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New Flight Rules to Enable the Era of Aerial Mobility in the National Airspace System

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Abstract

In the 21st Century, new aviation markets, vehicle types, and technologies are fast emerging, inspiring new operational concepts for the National Airspace System such as Unmanned Aircraft Systems Traffic Management and Urban Air Mobility. These novel operations envision a dramatic increase in *aerial mobility*, or the ability to navigate freely through the airspace with unprecedented access and operational flexibility. Implementing these concepts presents a major challenge to the existing operational modes of Visual Flight Rules (VFR) and Instrument Flight Rules (IFR), developed under the limitations of early 20th Century technology and procedures to ensure safe navigation and separation from traffic. To meet this challenge and to support the needs of operators in the 21st Century and beyond, this paper proposes that VFR and IFR be augmented by new flight rules – Digital Flight Rules (DFR) – that leverage modern and emerging technologies and are not bound by restrictions borne of the state of technology 75-100 years ago. The objective of DFR is to provide safe and unfettered access to the airspace to all participating vehicle operators under all visibility conditions without incurring the limitations in operational flexibility inherent to IFR and even VFR. Advancements in communications, navigation, surveillance, aircraft connectivity, information access, automation technology, and supporting ground infrastructure provide the opportunity for the vehicle operator to engage at an unprecedented level in managing their flights regardless of flight visibility. Under DFR, these advancements enable the vehicle operator to assume full responsibility for traffic separation and therefore full trajectory management authority in all visibility conditions and airspace regions. The changes in roles and responsibilities are expected to enable greater airspace access and operational flexibility than afforded by IFR and VFR, thus enabling the emergence of new operations and a new era of advanced aerial mobility.

1. Introduction

New aviation vehicles, markets, and technologies are fast emerging in the 21st Century, the second century of aviation, with emerging operations marked by burgeoning and anticipated advances in computation and digital information. These concepts are united by a common demand for increased aerial *mobility*, which we define as the ability to move freely throughout the airspace with unprecedented *access* and operational *flexibility*. Implementing these concepts presents a major challenge to the existing operational modes of Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) developed during aviation's first century.[1] The demand for Unmanned Aircraft Systems (UAS) is exploding, but the Air Traffic Control (ATC) system[2] that supports IFR operations is not structurally established to handle remotely piloted vehicles at scale, particularly small UAS (sUAS).[3] Similarly challenging to current flight rules is Advanced Aerial Mobility (AAM) and its especially ambitious application of Urban Air Mobility (UAM), which is envisioned to spawn large numbers of novel cargo- and passenger-carrying aircraft operating regionally and in the urban environment just a few thousand feet above ground level at high operational tempo. Other challenges to existing flight rules are invoked by the potential emergence of such highly diverse operations as domestic commercial supersonics, unpiloted and remotely piloted cargo vehicles, upper Class E Airspace (above Flight Level 600) operations, and more. The National Academy of Sciences has called for a national focus on aerial mobility, citing a coming "revolution in transportation with long-term, far-reaching implications, from how people get across town to how we connect broader regions and move goods or provide essential services."[4] Similarly, Boeing and Airbus anticipate the need to "support longer-term industry growth and innovation in respect to emerging aviation sectors" and call for a convergence of UAS Traffic Management (UTM) and Air Traffic Management (ATM).[5] Across the board, the drive for increased aerial mobility is accelerating. The convergence of all these forces requires a reassessment of whether VFR and IFR are adequate to meet the mobility needs of aviation in the 21st Century.

Establishing a relevant, long-term research portfolio for achieving mobility advancements across the broad spectrum of current and emerging aviation operations in the National Airspace System (NAS) requires us to look forward and envision future operations in the mid-21st century. To understand how to envision the NAS of the 2050s from the year 2020, let us flash back 100 years to 1920 and try to imagine "*envisioning the NAS of the 1950s*" from that early perspective. It would have been very hard to do! It would at least have been hard to get right. In 1920, who could have anticipated the new types of vehicles, markets, and technologies that would emerge? Who could have projected the ways that operations would evolve in the following 30+ years? With hindsight, we can say what happened during this period of aviation history: the birth of *flight rules*, especially IFR and the systems and infrastructure that enable those operations. IFR came about through a largely evolutionary process (though often punctuated by defining events such as key accidents and new technologies), while ATC evolved as an enabling service. Together, IFR with ATC services offered greater airspace access and safety to operators than visual flight alone could provide; they were a boon to aviation and enabled its tremendous growth. However, the evolutionary development of IFR also institutionalized operational restrictions (e.g., the prevalent use of airways) that resulted from the limitations of 20th century technology and infrastructure. These restrictions limit the potential mobility that 21st century technologies can deliver.

The primary purpose of flight rules is to ensure safe separation and navigation of the airborne vehicle. *Visual* Flight Rules allow the greatest flexibility in achieving safety by leveraging the direct coupling of the operating environment to the cognition of the human vehicle operator, through the pilot's *visual* perception of the environment. These rules permit the trained pilot to safely navigate the vehicle and maintain adequate separation from obstacles in the visual field. *Instrument* Flight Rules allow the greatest amount of access to the airspace by leveraging *instrumentation* on the flight deck and on the ground, working cooperatively to impose structure and translate *measurements* of the environment to the cognitive process of multiple human actors in both domains. These rules permit the pilot to safely navigate the vehicle using onboard sensors and technologies, and to work in cooperation with the air traffic controller who uses radar and other terrestrial instruments to provide separation services to the pilot. As will be discussed, VFR and IFR offer mobility trade-offs in airspace access and operational flexibility, with VFR operations having generally greater flexibility and IFR operations having greater access. Operators must choose which flight rules best suit the mobility needs of their operation.

The envisioned operational concepts of the 21st century demand a new type of mobility: *IFR-like access* to airspace with *VFR-like flexibility* to operate as desired. New technologies within and between the subsystems of the NAS have reached a level of maturation at which it is possible to relieve and, in some cases, replace the human cognitive processes involved in safe separation and navigation with *digital* processes. An increase in digital connectivity between systems, augmented by the application of complex algorithms within those systems, introduces a new *digital layer* between the environmental measurements and human actors. Incorporating this new digital layer into emerging operational concepts can maximize *both* operational flexibility and access to airspace, but these concepts require a distinct new set of flight rules to govern the use of these new technologies in flight operations.

The National Aeronautics and Space Administration (NASA), in partnership with the Federal Aviation Administration (FAA), is well positioned to lead the industry in defining and establishing a new, third set of flight rules for NAS users that will unify the approach to achieving the diverse mobility needs of current and emerging operations. Augmenting but not replacing VFR and IFR, the new flight rules – which we refer to as **Digital Flight Rules** (DFR) – will provide *all* operators, current and future, the opportunity to achieve unprecedented mobility. DFR will offer ubiquitous *access* to all airspace classes in both Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) and unmatched *flexibility* of operations to meet the wide diversity of operational needs at scale.

In this paper, we review the origins of IFR, the effect on current day mobility, and technology advances that pave the way to achieving newfound mobility through new flight rules. Multiple examples are given of current and future operations potentially benefiting from DFR. Key principles are then proposed to guide the aviation community in collaboratively defining the new flight rules to ensure the greatest possible benefit. The final section sets expectations for the implementation timeline and lays out initial leadership steps to facilitate the establishment of DFR. The work will build on the rich history of operational concepts and architectures explored by NASA, the FAA, and industry collaborators. E.g., [6]-[9] By focusing as a community on collectively establishing these new flight rules, we hold ourselves accountable to advancing mobility for all user classes so that, like VFR and IFR, Digital Flight Rules are available to everyone.

2. Evolution of IFR in the 20th Century

A century ago, the earliest aviators enjoyed complete operational freedom in an environment essentially devoid of rules.[8] However, they were limited by their physical capabilities to fly only in visual conditions, thus forgoing full access to the airspace in adverse weather or in clouds. Before gyroscopic instruments, it was not even possible to maintain control of the airplane without a visible horizon, let alone navigate to a distant point. Pilots followed railroads or the few roads that existed, or they "dead reckoned" by following a compass heading for a calculated time to reach an identifiable point along the way. "See and avoid" was the only method for staying safely away from other airplanes, and that method endures to this day as the last line of defense against mid-air collision in all flight operations.

Sperry's gyroscopic "artificial horizon" overcame the inability to fly without a visual reference, but flights in the clouds still could not use the visual landmarks to navigate. The visual checkpoints, bonfires, and lighted airways gave way to an invention – radio – as a means to navigate cross-country. Direction-finding antennas were used to "home in" on standard broadcast stations near the cities. A radio facility just for aviation was introduced in the 1920s called the "Four Course Range."[10] Its antenna arrangement on the ground created four lines of position emanating from the center on which a steady tone was heard in the airplane. Placing these ground stations so that the courses joined together created radio navigation "airways" that were used to fly from one city to another. Thus, *access* to airspace in and above the clouds was acquired at the cost of *flexibility* to navigate along any chosen path, relegating flight to just those few airways.

Flying in the clouds posed another challenge to early aviators: how to maintain safe separation from other aircraft in the clouds. Initially, ATC was used only to adjudicate the use of runways between arriving and departing traffic. In the mid-1930s, ATC was expanded in scope to assist in separating en route aircraft, literally "*airway* traffic control," and the resulting procedures for working with ATC would eventually become enduringly embedded in IFR operations.[11] Procedural separation based upon filed flight plans was used first. Airplanes at different altitudes or flying on different airways were "procedurally separated." Where airways crossed, if flights were at the same altitude, they had to cross the intersection at least ten minutes apart. Light guns and flags used in airport traffic patterns were supplemented with teletype communications between ATC centers and a company set up by the airlines called Aeronautical Radio Incorporated (ARINC), which had established a radio communications network for air/ground voice messages. Pilot estimates of intersection crossing times were passed through the ARINC operator by teletype to the ATC center. Any needed change to the time or altitude of crossing was returned via the same path. Direct radio communication between en route pilots and air traffic controllers came in the early 1950s and improved the timeliness and reliability of this essentially "one at a time" aircraft separation service. Poor navigational accuracy, surveillance by position report and estimate, and control loop times measured in minutes were sufficient for traffic levels of the 1930s. However, these limitations of early operations set a precedent for inefficient use of the airspace, and many of those inefficiencies remain with us in IFR operations today. Operational inefficiency and inflexibility were the price of all-weather access.

When radar was introduced to ATC in the 1950s, a new, smaller, distance-based separation standard was established between radar-identified aircraft. However, the coverage of radar was so limited and the reliability of radar and radio communications so poor that airways and procedural separation (later to be known as "non-radar" separation[2]) remained widespread. Procedural techniques are even still in use today, effectively separating aircraft from airspace, despite continual improvements in communications, navigation, and surveillance (CNS) technologies. Many improvements to radio and satellite navigation took place during the last half century, enabling position determination anywhere and the ability to fly with area navigation (RNAV) along any defined track over land or water, not just between ground stations, with a precision that has shrunk from several miles to a few feet. In theory, the CNS performance available today could safely support orders of magnitude greater traffic density, but there remains another constraint—the human cognitive processing at the center of ATC's separation service.

In solving the problem that operators cannot always see nearby traffic (and therefore, cannot fulfill the responsibility to see and avoid), the core premise of filing an IFR flight plan is the inherent delegation of control by the operator to a centralized authority, ATC, assigning the separation function to the air traffic controller who has access to concentrated information sufficient for making decisions to ensure safe separation. To accommodate the human cognitive process involved in ATC, much of the airspace is divided into sectors, within which a radar controller is responsible for providing separation services to all aircraft under his/her control.[2] Under IFR, controllers issue clearances based on flight plans and any subsequent changes as required by ATC or requested by the pilot. Using surveillance capabilities, they observe aircraft positions and project their paths forward to check for possible conflicts. Conflicts are resolved by issuing amended clearances, generally in the form of speed assignments, heading "vectors," or altitude changes. The amount of traffic that can be safely accommodated in a single sector is determined by a number of factors.[12] At the forefront of these considerations is acceptable cognitive workload for a radar controller assisted by supporting automation. Generally, less-complex routes, a homogenous traffic composition (i.e., similar aircraft types with similar speeds), and minimally changing altitude profiles make it easier for controllers to predict traffic conflicts and enable a greater number of aircraft to be accommodated in the sector at once. Climbing, descending, and maneuvering aircraft, and aircraft of different performance capabilities, complicate the conflict detection process and may reduce the number of aircraft that can be safely handled by this method. While automation tools have been gradually introduced to assist controllers in the cognitive task in an effort to accommodate more operations with increased complexity,[13] controller cognitive performance remains a driver in how IFR flights are managed, particularly as traffic demand increases. Thus, aircraft operating under IFR trade the *flexibility* to navigate as desired, despite the aircraft's advanced navigational capabilities, for *access* to airspace in and above the clouds. The inherent limitation on airspace capacity today is not the airspace volume, which is indeed vast, nor CNS performance, which has advanced significantly since the early days of aviation, but it is the cognitive method of ATC-based separation.

There are multiple potential solutions to overcome the human cognitive limits that restrict ATC-based separation services from scaling as traffic demand increases. Historically through the 20th century and into the early 21st century, advancements in technologies that support the human air traffic controller have been implemented to continue to increase the number and efficiency of IFR operations that can be safely performed. Although IFR operations will continue to benefit from advancements in ATC automation and procedures into the future, there is growing interest in evaluating fundamentally new structures for traffic management as new operations emerge, as evidenced by UTM[3] and proposals for managing UAM traffic.[14]

3. Technology Advances in the 21st Century

While the IFR system we have today has its roots in the pilot's original need to rely on ground systems and ATC services as the only viable solutions for navigation and separation in non-visual conditions, the practical age of all-weather navigation and airborne surveillance has since arrived. Technological advances have fundamentally changed the realm of possibilities for airspace operations. The NAS includes multiple secure, digital communication links which have produced a data-rich environment for ground and airborne systems. Along with the associated digital infrastructure, including cloud-based services such as the Enterprise Information Management Data Platform[15], System Wide Information Management[16], and airborne internet networked to onboard avionics systems using Aircraft Interface Devices[17], this newfound digital connectivity has given rise to a wave of innovative airborne and ground-based technologies that have created the "connected aircraft" and is enabling "net-enabled" operations.[18][19] The connected aircraft links onboard avionics, automation tools, and flight crews to the expanse of sharable information throughout the NAS. Managing this information network, third-party services can provide both broad-use and user-customized data on the operating environment such as winds, convective weather hazards, turbulence, restricted airspace status, forecast data, and even flight intent of other aircraft. Fusing and disseminating such broad information provides the airspace user with a comprehensive, up-to-date, and relevant operational context for their flight. This digital view of the NAS now available onboard the vehicle supports the consolidation of trajectory management responsibility into the user's hands to conduct safe and efficient flight operations in an all-weather, traffic environment.[20] With the advent of the connected aircraft, the "big picture" is no longer the sole purview of ground systems.

Navigation and surveillance have also reached the modern age. With satellite navigation and RNAV, aircraft can now navigate to any point on the planet, with additional increases in precision and flexibility coming with advances in ground and airborne navigation systems such as the Ground Based Augmentation System. Coordinated airborne and ground-based improvements such as Automatic Dependent Surveillance Contract and now terrestrial and space-based Automatic Dependent Surveillance Broadcast (ADS-B) have completed a global surveillance solution with available surveillance accuracies down to the meter. Furthermore, ADS-B allows aircraft to directly share their satellite-derived position and state data directly with *other* aircraft. Aircraft with an ADS-B receiver can know the positions of broadcasting aircraft at 100-plus-mile range, thereby far exceeding the visual surveillance used in VFR. With these improvements in CNS, augmented by advanced algorithms and increased data-sharing, the premise of IFR that separation services must primarily be provided externally to the aircraft is no longer a given.

The pilot – or rather the *aircraft operator* – of the future will have much more information under all weather conditions enabling users to conduct flights with "VFR-like" flexibility while in IMC. These improvements in CNS are part of important steps being taken for the future of IFR operations. Two example improvements to IFR operations are CDTI*-Assisted Visual Separation (CAVS) and Traffic Aware Strategic Aircrew Requests (TASAR). CAVS improves arrival performance by enabling an aircraft to temporarily maintain "virtual visual" contact with a lead

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[*] Cockpit Display of Traffic Information

aircraft using onboard surveillance when direct visual contact is lost.[21] TASAR improves en route flight performance, leveraging onboard automation and the connected aircraft to put flight-optimizing route-change solutions that account for local traffic, weather, airspace restrictions, and other constraints into the pilot's hands for request to ATC.[9]

While the strategy for moving IFR operations into the 21st century is beginning to provide benefits to the IFR community, the fundamental structure of IFR is likely incapable of scaling to the needs of aerial mobility in 21st Century aviation. For example, accommodating UAS in controlled airspace brings the challenge of working within the voice-centered ATC communications system and limits both operational acceptance and the ability to increase traffic volumes beyond what the controller is required to manage by voice.[22] Further issues are encountered when considering the challenges of low-altitude surveillance, operations in which remote operators control multiple UAS vehicles simultaneously, and the increasing demand for unstructured routing (e.g. for package delivery). A pathfinder for establishing a new operational structure is found in the UAS community, which is pursuing a paradigm in UTM that largely bypasses ATC altogether, but at the cost of accepting segregation from IFR operations by remaining below 400 ft.[3]

In summary, the 21st Century is changing the fundamental conditions of flight operations that evolved in the 20th Century. Advancements in CNS, aircraft connectivity, and automation technology provide the opportunity for the user to engage at an unprecedented level in managing their flights regardless of flight visibility. Fundamental to these advancements is their ability to enable the user to assume responsibility for separation and authority for trajectory management, thereby permitting increased airspace access and operational flexibility at scale. This change is expected to enable greater access and flexibility than afforded by IFR and VFR, thus enabling the emergence of new operations and a new era of advanced aerial mobility.

4. Operations Potentially Benefiting from New Flight Rules

Emerging operational concepts are well suited to leverage DFR in achieving their goals, given that many envision the operator having some degree of responsibility for separation. The examples given below are a snapshot in the year 2020. Many of these operational concepts will continue to evolve, as will the underlying technology forming the digital layer that enables them. Also shown are examples of where existing operators will also be able to benefit from DFR, though it is the emerging operations that would likely drive DFR development.

1. UAS Traffic Management

The FAA UTM concept allocates responsibility to the sUAS operator for separation from other sUAS and low-altitude manned aircraft. As stated in the FAA UTM Concept of Operations: [3]

> *"UTM Operators are ultimately responsible for maintaining separation from other aircraft, airspace, weather, terrain, and hazards, and avoiding unsafe conditions throughout an operation. Separation is achieved via shared intent, shared awareness, strategic de-confliction of airspace volumes, vehicle tracking and conformance monitoring, technologies supporting tactical de-confliction, and the establishment of procedural rules of the road (e.g., right-of-way rules)."*

Without changing the UTM concept, UTM could readily employ DFR as the formal mechanism under which this operator responsibility is authorized and met. In addition, rather than being inherently segregated from most existing airspace users by only enabling operations up to 400 ft above ground level, DFR would enable UTM operators to conduct flights in shared airspace as well.

2. Urban Air Mobility

The FAA UAM concept also allocates responsibility for separation to the UAM operator, although operations are restricted to "UAM Corridors." According to the FAA NextGen UAM Concept of Operations: [14]

> *"Separation of operations within UAM Corridors is assured through various strategic and tactical methods. The primary method is strategic deconfliction based on collaborative flight intent sharing. Tactical separation is allocated to the UAM operators, including pilot-in-command and aircraft capabilities and may include support from the Provider of Services to UAM (PSU). When operating within a UAM Corridor, the FAA regulations and Community Based Rules include the manner of strategic deconfliction and tactical separation. The strategic deconfliction rules are exercised by the PSUs. UAM operators remain responsible for the safe conduct of operations including operating relative to other aircraft, weather, terrain, and hazards and avoiding unsafe conditions. UAM separation is achieved via shared flight intent, shared awareness, strategic deconfliction of flight intent, and the establishment of procedural rules. In addition to strategic deconfliction within UAM Corridors that occurs during UAM flight planning, responsibilities also exist for in-flight coordination to ensure tactical separation is maintained. The Pilot in Command, supported by the UAM aircraft's capabilities (e.g., Detect and Avoid) and possibly PSU services (e.g., flight data from active operations in the UAM Corridor), maintains separation from other operations within the UAM Corridor."*

Similar to UTM, the UAM concept could readily employ DFR in this context. A UAM operator that contractually acquires their strategic deconfliction services from a PSU is still meeting their DFR responsibility for separation, in this case by assignment to a third party under their contractual control. The details of how tactical separation will be ensured are not specified in the initial NextGen concept, and DFR could help fill this void.

3. Upper Class E Traffic Management (ETM)

The FAA ETM concept is the way the FAA will support the expected expansion and introduction of novel operations of both manned and unmanned vehicles in upper Class E airspace above Flight Level 600. According to the FAA NextGen ETM Concept of Operations:[23]

> *"It is largely a community-based, cooperative traffic management system, where the Operators are responsible for the coordination, execution, and management of operations, with rules of the road established by FAA."*
>
> *"ETM consists of the following methods of separation management:*

- *Cooperative Separation – community-based separation, where the Operators are responsible for the coordination, execution, and management of operations, with rules of the road established by FAA.*
- *ATC Separation – provision of separation services by ATC."*

> *"Operators conducting cooperative operations are ultimately responsible for maintaining separation from other vehicles, and avoiding unsafe conditions (e.g., atmospheric conditions, solar flares) throughout an operation."*
>
> *"Cooperative services provide optimal operational flexibility and are, therefore, encouraged for operations that wish to fly with few restrictions (e.g., something other than a filed route)."*
>
> *"Under ETM, today's ATC services remain available to operations above FL600 upon request."*
>
> *"ATC-managed operations receive less operational flexibility than cooperative operations (e.g., fly filed route) as they are subject to the limitations imposed by airspace separation constraints and cooperative/ATC-managed traffic."*

ETM is therefore another good example of an emerging concept that, through the development of new operating rules, enables operator flexibility in return for assuming separation responsibility. DFR could form an integral part of those new operating rules, supporting high-altitude vehicles with vastly differing performance and operating characteristics (e.g., high-altitude long-endurance vehicles, unmanned free balloons, airships, and supersonic/hypersonic aircraft) operating in shared airspace with each other and ATC-managed traffic.

4. Large UAS / Increasingly Autonomous Cargo

Advancing UAS integration into the NAS requires the FAA to address key technological challenges to enable routine UAS operations, some of which are required to interact with ATC and others that are not.[22] To meet near term objectives, developers of autonomous cargo aircraft demonstrators are intending to operate under IFR. However, for a future end state beyond initial operations, there is interest in so-called "M:N" operations where multiple aircraft are managed simultaneously by a smaller set of remote supervisory operators. Automated detect-and-avoid and other onboard contingency management capabilities will be needed for M:N operations and to handle lost-link situations without the need for safety critical ATC communications. Such operations could employ DFR to reduce the demands on the remote operator, increase the number of manageable vehicles, and eliminate the dependency on ATC communications.

5. General Aviation (GA)

The General Aviation Manufacturers Association has published a white paper outlining a vision for Simplified Vehicle Operations (SVO) as the use of automation to reduce pilot training while increasing the level of safety. [24] Among the motivations for reducing pilot training is to grow the GA pilot population by reducing the cost of becoming a pilot and thereby growing the industry. Commercial aviation would benefit from this growth as well, as commercial operators typically recruit pilots with existing experience from the GA and military communities. Getting a private pilot's license, an instrument rating, and a commercial pilot's license, and then maintaining proficiency, require substantial training and expense, an impediment for many to becoming a pilot in the first place. DFR has the potential to accelerate the usage of advanced automation certified as fully “responsible” for certain functions, meaning it operates without reliance on human oversight or intervention, which are automation properties required both for DFR and SVO. In addition, new flight rules may be designed to simplify key aspects of flight operations normally associated with IFR, thus reducing training and proficiency costs. Conceivably, new highly automated GA aircraft could be certified for operation by pilots holding a “DFR rating” and not require a potentially more costly instrument rating.

6. Airline and Business Aviation

Even airlines and business aviation could benefit from DFR. Airlines are continually looking for ways to reduce operating expenses, such as those inherent to ATC-directed en route operations under IFR (e.g., airways, conservative “playbook” routing around weather, non-optimal speed assignments, step-down descents), which is the motivating interest in concepts such as TASAR. Business aviation is geared toward point-to-point operations and is often able to avoid flying into the major hub airports. DFR could provide greater access and flexibility to these traditional operators in addition to enabling new operations, consistent with the Airbus-Boeing call for UTM-ATM convergence.[5]

5. Guiding Principles for Defining New Flight Rules

Attempting to accommodate the emerging operational concepts of the 21st Century under the existing VFR and IFR structures highlights a shortfall in the complex rules and procedures of the existing system. Ad-hoc regulation and waivers will enable some new operations at first, but the current regulatory structure may eventually become overwhelmed if this process continues indefinitely. To meet this challenge, while IFR continues to modernize at its own pace[25] without the burden of needing to meet the accelerating demands and diversity of emerging operational concepts, we propose that new flight rules be defined that are based on technologies of today, are not bound by restrictions borne of the state of technology 75-100 years ago, and can leverage rapidly emerging new technologies.

To meet the needs of operators in the 21st Century and beyond, the objective of new flight rules should be to provide to all participating vehicle operators safe and unfettered access to the airspace in VMC and IMC, without incurring the access and flexibility limitations inherent to VFR and IFR, respectively This will be accomplished in large part by putting more separation responsibility and trajectory management authority into the users’ hands, which as shown earlier is a common thread to many of the emerging 21st century operational concepts. DFR would not replace IFR or VFR in any way; rather, they expand the rule-set options available to any airspace user.

In this paper, Digital Flight Rules are so named to emphasize their intended ubiquitous availability to the broad user community that adopts the digital layer. IFR is not "Airline Flight Rules" so we should not be defining “UAS Flight Rules”, “UAM Flight Rules”, “Air Taxi Flight Rules”, or “ETM Flight Rules”. Customizing separate flight rules for each type of operation is not only inherently too complex, it misses the point, which is to help *all users* of the National Airspace to achieve their mobility goals through a defined set of common rules and requirements. Whatever the new flight rules are eventually called in the regulations, our collective focus should be on defining these new flight rules (and everything that enables them) to increase aerial mobility, that is, airspace *access* and operational *flexibility*, for all users who choose to adopt them. The ideas espoused here are not new. Similar visions date back many decades, predating the technology needed to put them into practical use.[26]-[31] However, their time has now arrived due to technological advancements and the emergence of new markets, vehicle types, and use cases.

Careful consideration must be given in the development of DFR so that overarching goals are achieved. Adhering to guiding principles will help ensure DFR achieves the mobility goals for all operators. The following is offered as a starting point as we begin to define DFR as a community.

1. *New flight rules should preserve what already works*
   As discussed in the first part of this document, the development of a new set of flight rules should not fundamentally change those that currently exist and continue to serve the many segments of the user community well. While it is true that ground-based separation services were created to compensate for a lack of airborne information and operational capabilities that may soon no longer be lacking, IFR and ATC have evolved over decades into a highly interconnected, sophisticated, productive, and safe system that fuels much of the current aviation economy and adequately meets the needs of many aircraft operators. Similarly, VFR provides a high degree of flexibility to many operators who have no need for access in IMC. To disrupt these systems would adversely affect many operators who succcessfully use them every day. IFR and ATC also are highly complex and intricate, with webs of interdependence across rules, procedures, technologies, information flows, responsibilities, pilot/controller training, and regulations, not to mention the accommodations made in industry to work within this system. Introducing a fundamental change to IFR or ATC could easily upset this balance and have significant undesired repercussions throughout the system. The simpler approach is to leave what works alone and introduce the new capabilities in a parallel and non-interfering manner that does not impact existing VFR and IFR operations or burden ATC with having to adapt quickly to serve the emergent operations.

2. *New flight rules should be uniquely defined to be distinct from VFR and IFR*
   Starting from a relatively clean sheet, we will be able to construct just the right regulatory policies, performance standards, certification requirements, training programs, etc. that suit the needs of operations under DFR. The alternative of trying to modify and build upon the existing regulations defining VFR and IFR, rewriting them broadly enough to preserve current operations (the previous principle) while also encompassing emerging modes of operating (if even possible) would almost certainly compromise both the current system and the future promise of DFR. The current regulatory framework can accommodate exceptions to a point, but will eventually be overwhelmed. A new set of flight rules for NAS users that complements the existing (and evolving) rules and standards will allow enhanced mobility to be achieved incrementally through a *unified* implementation that supports emerging operational concepts.

3. *New flight rules should formally establish user responsibility for separation in IMC*
   Operating a flight under DFR will set proper expectations for pilots and controllers, but mostly pilots (and remote vehicle operators). The act of choosing the set of flight rules under which one will operate a flight is a formal declaration and acceptance of responsibility, particularly in the areas of flight visibility and traffic separation. Inherent in the conduct of VFR flight is to remain in VMC and adhere to the see-and-avoid requirement. By filing an IFR flight plan and receiving an ATC clearance, the pilot delegates responsibility for separation, navigation, and terrain clearance to ATC in return for authorization to operate in IMC. Under DFR, the

same unambiguous assignment of roles and responsibilities should exist. Filing a DFR flight plan will make clear the aircraft operator's intent and commitment to their responsibility for separation assurance, achieved through the digital layer and exercised throughout the flight regardless of flight visibility.

4. *New flight rules should create the opportunity for unprecedented mobility*
   Creating mobility means enabling maximally unfettered *access* to airspace in all-visibility conditions to the extent consistent with safety and community constraints. It also means granting operational authority for VFR-like *flexibility* to the aircraft operator. VFR provides significant user flexibility, but only in VMC; with the exception of provisions under Special VFR, it does not provide access to the airspace in IMC.[1] IFR provides airspace access in IMC, but at the cost of VFR-like flexibility due to the assignment of separation responsibility by the aircraft operator to ATC. To merit acceptance by the community, DFR must supersede these limitations and provide users with unmatched airspace access and operational flexibility.

5. *New flight rules should be equally available to all users that meet minimum requirements*
   Just as any aircraft can be flown under VFR or IFR, provided the appropriate requirements are met (e.g., equipage, training, proficiency, performance), the same should be true for DFR. Today, operators are able to choose whether VFR or IFR is appropriate for their operation, and in the future that choice will be expanded to include DFR. Given the diversity of potential users, it must be ensured that the new flight rules avoid any systemic bias that unintentionally delivers benefits to one class of airspace user over another. Flight rules are about where and how you operate, what you are responsible for, what equipment you must have, what performance levels you must meet, what services and support infrastructure you require, etc., to achieve operational safety and efficiency. Any user able to meet the requirements should have an equitable share of the benefits that come along with it. To that end, a diverse user community must participate directly in the development of DFR to ensure they are reflective of the diversity of operations the new flight rules are intended to serve.

6. *New flight rules should produce scalability while being robust and resilient to disruption*
   Scalability refers to the ability to organically grow and shrink with the level of demand. In practical terms, this means the ability to accommodate substantially increased numbers of aircraft without requiring fundamental changes in infrastructure or procedures. While IFR services provided under the ATC system have expanded over time to accommodate growing demand, its centralized architecture and reliance on human cognition are not generally flexible enough to support an order or two (or much more) of magnitude in growth. To achieve scalability, DFR should invoke greater distribution (i.e., of infrastructure, functionality, information, responsibility, and authority) and greater use of automation (i.e., fewer human bottlenecks, faster acting, more easily modernized). Adopting these characteristics will also enhance robustness and resilience to disruption due to fewer common failure points, increased redundancy, and judicious allocation of technical complexity among agents.

7. *New flight rules should enable operations in shared airspace*
   The DFR goal of maximizing mobility for the user community fundamentally requires the airspace to be equitably shared. Segregation runs directly counter to this goal. Fortunately, the coexistence of VFR and IFR in shared airspace demonstrates the feasibility of very high

levels of integration. They share airspace in essentially all but IMC and Class A airspace, where see-and-avoid is impractical (i.e., for safety). The design of DFR should include similar compatibility to ensure maximum access to airspace for all operators. This does not rule out localized segregation of homogeneous DFR operations (e.g., under conditions where VFR and IFR cannot safely operate) or segregation of DFR operations in the early stages of implementation, but it should not be the default condition nor the end state. In addition to increasing airspace access and flexibility, integrated operations also support interoperability, enabling operators to choose which flight rules are appropriate for each operation and to switch between them as needed, as currently happens with IFR and VFR. Research has shown that one way shared-airspace operations could be achieved, but not necessarily the only way, is for DFR aircraft to give right-of-way to IFR aircraft in essentially all encounters and to VFR aircraft until visually acquired, at which point VFR right-of-way rules are applied.[31][32]

8. *New flight rules should be capable of being introduced gradually*
   In the early days, mobility will be enabled for a limited number of operations by waivers and exceptions under IFR or VFR, while more significant regulatory actions are identified, planned, and prepared, staying in step with evolving and emerging concepts and technologies. Gradual introduction of certain DFR-like operations is therefore possible before DFR is officially in place. An evolutionary approach will accommodate growth and adaptation as the community learns and matures. With VFR and IFR operations proceeding uninterrupted and mostly unchanged, the capabilities that will enable DFR can be introduced gradually and safely, with careful monitoring. DFR's design should avoid a "critical mass" requirement for initial operations, allowing such operations to gradually phase in and to accommodate adjustments and improvements as needed as operational tempo increases and operations evolve without disruption to IFR and VFR operations. Once formally underway, DFR operators will gain immediate benefits without disrupting IFR and VFR operators.

6. Implementation

It is important to be clear-eyed about the time required to implement DFR. VFR and IFR took decades to emerge through an evolutionary process, albeit punctuated by key events and disruptive forces (e.g., removal of selective availability from the Global Positioning System). It is reasonable to expect a similar timeline for DFR, though compression may indeed be possible with an organized effort by the community under government leadership, or accelerated by large disruptive events (e.g., AAM market forces). A notional timeline might look something like this:

- 2025 to achieve community consensus on the vision for DFR
- 2030 to complete specification of system and performance requirements
- 2035 to complete and publish applicable regulations and standards
- 2040 to build to the standards
- 2045 to certify and approve the first operation
- 2050 to reach the first level of steady state maturity

This 30-year timeline is notional and unnecessarily linear for simplicity, but if it seems excessively long, consider that it has already been 15 years since the FAA embarked on the Next Generation Air Transportation System (NextGen), the modernization of America's air transportation system to make flying even safer, more efficient, and more predictable.[25] While significant infrastructural modernization has taken place, the NextGen Implementation Plan still extends for another 10 years.[33] Implementing significant changes in aviation takes time because the emphasis must be on maintaining safety. While DFR imposes new requirements on both the service providers and operators, an engaged user community directly benefiting from the addition of new flight rules will have an opportunity to influence directly the pace of progress. Research and operationalization timelines could be significantly accelerated through parallel activities and significant engagement by all parties. Under government leadership supported by public-private partnerships, several early steps can be taken to accelerate progress even further.

1. *Generate a starting proposal for DFR*
   A starting set of Digital Flight Rules is needed in order to communicate the vision effectively and to give the community something tangible to debate. NASA can help ensure compatibility with the various existing and emerging operational concepts, building on its extensive historical involvement in these projects, and the FAA can help ensure that the operational need is being met and that there is a practical path to implementation.

2. *Demonstrate key elements of DFR to the community*
   Demonstrating DFR in a variety of relevant use cases would significantly enhance the community's understanding of the proposed vision and accelerate their concurrence on its feasibility. The demonstrations should therefore be an early priority and a launching point for deeper and more detailed work. NASA's Aeronautics Research Centers and FAA research facilities are uniquely positioned to demonstrate how the vehicle technologies and procedures, supporting services, and CNS infrastructure work together to enable DFR. Each NASA Center is well suited to make valuable contributions: Langley for vehicle capabilities; Ames for services; Glenn for CNS infrastructure; and Armstrong for integrated flight-testing. The FAA fills critical gaps and complements the effort: the William J. Hughes Technical Center for NAS data and integration with existing flight rules operations, the Mike Monroney Aeronautical Center for pilot and controller demonstration and training, and the Florida NextGen Test Bed for advanced prototype interoperability demonstrations.

3. *Lead a hierarchy of community working groups to refine and finalize DFR*
   Under NASA and FAA leadership, working groups will work towards achieving consensus on the overall flight rules vision, while also working through detailed requirements to ensure the primary mobility objectives are equitably met for the diversity of users including existing operations and emerging concepts. The working groups will likely be organized into specialties (aircraft equipage and certification, operator training and procedures, advanced automation, supporting services, CNS infrastructure, compatibility and interoperability, regulatory considerations, etc.). The goal is to achieve a reasonably complete and stable definition of DFR to support system and performance requirements in which NASA and the FAA will play significant roles in collaboration with industry and academia.

4. *Identify viable paths to the future state that provide early benefits under current flight rules*
   Operations under DFR will require advances in automation technology, human-automation teaming, supporting services, and infrastructure. A variety of viable implementation paths can be defined and pursued in parallel in which select future elements can be preliminarily

exercised under current flight rules, potentially starting as non-safety-critical applications or conducted under waivers. This approach provides the opportunity for government, academia, and industry to develop, deploy, and mature these functions incrementally and to determine requirements and methods for safety-critical certification under DFR. Meanwhile, they would produce operational benefits to the user community in the near term. NASA will play a critical role in strategically analyzing these various paths, testing them in simulation, working with the community on their implementation, and working with the FAA on certification methods.

7. Summary

With the hindsight and experience of the first 100 years in aviation, we are better positioned now than our colleagues were in 1920 to assess the needs and possibilities of future aviation, and indeed, we have many new operational concepts under development as positive proof. However, we should approach forecasting the future aviation system with humility, as we cannot truly know the emergent forces that will drive aviation markets. For instance, we do not yet know the long-term impact of the current pandemic on aviation, but we can surmise that substantial lasting effects may significantly change the assumptions of our previous forecasting. In some cases, the effect may even be to accelerate the demand for advanced mobility solutions. Among many of the emerging concepts, a common theme is the need for greater airspace access and operational flexibility than afforded by the existing VFR and IFR constructs, which trade access against flexibility in different ways. VFR is highly flexible but restricts access to conditions where see-and-avoid is possible. A review of the origins of IFR has shown how the state of nascent radio navigation technologies, permitting early access to IMC, led to the assignment of separation responsibility to ATC and in turn put limits on flexibility that endure today. Mobility goals of the 21st Century call for new flight rules that formalize the operator's responsibility for all-visibility separation assurance, in turn granting VFR-like operational flexibility with IFR-like IMC access, without disrupting the well-established VFR and IFR systems.

In developing DFR, an opportunity space will emerge for advanced mobility to expand across the aviation sector for current and future operations alike. Rather than focus on a particular target year, operator class, use case, or operational procedure, we should develop a unifying approach to mobility for all operators and operations that leverages advances in digital technologies and CNS. While the aviation community did not know in 1920 that they were slowly building the IFR system that has benefited operators of all sorts, we can now say that in 2020 we are purposefully dedicating ourselves to building the next flight rules system for this century. Primary elements include advanced automation-enabled vehicle/operator capabilities (up to and including eliminating the onboard crew), supporting services purposefully designed not to be the constraining factor on access and flexibility, and enabling CNS infrastructure, all with an eye towards ensuring compatibility with VFR and IFR in shared airspace. Many new technologies will be needed, not to mention new methods for certifying these technologies into a fully responsible role without reliance on human oversight or intervention. For that, we need to establish viable implementation paths, starting even now, that provide early benefits as technologies are introduced, matured, and certified for their eventual safety-critical role under DFR. Foremost, we need to collaboratively create a single, harmonizing set of new flight rules, setting aviation on a path toward achieving advanced mobility for all operators in the 21st Century and beyond. There is much work to do, and mobility awaits.

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9. Abbreviations

ADS-B	Automatic Dependent Surveillance Broadcast
ARINC	Aeronautical Radio Incorporated
ATC	Air Traffic Control
ATM	Air Traffic Management
CAVS	CDTI Assisted Visual Separation
CDTI	Cockpit Display of Traffic Information
CNS	Communications, Navigation, and Surveillance
DFR	Digital Flight Rules
ETM	Upper Class E Traffic Management
FAA	Federal Aviation Administration
GA	General Aviation
IFR	Instrument Flight Rules

IMC	Instrument Meteorological Conditions
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
PSU	Provider of Services to UAM
RNAV	Area Navigation
sUAS	Small UAS
SVO	Simplified Vehicle Operations
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UTM	UAS Traffic Management
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

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14. ABSTRACT

In the 21st Century, new aviation markets, vehicle types, and technologies are fast emerging, inspiring new Concepts of Operation for the National Airspace System such as Unmanned Aircraft Systems Traffic Management and Urban Air Mobility. These novel operations envision a dramatic increase in aviation mobility, or the ability to move freely throughout the airspace with unprecedented access and operational flexibility. Implementing these concepts presents a major challenge to the existing operational modes of Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) developed under the limitations of early 20th Century technology and procedures to ensure safe navigation and separation from traffic. To meet this challenge and the needs of operators in the 21st Century and beyond, this paper proposes new flight rules – Mobility Flight Rules (MFR) – that leverage modern and emerging technologies. These advancements enable the vehicle operator to assume full responsibility for traffic separation and therefore full trajectory management authority in all visibility conditions and airspace regions. This change is expected to enable greater airspace access and operational flexibility than afforded by IFR and VFR, thus enabling the many emerging Concepts of Operations and a new era of advanced mobility.

15. SUBJECT TERMS

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