four dimensions (spatial plus time), and data accreditation. Standards for the connectivity infrastructure may address attributes such as bandwidth, availability, security, and redundancy. Standards for shared traffic information may consider requirements for minimum content, update rates, range, and fidelity of intent, as well as the surveillance technologies themselves (cooperative and non-cooperative). Standards for cooperative practices may address such factors as decision time horizons, adaptive pairwise separation criteria, and maneuver coordination requirements. Standards for separation automation may include elements such as aircraft performance modeling (including capability margins), access to real-time avionics data (e.g., auto-flight modes, energy remaining, power profiles, onboard sensor data), layered separation-assurance functionality, and user interfaces.

Standards also require the establishment of appropriate means of compliance. R&D will be informative here as well and will likely emphasize the opportunity that early applications give to collecting operational data on Digital Flight applications conducted under VFR and IFR in advisory and assistive roles. A flexible approach to establishing compliance will be critical, given the wide diversity of user categories and operational domains to be supported by Digital Flight.

6. **Conclusion**

Digital Flight is presented as a proposed third operating mode to complement VFR and IFR. Much of this description has been the *capabilities* of Digital Flight: the operator ensures flight path safety through cooperative practices and self-separation, enabled by connected digital information and technologies. Digital Flight capabilities can be initially employed in advisory or assistive fashion by VFR and IFR operators, and these early applications will enable capability maturation while providing initial benefits. However, to fully achieve the Digital Flight vision requires regulatory changes to codify it as a formal new operating mode, DFR, that authorizes *sustained* Digital Flight as the primary means of separation in VMC and IMC in lieu of visual "see and avoid" procedures and ATC separation services. Regardless of whether the resulting operating mode is designated DFR or some other name, the importance of its specification in the regulations as a unique operating mode from VFR and IFR is paramount to ensuring that it is properly defined without confounding the existing operating modes which ably serve the incumbent user community today.

Criteria that drive the decision for regulatory change include determinations of (1) whether it is in the public interest, (2) its effects on safety, and (3) the cost impact of the proposed regulatory change. As DFR is intended to increase airspace access and operational flexibility for all airspace user categories and to create opportunities for new entrants to provide new aviation services, the public interest would clearly be served. Similarly, the safety case for DFR would certainly be more robust than the current VFR "see-and-avoid" approach and would likely equal IFR safety, if not surpass it at high traffic density. The implementation cost of DFR is an open question, but creating this third operating mode will provide regulatory certainty to the user community, enabling them to evaluate the cost-benefit trade relative to the existing operating modes and their own operational objectives. For some user categories, DFR may indeed be the only feasible operating mode for their mission type. Given the DFR objective to integrate with VFR and IFR without adverse impact, non-DFR operators should have few if any mandated costs. The cost of supporting infrastructure and services provided by third-party service providers would be borne by the user categories which they serve, and therefore the operational cost to the government for DFR should not be significant.

The value to the aviation industry overall is the mechanism Digital Flight provides to safely advance the industry in concurrent fashion, enabling a significant expansion to the diversity of aviation operations while reducing friction for new entrants and their growth. Regulatory implementation of DFR that focuses on optimizing the benefit to the broad user population is a rare generational opportunity for the industry to embrace and empower aviation's growth in the 21st century.

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