PERFORMANCE BASIS FOR AIRBORNE SEPARATION

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Abstract

Emerging applications of Airborne Separation Assistance System (ASAS) technologies make possible new and powerful methods in Air Traffic Management (ATM) that may significantly improve the system-level performance of operations in the future ATM system. These applications typically involve the aircraft managing certain components of its Four Dimensional (4D) trajectory within the degrees of freedom defined by a set of operational constraints negotiated with the Air Navigation Service Provider. It is hypothesized that reliable individual performance by many aircraft will translate into higher total system-level performance. To actually realize this improvement, the new capabilities must be attracted to high demand and complexity regions where high ATM performance is critical. Operational approval for use in such environments will require participating aircraft to be certified to rigorous and appropriate performance standards. Currently, no formal basis exists for defining these standards.

This paper provides a context for defining the performance basis for 4D-ASAS operations. The trajectory constraints to be met by the aircraft are defined, categorized, and assessed for performance requirements. A proposed extension of the existing Required Navigation Performance (RNP) construct into a dynamic standard (Dynamic RNP) is outlined. Sample data is presented from an ongoing high-fidelity batch simulation series that is characterizing the performance of an advanced 4D-ASAS application. Data of this type will contribute to the evaluation and validation of the proposed performance basis.

1 General Introduction

As the Air Traffic Management (ATM) community defines new operational paradigms capable of accommodating significant increases in traffic demand and diversity[1], a key concept is being adopted: *Performance-Based Operations and Services* (PBO) [ref. 1]. In summary, the philosophy of PBO states that aircraft capability requirements are specified in terms of achievable performance rather than installed equipage. Operational approval is based on certifying aircraft ability to meet performance targets within tolerances specified for a particular operation. The PBO philosophy also states that ground-based ATM services are matched to the performance capability of the aircraft, implying that more capable aircraft will receive in-kind support from the Air Navigation Service Provider (ANSP).

PBO is expected to benefit both the operators and the ANSP. Operator benefits, such as scheduling priority and airspace access to congested areas, are awarded to aircraft as an incentive for being certified to a higher performance standard. ANSP benefits derive from the higher individual performance of many aircraft collectively producing higher system-level performance and predictability.

This paper addresses the appropriate role for Airborne Separation Assistance System (ASAS) technology and applications within this PBO philosophy. Defining a formal performance basis for ASAS is of paramount importance to quantifying safety, maximizing

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[1] More point-to-point operations and an increasing variety of aircraft types and capabilities

operational applicability, and generating widespread community acceptance of these new operations. Currently no formal, rigorous methodology exists for identifying the limiting conditions under which these operations can be applied safely (e.g., levels of traffic density and complexity). As a result, it is often assumed, for example, that self-separation can only be applied safely in low density or complexity conditions. Unfortunately, this assumption contradicts the intended purpose and unique value of ASAS, which is to apply a currently underused resource in ATM – the aircraft system itself – to help solve some of ATM's greatest challenges for the benefit of both the system and the operator.

For ASAS to be accepted as an integral component of a future ATM system founded on PBO, two fundamental requirements must be met. First, ASAS must provide capabilities that are relevant to the functions of ATM. That is, ASAS must help achieve traffic management goals that would need to be met one way or another, if not by ASAS, then by a ground system. ASAS clearly provide capabilities that are relevant to the functions of managing traffic, as can be seen from the many practical applications studied in recent research. For instance, defining maneuvers to reposition an aircraft relative to a reference aircraft can be accomplished using an ASAS merge [ref. 2]. Monitoring and maintaining this relative position, and therefore increasing throughput, is achievable with airborne precision spacing [ref. 3]. Optimizing trajectories based on user preferences while ensuring traffic separation can be accomplished with airborne self-separation technology [ref. 4]. Many such ASAS applications have been developed to play an active role in achieving these and other important ATM objectives. Most ASAS capabilities are also consistent with four dimensional (4D) trajectory-based operations (TBO), giving rise to the term '4D-ASAS' used later in this paper [ref. 5].

Secondly, ASAS must produce these accomplishments reliably and within measurable performance tolerances, taking into account relevant error sources. Although research efforts have collected some limited performance data on ASAS applications, research has generally focused more on design and on assessments of feasibility and benefits.

A construct for formally defining ASAS applications in performance terms is not well defined or understood. The lack of this performance basis may lead to a perception that ASAS applications lack predictability or reliability. Such a perception could explain why ASAS applications have not generally been given purposeful and central roles in future system concepts and have instead been relegated to highly restrictive environments where demand or complexity is low [ref. 1].

If indeed ASAS capabilities can provide significant benefits in capacity and efficiency, as research has shown, then these capabilities need to be attracted to where the need is greatest, not restricted to where the need is the least. To be considered an asset to the most challenging environments, ASAS applications must be defined in performance terms to provide the highly predictable and reliable results required in the future ATM system. This paper presents an initial construct for establishing the performance basis of ASAS.

In Section 2, the performance range of aircraft capabilities anticipated for the future ATM system is discussed, highlighting the unique characteristics of ASAS capabilities. Section 3 discusses the variety of operational constraints on trajectories and their implications for developing a performance basis for certification. A proposal is made for a dynamic performance standard derived from the current construct of Required Navigation Performance (RNP). In Section 4, sample experimental data from an ongoing performance assessment of an advanced ASAS application will be presented. Conclusions are presented in Section 5.

2 Performance Range

The performance range of the future ATM system can be characterized in two dimensions referred to in this paper as performance tiers and performance levels. Performance tiers represent significant differences in operational capability. Performance levels generally represent a range

of achievable precision within a given performance tier.

2.1 Performance Tiers

Performance tiers govern the degree of ATM services that must be provided to the aircraft by the ANSP. Each tier, from lowest to highest performing, must satisfy the basic requirement of allowing aircraft trajectories to be generated and revised in flight to meet a diverse and dynamic set of operational constraints.

The NextGen Concept of Operations defines the functions of Trajectory Management (TM) and Separation Management (SM) to meet this fundamental need [ref. 1]. Together, these functions adjust trajectories to meet flow management constraints, manage complexity, improve efficiency, and ensure separation from traffic, weather, airspace, terrain, and other hazards. These objectives and obstacles are all forms of operational constraints on an aircraft's trajectory, and the TM and SM functions ensure that the trajectory properly accommodates them. However, these functions need not always be performed by the ANSP. Provided that the degrees of freedom can be clearly specified, the aircraft can employ ASAS technologies and applications to contribute to these functions.

At least three major performance tiers are defined here based on the capabilities brought by the aircraft. The tiers are shown in Table 1, along with some important properties.

3D-Classic Tier

The first and lowest performing tier is for 'unequipped' aircraft, those that have no data link ability for receiving trajectories and have no on-board trajectory generation ability to perform the TM or SM functions. These classic operations depend entirely on the ANSP to provide all the TM and SM services and to issue trajectory instructions similar to today, i.e., by piecewise instructions modifying a pre-established 3D flight plan using voice communications. The subject of negotiation and performance agreement between the aircraft and the ANSP are the flight instructions, and the performance achievement method is simply to follow the instructions without undue delay. This dictates a significant level of ground-based service, one which is already accepted to have reached its capacity potential and a limited degree of operational performance in complex airspace.

4D-Managed Tier

The second tier is for aircraft capable of uplink and automatic loading of a trajectory into the flight management system. This tier enables a significant increase in system performance over 3D-Classic tier operations because complex 4D trajectories devised by automated or semi-automated ground systems (performing the TM and SM functions) can be data linked directly to the aircraft, frequently updated, and potentially negotiated through trajectory downlink. The subject of agreement and negotiation between the aircraft and the ANSP is the complete 4D route definition, and the required performance is achieved by the aircraft applying conventional RNP procedures to the resulting 4D trajectory. Aircraft at this performance tier are considered higher performers because the data link significantly reduces the dependency on voice communications and vastly increases the diversity and complexity of trajectories that can be assigned.

Table 1. Performance tiers.

Performance tier	Communication method	Airborne capability in TM/SM	Subject of air/ground agreement and negotiation	Performance achievement method
3D-Classic	Voice	None	Flight instructions	Follow the instructions
4D-Managed	Trajectory data link	None required	4D route definition	RNP on the 4D trajectory
4D-ASAS	Data link	Partial or full	Operational constraints	Dynamic RNP on the operational constraints

4D-ASAS Tier

ASAS capabilities applied to 4D trajectory management enables a third performance tier to be defined. The basic function of most "4D-ASAS" applications is to enable an aircraft to define and execute changes to path and/or speed to achieve operational goals and restrictions that have been defined for that aircraft *relative to other traffic*. Effectively, the aircraft itself is performing SM and TM functions, the degree of which is dependent on the particular 4D-ASAS application. This relieves some of the burden on the ANSP to completely supply these functions. However, the ANSP still needs to supply the aircraft-specific operational goals and restrictions. As will be discussed in the next section, these goals and restrictions are specified and treated as operational constraints that define the set of acceptable trajectories.

The primary difference relative to the 4D-Managed tier is that, instead of uplinking full 4D route definitions, the ANSP communicates *just the constraints*. The aircraft then matches its trajectory to the constraints within the available degrees of freedom provided by the particular 4D-ASAS application. For instance, a spacing application might constrain an aircraft to a defined 3D path and specify a target interval to be achieved behind a lead aircraft. The pilot uses conventional RNP along the 3D path, as in the 4D-Managed tier, and uses the airspeed degree of freedom along the constrained path to achieve the specified interval. In this case, the along-path portion of the TM and SM functions is being performed by the aircraft, and the remainder is provided by the ANSP.

At this tier, the object of agreement and negotiation, i.e., the air/ground "contract", are the operational constraints themselves, not the 4D trajectory selected by the aircraft to meet them. If the aircraft determines that it cannot meet all constraints, then negotiation with the ANSP focuses on modifying the constraints, relaxing them, or exchanging them with another aircraft. Performance achievement for this tier is accomplished by applying an extension to RNP referred to as 'Dynamic RNP', proposed later in this paper.

Applications within the 4D-ASAS Tier

An operation that applies an ASAS capability to achieve an operational objective is typically referred to as an ASAS application. The FAA / Eurocontrol Action Plan 1 defined four categories of applications: air traffic situation awareness, airborne spacing, airborne separation, and airborne self-separation [ref 6]. For the latter two categories which involve separation responsibility transfer to the aircraft, Action Plan 23 is currently defining application elements, the building blocks of ASAS applications, and identifying the high-level avionics functions required to support these elements. These elements and functions will be combined to create a range of different capabilities related to TM and SM.

The 4D-ASAS tier represents not a single capability but rather a range of capabilities, from managing only a single degree of freedom as in the spacing example, up to managing multiple degrees of freedom as in conflict management. Not all of these capabilities need to be simultaneously resident on every aircraft in the tier. For example, an operator may elect to equip for a spacing application but not for a conflict management application because their business model does not support the latter need. Similarly, another operator might prefer to equip for the latter capability but not the former. The ASAS applications chosen by the operator define the capability of a given aircraft. They are joined by the common thread of the aircraft having the performance capability to manage the agreed-upon trajectory within a prescribed set of operational constraints that define the set of acceptable trajectories.

2.2 Performance Levels

Performance levels generally represent a range of tolerance achievability, either discrete or continuous, within a given performance tier. Examples of performance levels in use or emerging today are the ability to navigate defined paths with predetermined precision and the ability to control to a specified arrival time at a specified location, both forms of RNP [ref. 7]. RNP certification enables a specified accuracy of knowledge, prediction, and control

of aircraft position. For example, RNP in the lateral dimension defines the precision in nautical miles to which an aircraft must reliably fly a fixed, Earth-referenced navigation path, e.g. RNP-0.3 (higher navigation performance) and RNP-1 (lower navigation performance, by comparison). Currently the path navigation capability is used for approaches to terrain-challenged airports in low visibility conditions. For the future ATM system, consideration is being given to also using it as a basis for organizing compressed traffic streams and reducing separation standards. Aircraft capable of RNP-0.3 could be compressed into tighter streams than those capable only of RNP-1. Similarly, arrival time control is being considered as a basis for precise metering of traffic flows. Both uses would benefit the ATM system by increasing capacity, the first laterally and the second longitudinally.

In the 4D-ASAS performance tier, where operations are defined in terms of the aircraft defining its trajectory within a set of operational constraints, performance levels can be used to describe the degree of precision to which those constraints are met. For this purpose, an extension of the RNP concept is proposed and discussed in the next section.

3 Defining a Performance Basis for 4D-ASAS Tier Applications

To qualify as PBO, 4D-ASAS tier applications must be developed such that they produce measurable and reliable performance. This section introduces a proposed approach, the details of which are to be further defined and developed over the next year, to formalize the basis of performance for such applications. The approach uses RNP, a well developed current implementation of PBO, as a model that will be expanded to encompass 4D-ASAS applications.

In current-day RNP, the navigation path itself is the operational constraint. RNP standards provide the certification basis for ensuring compliance to the prescribed tolerance on the navigation path, considering the variety of error sources that can cause deviation. 4D-ASAS tier applications have a larger set of constraints to contend with, but it is

hypothesized that the construct of current-day RNP can be expanded and generalized for the larger variety of trajectory constraints and error sources applicable to the 4D-ASAS tier applications. Since the primary performance objective is to develop trajectories that conform to operational constraints, a review of the different constraint types is presented.

3.1 Defining Operational Constraints

In the absence of traffic, hazards, or any other airspace restrictions, the user-optimal aircraft trajectory would typically be the route and flight level that provide the fewest air-miles between the origin and destination. It would also likely incorporate a cruise-climb and continuous descent, and the arrival time (and therefore the departure time) would be the choice of the operator. However, the presence of traffic, hazards, and airspace restrictions impose operational constraints that require deviation from the user-optimal trajectory. Managing trajectories to meet these constraints give purpose to the TM and SM functions of ATM.

For operations involving the 4D-ASAS performance tier, the aircraft and ANSP communicate and negotiate in the language of the operational constraints. The ANSP specifies as many constraints as needed to accomplish the objectives of ATM for that aircraft. The aircraft then matches its trajectory to comply with these constraints, making adjustments to maintain conformance with the constraints if they change.

Constraint Types
In its most general form, the 4D-ASAS tier must contend with all types of trajectory constraints, not just those related to traffic. Trajectory constraints come in a variety of types, and each type can be applied multiple times to a single aircraft trajectory. The constraint types shown in Figure 1 should provide the controls necessary to accomplish all ATM objectives for an aircraft. Each type is briefly described.

Position constraints require the aircraft to cross over a specific geographic fix. These might be used to create a predictable airspace entry/exit point for 4D-ASAS aircraft or to establish a handoff location for control authority transfer.
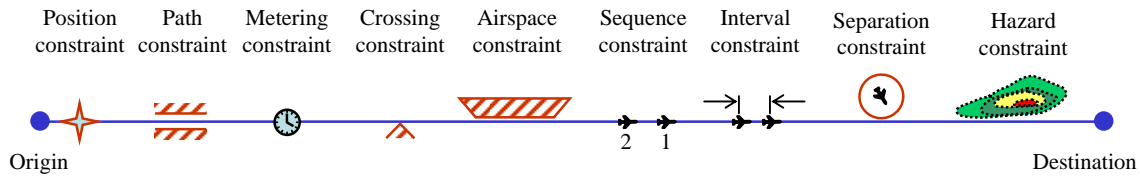
Fig 1. Operational constraints of various types bound the set of acceptable trajectories.
The trajectory is otherwise unconstrained and available for user optimization.

Path constraints specify the precision to which an aircraft must navigate a defined path. These are typically used for approaches to terrain challenged airports, but may also be used to allow adjacent traffic streams to be compressed for increased capacity. Path constraints can be two-dimensional, specifying the lateral path only, or three-dimensional, including a lateral path with a vertical component.

Metering constraints specify a required time of arrival over a fix or airspace boundary. These constraints are typically used to regulate the flow rate of traffic into or through a limited-capacity resource. As a byproduct, they also provide strategic deconfliction for some of the traffic by scheduling adequate intervals between arriving aircraft.

Crossing constraints typically place a boundary condition on a position constraint, such as an altitude restriction. They might be used to keep an aircraft high when crossing a managed traffic stream (e.g., 'cross FIX at or above …'), thereby preserving the integrity of that flow. Crossing constraints could also be time-based (e.g., 'cross FIX at or before…').

Airspace constraints protect against entry into an airspace region reserved for special purposes. These regions typically have static dimensions but may be dynamically active or inactive based on the purpose of the airspace. In the future, the timing and location may in some cases be established with short notice, for example to protect a space flight vehicle on reentry.

Sequence constraints specify an aircraft to follow but convey no interval size requirement. They are used to organize converging traffic flows where the flow rate is not constrained. Where it is, metering or interval constraints

(described below) would be used to establish the sequence in addition to the flow rate.

Interval constraints specify the spacing interval to be achieved and/or maintained behind a lead aircraft. They may be used to maximize throughput to a runway or through a congested area. Interval constraints can be applied as an ongoing constraint along a specified segment of a trajectory or as a condition to be achieved at a future location (e.g., the runway threshold).

Separation constraints impose the requirement to ensure the separation standard minima are exceeded when passing near other traffic. As with weather hazard constraints, these constraints move with the traffic but they require strict, uniform adherence (whereas weather hazards may differ by perspective). Individual constraints may be specified for particular traffic encounters, or an ongoing constraint for traffic separation may be imposed for all traffic encountered along a specified portion of the trajectory.

Hazard constraints establish safe distances from hazards, typically weather phenomena, for flight safety. Although similar to airspace constraints, they may have less determinant boundaries and they may move and change dimensions with the dynamic hazard. These constraints may originate or be derived from sources other than the ANSP, such as company policy or the operator's experience with or tolerance for the hazard (e.g. turbulence level).

Constraint Categorization
There are four categories of constraints, defined by the dimensions of achievement or exclusion, and fixed or dynamic constraints. The association of constraints to this categorization is shown in Table 2. The categorization will assist in defining the required performance

capabilities of the aircraft, discussed in section 3.2, "Performing to Operational Constraints."

Achievement constraints are those that define position or timing targets for the aircraft to meet within the prescribed accuracy. They are position, path, metering, sequence, and interval constraints, all of which should be achieved within the defined tolerance. These can be thought of in terms of attraction, i.e., the trajectory needs to be aligned with these targets within a tolerance "window." In contrast, exclusion constraints are those that define conditions to be avoided. They are crossing, airspace, hazard, and traffic separation constraints. For each of these, any trajectory that remains clear of the constraint is considered acceptable. In some cases, buffers may be applied, but then this essentially shifts the constraint by the size of the buffer.

Fixed constraints are referenced either to the Earth or to an absolute clock (e.g. Coordinated Universal Time). They are position, path, metering, crossing, and airspace constraints. Conforming to these constraints require accurate knowledge of the own aircraft position and timing in absolute terms. Dynamic constraints are referenced to a moving target. They are sequence, interval, hazard, and traffic separation constraints. Dynamic constraints additionally require surveillance of the moving target and incorporation of associated uncertainties into defining trajectories for conformance.

Trajectory Flexibility Outside of Constraints

The key distinction between the 4D-Managed and 4D-ASAS performance tiers is the degree of flexibility available to the operator to self-optimize the trajectory within the constraints.

Table 2. Categorization of constraints based on common characteristics.

	Achievement	Exclusion
Fixed	•Position •Path •Metering	•Crossing •Airspace
Dynamic	•Sequence •Interval	•Hazard •Traffic separation

In the 4D-Managed tier, where the ground system is responsible for managing the interaction between aircraft, the 4D routing for each aircraft would likely be highly specified, providing little flexibility other than the opportunity for renegotiation of the 4D route. In the 4D-ASAS tier, all pertinent constraints derived from operational needs are specified, and therefore any trajectory that meets these constraints is considered acceptable.[2] The remainder of the trajectory is unconstrained and can be adjusted to suit the particular optimization objectives of the operator without further ANSP review and approval. An advantage to the operator is that these optimization objectives may remain proprietary information.

In addition to the benefits of priority scheduling and airspace access, as discussed earlier, it is this flexibility, ownership, and control of the trajectory that constitutes the incentives for operators to consider equipping for this performance tier. Depending on their business model, some operators may determine the 4D-ASAS tier is cost-effective, whereas others may not. Therefore it is not expected to replace the 4D-Managed and 3D-Classic tiers, except perhaps in domains lacking adequate ground-based surveillance, such as the oceanic environment.

The benefit of the 4D-ASAS performance tier to the ATM system is that, by definition, all ATM objectives for the aircraft, as defined by the assigned constraints, will be met to within a predictable performance tolerance. Presumably, this individual performance, when aggregated across many aircraft, would result in improved system-level performance and predictability, the investigation of which is the subject of planned research. For this operational method to work, ATM objectives must be translatable into aircraft-specific operational constraints. This is a rich and largely unexplored area of research.

Properly Establishing the Constraints

To maximize individual aircraft performance and efficiency while maintaining operational objectives of the ANSP, it is important to not

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[2] If this were not the case, then the set of constraints communicated to the aircraft was incomplete.

over-constrain or excessively constrain the trajectories of 4D-ASAS aircraft. Doing so may significantly restrict the degrees of freedom such that an otherwise flexible and adaptable capability would become rigid, brittle, or even infeasible. It also may limit or eliminate the self-optimization incentive for 4D-ASAS operators.

Over-constraining occurs when no single trajectory solution could be devised that would meet all constraints simultaneously within the tolerances proscribed for the constraints. A simple example would be the establishment of two sequential metering constraints that require airspeed between them to exceed the maximum airspeed of the aircraft. Whereas an occasional occurrence could be handled through negotiation, the ANSP would need certain information about the flight and its performance capabilities to avoid frequent occurrences of unachievable trajectory constraints.

A trajectory is excessively constrained when more controls are placed on it than are needed to accomplish the ATM objectives for that aircraft. This can take the form of too many constraints or constraints with unnecessarily tight tolerances. In Figure 2, two pictures of the same trajectory scenario are shown. In the left picture, the red arrows represent position, crossing, and/or metering constraints imposed on the trajectory. The constraints define a specific 4D path for the aircraft and do not afford flexibility for optimization or for easy adaptation to the dynamic weather. In the right picture, the constraints relate directly to the ATM objectives of controlling flow rates at the airports and avoiding special-use airspace and the weather hazards. Where constraints are not needed, none are applied, yielding plenty of self-optimizing flexibility to the operator.

Excessive constraints can also take the form of tolerances that are tighter than needed. For instance, a metering constraint to control an arrival rate might be established with a tolerance of, say, ±10 seconds arrival time at the fix. This tight tolerance might eliminate maneuvering flexibility prior to reaching the fix that could be used, for example, to solve a traffic conflict. Expanding the metering constraint tolerance to, ±30 seconds, for example, might still achieve the arrival rate objective while providing more flexibility to the operator. Trajectory flexibility has substantial implications in managing traffic complexity [ref. 8].

3.2 Performing to Operational Constraints

A performance basis for the 4D-ASAS tier should match capabilities to each constraint type. The constraint type categorization shown in Table 2 provides a structure for outlining these capabilities.

Fixed Achievement Constraints

This constraint category includes path, position, and metering constraints. The performance basis for path constraints already exists. Conventional RNP (as used today) provides the certification basis for conformance to a fixed, Earth-referenced navigation path within a prescribed tolerance. For lateral navigation, the performance tolerance is the RNP value for conformance 95 percent of the time and a containment limit of twice the RNP value, e.g., 1 and 2 Nautical Miles (NM), respectively, for RNP-1. High performing RNP may enable reduced separation standards. For vertical path navigation, a vertical path performance limit defines a 99.7 percent bound on all system
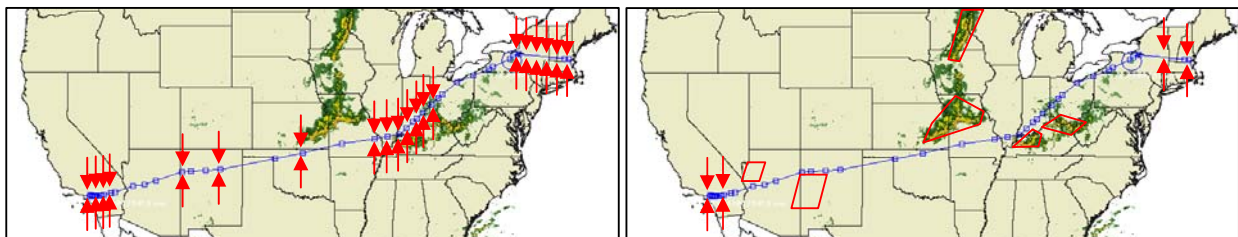

Fig 2. The method of specifying constraints can determine whether the resulting operation will be rigid and brittle or flexible and adaptable with respect to the dynamic environment. Red arrows represent position, crossing, or metering constraints. Polygons represent airspace and hazard constraints. Traffic separation constraints are not shown.

vertical errors. [3]

Since position constraints are essentially a subset of path constraints, conventional RNP also provides the performance basis for meeting position constraints. For loose performance tolerances, the ability to navigate using fly-by turns is probably sufficient. For tighter performance tolerances, the use of Radius-to-Fix capability may be required to eliminate significant fly-by distances stemming from high ground speeds or large heading changes at the fix.

RNP also provides the basis for conformance to arrival times. According to [7], only a single performance tolerance for time-of-arrival-control (TOAC) is specified, ±30 seconds, which is probably not sufficiently precise as a tool for maximizing throughput. The absence of multiple performance levels makes it inflexible to changing requirements, and it is therefore hardly used today. Nevertheless, it is precisely the capability needed for metering constraint conformance in the future ATM system, provided that additional performance levels are defined to address a greater variety of precision requirements.

Fixed Exclusion Constraints

Aircraft performance for this category of constraints, which includes crossing and hazard constraints, requires the capability to execute a trajectory that remains clear of the specified boundary. Again, current RNP provides the required performance basis for this capability, provided the constraints remain fixed in space. Performance tolerances for these constraints would generally be one-sided: penetrating the constraint is unacceptable but remaining clear of the constraint is equally acceptable regardless of how far. It is therefore necessary to take RNP into account when planning the trajectory in the vicinity of fixed-frame exclusion constraints.

Dynamic Achievement Constraints

This constraint category, which includes interval and sequence constraints, is distinct from the two previous categories in that the target state to be achieved is dependent on a moving reference frame – the position or progress of a reference aircraft. Interval constraints, in particular, tend to present a greater challenge than sequence constraints because their typical use to maximize throughput calls for tight tolerances.

Two versions of interval management are considered. The first is open-loop spacing along a common route. The aircraft would be given a constraint to achieve and maintain, say, 90 seconds behind a specified lead aircraft for an indefinite period (assuming spacing is time-based). The second version is an instruction to achieve the interval constraint at a specified future target location, such as a merge point, the final approach fix, or even the runway threshold. In both versions, the assignment would be accompanied by a performance tolerance, such as ±10 seconds. The distinction between them is actually an additional crossing constraint: achieve the interval *at or before* this location.

The performance basis to achieve and maintain interval constraints is not fully satisfied by the TOAC component of RNP. TOAC is referenced to an absolute time source. The capability here must be dynamic such that, if the reference aircraft changes speed, the change is sensed and accommodated by corresponding changes by the 4D-ASAS aircraft to still meet the assigned interval. Also, more flexibility will be needed than the single large performance tolerance of ±30 seconds specified for TOAC.

In order to provide a performance basis for dynamic achievement constraints such as this one, the variables affecting performance for achieving fixed constraints need to be augmented with the variables associated with surveillance of the position and dynamic behavior of the dynamic reference object – in this case, the reference aircraft. In the case of interval management, the primary surveillance variable is typically the reference aircraft's speed or its estimated arrival time at the target location where the interval must be achieved. But also of interest may be the reference aircraft's path conformance to identify failure modes of the procedure. Failure modes can lead

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[3] RNP also has additional requirements, such as containment integrity and continuity. For a complete description, see [7].

to an inability to comply with the constraint and are therefore important to include in the performance basis.

Dynamic Exclusion Constraints

As in the previous category, the constraints of traffic and hazards are dynamic. The goal, however, is exclusionary – to navigate in such a way that proximity to the hazard or traffic meets or exceeds established separation criteria. In other words, although the actual hazard is the physical encounter with the weather phenomenon or a collision with the traffic aircraft, the trajectory constraint includes a buffer from the hazard, and the goal is to remain outside the buffer. In the case of traffic, the separation standard in use today is a generally static set of values – 5 NM lateral and 1000 feet vertical in en-route airspace. In the future ATM system, these values may be unique to each encounter. Any proximity closer than these values is considered a breach of the constraint, but all trajectories that provide separation greater than these values have equally acceptable safety performance.

Hazard constraints may have boundaries that are subject to interpretation and compromise, due to the complex and often subjective nature of these constraints. Since trajectory planning requires knowledge of the constraints long before the hazard has been reached or even materializes, the constraints are initially derived from probabilistic forecasts and then updated as needed. Buffers applied to these constraints are also more complex. Besides needing to take into account probability and risk, they are often just guidelines rather than hard requirements. An example is the distance by which aircraft avoid convective weather. A lighter passenger aircraft would be more likely to use a greater buffer, whereas a heavier cargo aircraft with more tolerance for turbulence may elect to navigate closer.

A certified ability to conform to these dynamic constraints requires the definition of a new dynamic performance basis. RNP is the accepted performance basis for 2D or 3D navigation relative to a fixed path, but it provides us a model from which to define a performance basis for dynamic exclusion constraints. In particular, the construct of RNP would need to be expanded to a dynamic frame of reference for hazard constraints and then also to 4D for traffic separation constraints.[4]

3.3 Dynamic RNP

Research is underway to explore the requirements for a 4D, dynamic RNP-like specification as a performance basis for 4D-ASAS tier applications. This "Dynamic RNP" specification would likely need to account for all error sources found in the current basis (e.g., flight technical error, path definition error, position estimation error, horizontal coupling error). In addition, it would also need to account for error sources associated with surveillance and trajectory prediction of dynamic reference objects – the hazard or the traffic aircraft. Entering into this may also be environmental variables like wind prediction error. For dynamic exclusion constraints, it must be remembered that the performance requirement is only to remain clear of the constraint with measurable confidence. To achieve measurable confidence, the definition of Dynamic RNP will need to consider the impact of the dynamic reference object's behavior and failure modes on the containment region, as well as the factors of containment integrity and continuity.

The issues raised here are intended only to illustrate some of the initial thoughts on developing a suitable performance basis. The conceptual and mathematical expansion of RNP to Dynamic RNP is expected to be an involved undertaking. A research activity currently investigating the issues is aiming in the next 18 months to produce an initial conceptual and mathematical construct of Dynamic RNP. The concept and its validation will be documented in future reports.

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[4] 4D may be less important for hazard constraints because their dynamics are much slower than aircraft speed. However, for longer term trajectory planning, the predicted hazard dynamics will be a dominant factor.

4 Measuring Performance of Self-Separation

Concurrent to the ongoing conceptual development of the Dynamic RNP concept, a series of high-fidelity batch simulations are being conducted to characterize the performance of a 4D-ASAS tier application designed for TBO in the presence of traffic separation, airspace, and metering constraints. The simulation is being conducted in the Air Traffic Operations Lab at the NASA Langley Research Center. Once the Dynamic RNP concept is mathematically constructed, data from simulations like these will be used to test and validate the model's usefulness.

The basic scenario, shown in Figure 3, is random and generic to enhance generalizability of the performance results. It consists of a 160 NM diameter circular test region in high altitude airspace. The aircraft are confined to a single flight level, thereby providing a challenging, highly constrained, maneuvering environment. (Future testing will expand to trajectory management in 3D airspace.) Each aircraft enters the perimeter of the test area at a random location, time, and entry angle, and is assigned a straight 4D trajectory that has not been de-conflicted with any other aircraft's trajectory. Traffic density is controlled by the rate of aircraft introduced, and the density is sustained for the experiment run time. As a result of the scenario design, traffic conflicts (i.e., trajectories that would breach the traffic separation constraint if left unmodified) occur naturally and randomly throughout the airspace.
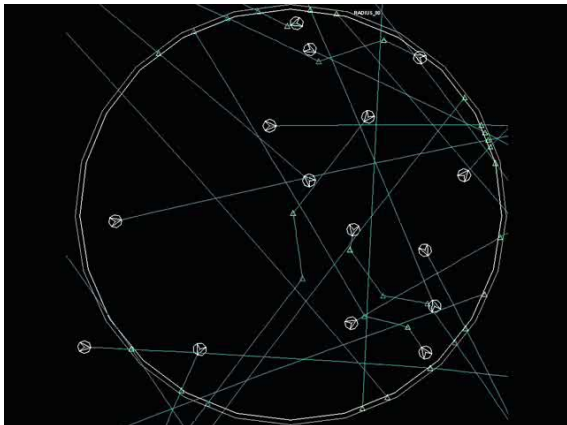

Fig. 3. Batch simulation scenario to be used for characterizing the performance of airborne separation.

Each aircraft is equipped with a simulated Mode-S Automatic Dependent Surveillance Broadcast (ADS-B) data link and a NASA-developed, research-prototype, 4D-ASAS automation system for trajectory management [ref. 9]. This system, the Autonomous Operations Planner, is capable of strategic (i.e. closed-loop, trajectory-based) traffic conflict detection and resolution while avoiding airspace constraints and conforming to a downstream metering constraint.

Some sample simulation results on traffic separation performance of self-separation at various sustained traffic densities are presented in Table 3. Portions of these data were published in [ref. 10]. For traffic separation, the critical performance metric is the frequency of loss of separation, which in this simulation was a penetration of the 5 NM lateral separation zone[5]. In total, out of over 10,000 simulated flights and 5770 conflicts, no reportable losses of separation occurred. This performance result is encouraging but is not yet conclusive. Few error sources were included in this preliminary baseline study. Currently underway are additional data collection activities, using the same scenario, that are introducing sources of potential performance degradation, such as uncertainties, delays, information exchange limitations, and errors. This research will allow

Table 3. Sample data of traffic separation performance from [9].

Sustained Mean Density*	Sim. Hours	Simulated flights	Traffic conflicts	Losses of Separation[5]
3.45	36	881	195	0
6.11	36	1527	550	0
8.61	36	2195	1018	0
11.64	36	3000	1788	0
15.24	12	1302	963	0
17.18	12	1560	1256	0
Totals	168	10,465	5770	0

Normalized to aircraft per 10,000 NM^2

[5] Separation zone penetrations of less than 100 feet are not counted. Simplified turn modeling without the use of buffers resulted in negligible incursions in rare instances.

the characterization of safety performance as a function of these variables, as well as other performance metrics.

5 Conclusions

The application of ASAS technologies to accomplish functions in 4D trajectory-based operations is a bold operational concept that appears to offer significant promise in terms of system-level performance and individual operator benefits. Although research and early flight trials around the world are continuing to demonstrate the potential for significant benefits to operators and the ANSP, these applications will be challenging to implement because they are largely outside of our operational experience base and more particularly because they involve the apparent release of control from the ANSP to the aircraft.

However, reduced ground control over the actual trajectory flown need not mean reduced predictability or conformance to ANSP expectations. As described, operational constraints that define the set of acceptable trajectories become the new mechanism for air/ground coordination. A performance approach to certifying 4D-ASAS applications should provide the basis for normalizing aircraft behavior with ANSP expectations, while also providing the tools necessary to apply these powerful capabilities in strategic and surgical ways to benefit the overall system.

A proposal has been outlined for defining a performance basis applicable to any 4D-ASAS application. Attention was focused primarily on the various types of trajectory constraints and the performance requirements they generate. A detailed analysis of the error sources and their mathematical contributions to the proposed concept of Dynamic RNP is the subject of ongoing research and will be reported in future publications as the work progresses. It is anticipated that a performance basis for certifying 4D-ASAS applications will provide the foundation necessary for attracting these high-performing capabilities to where they would provide the most capacity-increasing benefit.

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