

Federal Aviation Administration

**Research, Engineering and
Development Advisory Committee**

Separation Standards Working Group

Final Report

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Executive Summary

The Federal Aviation Administration (FAA) and Joint Program Development Office (JPDO) estimate that by 2025, the number of operations that the Air Traffic Management (ATM) system must accommodate will grow between 100 and 200 percent, depending on the mix of aircraft in use. The JPDO determined today's system must be transformed to accommodate the increased air traffic. This transformation will require that modern technologies be fully leveraged to enable higher aircraft densities while maintaining or improving current levels of safety. These technologies give us every reason to believe that aircraft to aircraft separations can be safely reduced to accommodate increased demand.

The National Airspace System (NAS) Operations Subcommittee of the FAA's Research, Engineering and Development Advisory Committee (REDAC) established the Separation Standards Working Group (SSWG) to examine how to reduce separation standards, without jeopardizing safety, and recommend Research and Development (R&D) that would facilitate the reductions. The SSWG first examined the basis for current separation standards, and reviewed past and ongoing studies of separation requirements. The Working Group then considered improved methodologies for establishing separation standards, as well as changes that new technology may bring. The process resulted in ten findings, with accompanying recommendations.

The current aviation system, to the great credit of the pioneers and the practical application creators, is both practical and safe. Refinements to the standards have preserved safety even as air traffic levels grew.

However, the development of many existing separation standards was largely empirical, based on the experience and judgment of operations experts. Analytical and probabilistic studies have been occasionally used to inform and quantify those judgments. Recent work shows that modern analytical and statistical studies, based on extensive field data, are essential for developing new standards, but must still be complemented by operational trials and human factor considerations.

Judgment and experience will continue to be needed to address rare, unpredictable events. However, the practice of compensating for "diabolical" threats or similar anomalies by setting arbitrary performance standards can impede legitimate initiatives. For example, there was only anecdotal evidence about blunders for Precision Runway Monitor (PRM) and over ocean operations, and thus no way to validate or challenge the government's performance standards, a frustrating outcome for system developers and aircraft operators.

In summary, it is clear that a more data driven, objective methodology is needed to address the challenge of separation reductions if the forecast traffic levels are to be met.

Findings¹ and Recommendations²

Finding 1. The current system, based on the separation standards that have evolved over the last 50 years, is safe, but still unable to meet projected demand. The separation standards (and the approach to establishing separation standards) now need to be reconsidered in order to meet the demand for increased capacity.

Finding 2. Most current separation standards have been developed empirically based on judgment, extrapolation of past experience, and limited analysis. In recent years, a more analytical approach has been applied. The current standards are not based on a consistent philosophy, varying from one part of the airspace to another; using varied analytical approaches and assumptions about behavior.

Finding 3. Some separation standards are strongly influenced by the possibility of gross deviations, or blunders. However, little is known about such blunders: their frequency of occurrence, their magnitude, under what circumstances they are most likely to occur. Existing information about blunders is primarily anecdotal.

Finding 4. Mathematical analyses require substantial data to accurately characterize reality. Historically, sufficient data has not been available. The result of insufficient data is overly conservative separation standards.

Finding 5. New separation standards may be developed by comparison with a reference system or by evaluating system risk against a threshold level. Comparing to a reference system is an appropriate method to support incremental changes to the current system. To evaluate the major changes in separation standards that will be required for the Next Generation Air Traffic System (NGATS), the evaluation against a threshold methodology may be necessary.

A disciplined process for identifying and analyzing risk when developing or revising separation standards is of vital importance. Analytical and probabilistic studies are essential in the determination of safe standards, but, by themselves, are not enough. They should be used together with judgment. Their role is to inform and quantify judgment.

¹Findings 1 through 5 all deal with the historic establishment of separation standards, and the limitations of some of the methodology used. They are treated together in this section in order to establish a consistent set of recommendations.

²Recommendations are presented in two time frames, Immediate and Longer Term. The Immediate recommendations are those that should or can be undertaken immediately. Some of them could increase efficiency, if applied, in the current National Airspace Space system. Longer Term recommendations are must be preceded by other work or do not apply to today's system.

Guarding against unrealistic or diabolical phenomena should not be a basis for the establishment of separation standards.

Recommendation:

Establish an R&D program that will lead to consistent and safe reduction of separation standards and that will support NGATS. The process outlined below for setting separation standards should be adopted. This R&D program should include, but not be limited to:

- **Immediate**
 - Establish a research program to develop an understanding of the nature and frequency of blunders.
 - Performance Data Analysis & Reporting System (PDARS) appears to be a possible source for needed data.
 - Develop new systems, if needed, for automated reporting of such anomalies.
 - Establish data needs for establishment of separation standards early in NGATS development so opportunities, such as demonstrations, can be used collect data.
 - If conservative separation standards are put in place, such as RNP Parallel Approach Transition (RPAT), establish a data collection process early in the implementation so operational data collected to reduce separations in the future.
- **Longer Term**
 - Conduct research to develop consistent approaches for the development of separation standards with all assumptions stated concisely.
 - Conduct research to improve the methodology for evaluating separation standards against an absolute threshold (target level of safety). In particular, there needs to be a consistent, credible way to take into account the response of humans to rare events.

Finding 6. The next generation air transportation system will have:

- **new roles and responsibilities for pilots and controllers and the automation that supports them,**
- **increased shared situational awareness on board the aircraft that will provide more timely and accurate information including intent of nearby vehicles,**
- **the potential, through good system design, for fewer unexpected deviations, and**
- **new backup systems to deal with system/subsystem failures, possibly accepting lesser performance capability than the system being backed up.**

As surveillance, navigation, and communication performance increases, including communication of intent, separation standards will be driven more by the need to accommodate system failures than by variations in nominal system performance.

Recommendations

- **Longer Term**
 - Establish a research program to develop an understanding of the roles of the human and automation in dealing with failures and the implication of those roles on separation standards.
 - Managing failure gracefully is perhaps the most difficult design aspect of the NGATS. Specific and intense research into the human and automated alternatives will be required.

Finding 7. New technologies (e.g. GPS, ADS-B, CDTI, Datalink) offer the potential for reducing required separations. In particular, GPS-based RNP, together with the concept of containment, provides much more precise control and knowledge of an aircraft's intended trajectory, and ADS-B permits the pilot of other aircraft, as well as the air traffic controller, to monitor the flight path of a proximate aircraft and rapidly sense deviations from its intended path.

Recommendations

- **Immediate**
 - As more and more aircraft use RNP-based navigation, monitor their performance, and gather and analyze data to develop a statistical understanding of the performance of RNP-based systems in various flight regimes.
 - Re-examine the design of parallel and converging approaches and departures based on an appropriate probability distributions (may not be Gaussian) or on data gathered using RNP-based navigation.
 - The Performance-Based Advisory Rulemaking Committee (PARC) should redefine the definition of "established on approach" to include LNAV and VNAV. The requirement to be aligned with the runway centerline should be studied for possible elimination.
 - Research into potential reduction of Arrival/Departure and Departure/Departure separations due to RNP guided missed approaches and departures should be pursued.
- **Longer term**
 - Develop (recommendations for) new separations standards based on the improved navigation, surveillance, communication, control, and automation technologies, which will be part of NGATS. Utilize lessons learned during the analysis of other standards.
 - When the nature and frequency of blunders off an ILS course are better understood using data ILS/RNP parallel runway separation should be reevaluated. RNP/RNP parallel approach separation should be established.
 - The No-Transgression Zone (NTZ) role for ILS operations should be re-defined based on real blunder information. Then, if still required, appropriate dimensions and shapes should be established.
 - The role of the NTZ in RNP/RNP separations should be established. The NTZ may not be needed.

Finding 8. In designing NGATS, an air-based independent (from ATM system) backup collision avoidance system (similar to TCAS or perhaps a modified TCAS) will be required.

Back-up safety systems in the aircraft and air traffic control facilities have been set to prevent collision while minimizing false alerts when aircraft are operating at today's separation standards. As separation standards are reduced, procedures and alerting logic must be reexamined to optimize the balance between collision avoidance and false alerts.

Recommendations

- **Longer Term**
 - Research is required for the future independent airborne collision avoidance system in the context of the ATM system construct and the associated separation standards.
 - Research and analysis of alerting systems, such as Traffic Alert and Collision Avoidance System (TCAS), Terrain Awareness and Warning Systems (TAWS), Minimum Safe Altitude Warning (MSAW), and Conflict Alert (CA) function, should be initiated to minimize false alerts as separation standards are reduced and revised.

Finding 9. Evaluating the controllers' performance by distribution (stochastic control) rather than a hard limit may be able to increase capacity and effective throughput without compromising safety.

Recommendation

Immediate

Research into the practicality of stochastic control in terminal operations (specifically landing spacing) should be initiated. Research should pursue the question of practicality and unintended consequences. This is an important area for research because it offers the prospect of some near term improvement in landing rates, and because stochastic control is more appropriate than deterministic control in automated systems such as NGATS.

Finding 10. In considering the possibilities for reducing separations standards, wake turbulence becomes the driving consideration. For NGATS, wake turbulence could become the primary limiter of capacity.

Recommendations

- **Immediate**
 - Full support of existing research and implement program should continue.
 - Commission a team to conduct in-depth annual technical and programmatic reviews of the wake research and implementation program. The reviews should include the objectives, technical approach, schedule, and funding. The team should be composed of external experts knowledgeable in the areas of wake vortices in normal operating configurations, advanced Light Detection and Ranging (LIDAR) and other sensors that may be useable in detecting the strength of a wake vortex, aircraft behavior in the presence of wakes, and how this information can be used in the flight deck and air traffic facilities. This team should be structured along the lines of the Department of Defense Science Board and report to ATO leadership.
- **Longer Term**
 - Investigate advanced instrumentation such as LIDAR or other sensing methods to obtain direct measurements of vortex strength.
 - Investigate the feasibility and practicality of wake vortex sensing/tracking to provide the flight crew an indication of encroaching wake vortex location, strength and upset risk.

Reducing separations standards, while preserving safety, is an intricate process. An evaluation of the overall system risk is necessary when the proposed separation is much different from the current. Mathematical analysis, real time simulations, field demonstrations, risk assessments, judgment, and a structured introduction should all be utilized.

Table of Contents

Executive Summary	i
Findings and Recommendations	ii
Table of Contents	1
Introduction	2
Section 2	4
Need and Opportunity for Separation Standards Change	4
Section 3	6
History of Separation Standards	6
3.1. Target Level of Safety	6
3.2. Enroute Separations (Containment)	6
3.3. Oceanic Separation	7
3.4. Radar Separation Standards	7
3.5. Obstacle Clearances	8
3.6. Successive Arrival Separation	8
3.7. Parallel Approach Separation Standards	8
3.8. Lessons Learned from Historical Record	9
Section 4	12
Current State of the Art to Establish Separation Standards	12
4.1. ICAO Guidance on Separation Standard Analysis	12
4.2. Examples of Successful Separation Reductions	13
4.3. Introduction of Required Navigation Performance (RNP) operations	13
4.4. FAA Safety Risk Management Process	13
Section 5	15
Discussion	15
5.1. Influence of New Technologies on Separation Standards	15
5.2. Potential Impact of Automation	16
5.3. TCAS and other alerting system implications	17
5.4. Stochastic Separation Standards	18
5.5. Wake Vortex	18
Section 6	20
Findings and Recommendations	20
Appendix 1	26
SWAG Members	26
Appendix 2	27
Terms of Reference	27
Appendix 3	28
Summary of Presentations and list of presenters	28
Appendix 4	30
Current MITRE Research Related to Separation Standards	30
Current NASA Research Related to Separation Standards	32
Appendix 5	33
List of IFR Separation Standards	33
Appendix 6	37
PRM for Simultaneous Parallel Approaches	37
Appendix 7	40
ILS/RNP Separation Standard	40

Section 1

Introduction

The Federal Aviation Administration (FAA) and Joint Program Development Office (JPDO) estimate that by 2025, the number of operations that the Air Traffic Management (ATM) system will have to accommodate will grow between 100 and 200 percent, depending on the type of aircraft that will be used. Initial analysis by the JPDO has shown that the current system cannot accommodate this increase in demand, leading to the conclusion that a transformation of today's system will be required. Technology can be deployed that increases efficiency by separating aircraft closer to existing separation standards. However this will not be sufficient to achieve the needed capacity increase. One of the means for achieving increased capacity, particularly at some of the nation's busiest airports, is through a reduction in separation standards.

In air traffic control, "separation" is defined as the spacing of aircraft to achieve their safe and orderly movement in flight and while landing and taking off. "Separation Minima" are the minimum longitudinal, lateral and vertical distances by which aircraft are spaced through the application of air traffic control procedures. In this study, "separation standards" refer to the minimum distances by which aircraft are spaced in all phases of flight.

Establishing appropriate separation standards is an important element of achieving increased National Airspace System (NAS) capacity and flexibility, especially in terminal airspace. Three principal elements of required inter-aircraft separation, navigation accuracy, efficient communications, and surveillance capability, have improved markedly since the current separation standards were established. However the question still remains whether it is possible to reduce inter-aircraft separation without an acceptable degradation of safety.

The NAS Operations Subcommittee of the FAA's Research, Engineering and Development Advisory Committee (REDAC) established the Separation Standards Working Group (SSWG) to examine this question and recommend Research and Development (R&D). The SSWG looked at the basis for current separation standards, and reviewed past and ongoing studies of separation requirements. The Working Group also examined improved methodologies for establishing separation standards. The process resulted in ten findings, with accompanying recommendations that include research topics. The Terms of Reference for the Working Group is shown in Appendix 2, and the membership is in Appendix 1.

Study Process

The SSWG solicited inputs from many members of the aviation community with a stake in improving capacity by reducing separation standards or with subject matter expertise. These included airlines, manufacturers, FAA NASA and The MITRE Corporation.

A listing of these presentations is shown in Appendix 3. To the extent available, copies of the presentations by these organizations are included in the "Appendices" section of the enclosed CDROM.

In addition to these inputs, SSWG members contributed substantially from their own knowledge and experience.

Comment [MEP1]: Sarah and Working Group members. We have not agreed to this approach, but it gives serious readers all the background information that we have, and doesn't make our report so thick as to be forbidding.

Structure of the Report

The report begins with a description of the need for separation standard reductions and a discussion of the opportunity presented by new and currently available technologies.

A short history of separation standard establishment is presented followed by a summary of current methodologies used by FAA and ICAO for establishing or revising separation standards.

The Discussion section presents a series of discussions of various topics all of which are relevant to the establishment or modification of separations standards. These topics are also relevant to the transformation of the NAS as envisioned by the JPDO.

Findings are embedded throughout the report adjacent to the relevant discussion. The final section of the report repeats the Findings and includes the SSWG's Recommendations for R&D and other actions to address each Finding.

The report contains a number of appendices pertinent to the Working Group effort.

Section 2

Need and Opportunity for Separation Standards Change

FAA and JPDO projections indicate an average annual revenue passenger mile growth rate of 3.9% from now to 2016. The JPDO expects enplanement demand in 2025 to be between 1.5 and 2.5 times the 2004 demand. While the crystal ball for 2025 demand is somewhat cloudy, the JPDO estimates that, depending on the type of aircraft that will be used, the number of operations that the Air Traffic Management (ATM) system will have to accommodate will grow between 100 and 200 percent (see Figure 1).

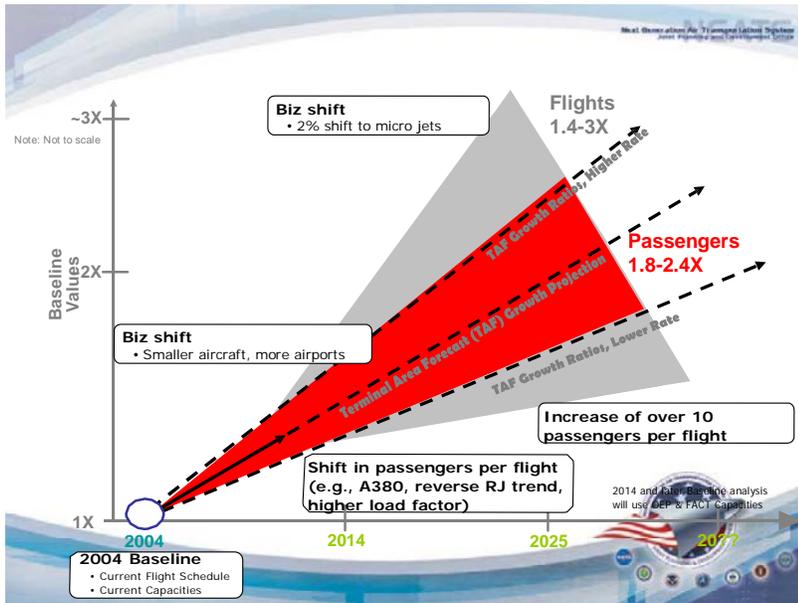


Figure 1 – JPDO Demand Projection Range

The current air traffic control system has a remarkable safety record and has met the growing capacity demand for the last 50 years. This has been achieved by careful conservatism in the operation and modification of the hardware and procedures. There have been improvements to the system in response to safety concerns (e.g. terrain and aircraft collision avoidance systems, improved sensors and displays, and weather radar), and in response to capacity demands (e.g. precision runway monitor, and re-sectorization). And some separation standards have been changed (reduced vertical separation between Flight level 290 and 400, separation reductions in oceanic airspace, and wake vortex driven landing and takeoff spacing). But there has been no change in the fundamental operating concept of the system since the introduction of radar about 50 years ago.

The current approach to accommodating increasing capacity requirements in the en route airspace is to subdivide control sectors so as to maintain an acceptable number of aircraft in each controller's purview. The price of this is that each such subdivision increases the number of sector transitions that the aircraft must make as it flies its route. Notionally, if the number of sectors is doubled to accommodate the capacity demand, the number of sector transitions also doubles. When the sectors are large, this does not pose a major problem; but in the high-density airspaces, such as the East Coast Corridor (Boston/New York/Philadelphia/Baltimore-Washington), the sectors have become so small that the sector transition rate cannot be increased without imposing an unacceptable load on the controllers and pilots who must service each transition.

This diminishing returns aspect of re-sectorization has reached the point where we cannot accommodate the projected increase in demand without some fundamental change in the air traffic control system.

In the terminal area, the increasing capacity demand has been met by strictly structuring both the arrival and departure streams, and by utilizing multiple runways. The limiting factor in the terminal area is most often wake vortex, although runway utilization is also limited by provisions for safe resolution of blunder events. Further increases in terminal area capacity (other than building new independent runways at new airports or by expanding existing airports) will require new operational concepts (such as synchronized paired approaches and departures¹), and a solution to the wake vortex problem (such as a separation system which is responsive to real time determination of the actual wake vortex situation).

Today, several large airports (e.g. Chicago O'Hare, LaGuardia) are capacity limited and require some form of demand management. En-route airspace is also showing signs of capacity limitations, particularly in the northeastern U.S. Projected demand increases are exacerbated by the growing shift to smaller aircraft and the impending arrival of a potentially large number of Very Light Jets.

Initial analysis by the JPDO has shown that the current ATM/ATC approach cannot accommodate the projected increase in demand and have concluded that a transformation of today's system will be required. Technology can be deployed that increases efficiency by reducing the "buffer" between actual separations and existing separation standards. However this will not be sufficient to achieve the needed capacity increase. One of the means for achieving increased capacity, particularly at some of the nation's busiest airports, is through a reduction in separation standards. The challenge is to design and implement the new approach without compromising safety.

A number of modern avionics and ground and space based technologies, many of them already available today, offer opportunities to reduce separation standards. These include:

- better ability to control the path of flight and the associated reduction in flight technical error;
- the ability for an Air Navigation Service Provider and aircraft (pilot, cockpit automation, or both) to have more precise position knowledge
- the ability for an aircraft to know where nearby aircraft are
- better prediction of an aircraft's future position
- pilot knowledge of the intent of nearby aircraft
- potential for coordinated separation assurance maneuvers
- better information regarding terrain and runway location
- higher bandwidth, lower latency communication between the ground and the cockpit
- the ability to detect and avoid wake vortices

In the longer term, the move towards the Next Generation Air Traffic System (NGATS) will change the control paradigm and make new airspace structures possible. For example, 4D trajectories allow new ways to fly – not necessarily on pre-charted airways.

Finally, an improved ability to collect and manage data leads to improved process. We have the ability to collect data to better understand the frequency and severity of flight path deviations. This will allow a more informed approach to the design of blunder tolerant systems.

Finding 1. The current system, based on the separation standards that have evolved over the last 50 years, is safe, but unable to meet projected demand. The separation standards (and the approach to establishing separation standards) now need to be reconsidered in order to meet the demand for increased capacity.

¹ NASA's "Virtual Airspace Modeling and Simulation System-Wide Concept Report", Volume 1

Section 3

History of Separation Standards

In considering new approaches to the establishment of separation standards in aviation, it is necessary to understand the basis of current standards and to rationally assess system changes that permit safe changes to those standards. The following section describes the background and derivation of current separation standards, and the initial attempts to derive separation standards in an analytical manner.² A list of today's Instrument Flight Rule separation standards is located in Appendix 5.

3.1. Target Level of Safety

A widely used approach to separation involves establishment of a "target level of safety" based on rational numerical analysis, judgment and comparison to achieved safety records of other applications. The British Air Registration Board (ARB), the United Kingdom's (UK) certifying authority, first invoked this approach in the late 1950's. The issue was approval of an automatic "all-weather" landing system for passenger aircraft.

The ARB started by looking at history to establish the landing accident rate then being achieved. Based on a study of nearly twenty airline-landing accidents (mostly propeller aircraft), they found there had been about one accident for each million landings. They reasoned that introduction of a new capability such as automatic landing should be designed with the motive of improving the safety record, but could, in no event, allow safety to deteriorate. They called for a design that would have a predicted (and, to the extent possible, demonstrated) failure rate of no more than one in ten million landings, ten times better than the rate experienced in normal operations. They imposed a further assumption that any failure of the automatic landing system would result in a fatal accident.

Many people and organizations tested the idea of establishing a target level of safety, especially the idea of one accident in ten million events. A study done by the International Civil Aviation Organization's (ICAO) Review of the General Concept of Separation Panel in 1975, using UK mortality rates, showed that the risk of mortality in the healthiest age groups was six in ten million person hours (yet another yardstick), while an analysis of observed fatal accident rates from 1965-1973 yielded a figure of 10.5 fatal accidents in 10 million (10^7) flying hours - similar to the postulation of the U.K. Air Registration Board.

ICAO published further corroborating information in a comprehensive study by several countries. This study looked at fatality rates in manufacturing, railway work, and public road vehicles, mortality rates in the general populations; and a variety of air accidents from landing to midair collisions. The bottom line finding, using many logical choices but only a few assumptions, was that an appropriate target level of safety might be between one and six fatal accidents in 10 million aircraft flying hours, with the resulting risk appropriately shared among mechanical failures, midair collisions, and other accident causes. Again, the target of a few chances of a fatal accident in 10 million flying hours seemed credible.

3.2. Enroute Separations (Containment)

Before radar of any kind was used for air traffic control, separation depended on dead reckoning and pilot reports. The controller, using flight strips to "see" his targets, separated aircraft by feeding them into certain routes with time separation, knowing that designated aircraft speeds over the route distance would keep them apart by "procedural control". Pilot reports by radio, when available, were used to update positions. Of necessity, separation distances were quite large since little was known about winds aloft and the like. The earliest standards for ATC separation between aircraft, usually for longitudinal spacing, were entirely based on time separation along a pre-established

² Some of this material draws on *History and Evaluation of Separation Standards*, S.B. Poritzky, prepared for The Boeing Company by Applied Techno-Management Systems, Inc., under Contract JE5476, July 31, 1996.

route, using best estimates of the physical and environmental vagaries. Early uses of navigation aids, starting with light beacons and later radio beacons, still used time as the basic separation tool.

With the introduction of more sophisticated navigation aids, particularly VOR, computations of probable displacement from desired paths were introduced. The FAA, in its air route and separation computations, based them on a concept of "system use error." It created airway (route) width designations, on a "95% containment probability" basis, based on root-sum-square (RSS) combination of ground station error (at the greatest usable distance from the facility), airborne navigation system and display error, and a pilotage factor. It assumed that the error distributions were normal.

A "95% containment probability" means that aircraft flying along a designated route:

- may be expected to remain within the airway confines on 95% of the occasions on which observations are made; and
- that any particular aircraft will remain within the airway confines 95% of the time that it is flying along the airway.

In practical terms, the meaning often assumed was that the navigation capability of the system is such that when masses of aircraft are observed flying along a route, they will be essentially normally distributed about the route centerline, and 95% of the observations will show aircraft to be within the airway width assigned.

3.3. Oceanic Separation

Application of risk modeling was attempted in the 1970's on the North Atlantic aircraft organized track separation system. There had been no collisions over the oceans at the 120-mile track separation (the 120 mile number being a figure selected by The International Air Transport Association (IATA) in 1954 - it was the distance traversed by a four-engine propeller transport aircraft flying orthogonally to its course for a half hour). The task was to try to "prove" the safety of a smaller (90 mile) spacing, and to consider improved navigation and cockpit capabilities.

After months of discussions between the United Kingdom, the United States and the International Federation of Air Line Pilots Associations (IFALPA), the mathematicians and the practical problem solvers agreed on a compromise "collision risk model". It was realized at the time that the mathematics and the meaning of the numbers were suspect because many of the assumptions and variables were unproven. However, an analysis that was acceptable to reasonable and knowledgeable experts was needed.

As noted by Robert Machol, one of the participants for IFALPA, in the North Atlantic separation discussions, "the actual mechanism that was finally agreed on for arriving at a target level of safety (for the oceanic system) was to take the total rate of accidents of all aircraft (not just those over the North Atlantic Region), and shoot for something ten times as safe. Putting numbers into this turned out to be rather difficult; it was never possible to arrive at a single number, but we finally agreed that the target level of safety lay between 0.45 and 1.2 accidents due to collision per 10 million flying hours."³

3.4. Radar Separation Standards

Radar separation standards have traditionally required air traffic controllers to maintain at least three nautical miles (NM) between aircraft that are within 40 NM of the radar and, typically, the airport. Aircraft further than 40 NM from the radar must be separated by at least 5 NM. 5 NM separation is also required when the two aircraft are not observed by a common radar. These requirements were based on maintaining, "green in between" the targets as seen on a plan view display of primary radar target video. Mode S and Monopulse Secondary Surveillance Radar (MSSR), deployed in the 1980s, provide reliable surveillance data that is more accurate than the primary radars, by a

³ "An Aircraft Collision Model" Robert E. Machol, Northwestern University, [The Institute of Management Sciences](#), Vol. 21, No. 10, June 1975.

factor of ten. However, the FAA did not initially exploit those benefits. Recently, the need to maintain three NM separations within large terminal areas such as Southern California, or Potomac, has caused the FAA to change the standards, allowing 3 NM separation out to 60 NM from the radar.

3.5. Obstacle Clearances

The FAA Terminal Instrument Procedures (TERPS) have, for many years, been based on a technique similar to that used for airways, except that, as noted above, the containment criterion is based on 99.7% for aircraft-to-terrain separation vs. the 95% for aircraft-to-aircraft separation. The “99.7% probability” means that the minimum distance of any obstruction must be three times the standard deviation of assumed navigation system use error.

In the development of safe procedures, it is recognized that the planes and surfaces protected against are seldom-continuous physical barriers; instead of a surface, the problem obstruction may be a hill, an apartment block, or a tree. To remain reasonable in the application of standards, the FAA has developed a collision risk model, which is used to make informed decisions in developing approach obstruction clearance criteria.

Frequently, there are obstructions close to airports in the U.S. that violate the obstacle clearance criteria in the final approach area. Often such obstructions have existed for many years, and vast numbers of safe arrivals and departures have been made. The decisions to allow such deviations from standards have been made in part because the obstructions are single incursions into the obstruction planes called out in TERPS, judged by operations experts to be benign, and frequently offset by other improvements such as obstacle lighting to provide an overall “equivalent level of safety.”

3.6. Successive Arrival Separation

The standard radar separation in the terminal area is 3 NM. Several studies in the 1970s investigated the feasibility of reducing the minimum separation on final approach to 2.5 NM in order to increase Instrument Flight Rules (IFR) arrival capacity. Two issues required special consideration: wake vortex effects and runway occupancy time. Additional separation is needed behind a Heavy or B757 aircraft to avoid wake turbulence. Wake turbulence behind Large aircraft was not considered to be a hazard at 2.5 NM for another aircraft that was also in the Large category or heavier, based on operational experience with visual separations that typically are less than 3 NM for these aircraft.

For those aircraft pairs with the reduced separation, the lead aircraft would still need to exit the runway before the trail aircraft crossed the runway threshold. A maximum average runway occupancy time (ROT) that would be compatible with the 2.5 NM minimum separation needed to be specified in order to prevent an increase in the rate of go-arounds to avoid simultaneous occupancy. After analysis of current operations and some discussions with controllers, it was decided that a mean ROT of 50 seconds or less would be needed for 2.5 NM separations.

When the reduced separation was initially implemented, there was an additional requirement that the runways needed to be clear and dry. Here the concern was that wet runways would increase ROT and the rate of go-arounds would increase. After collecting ROT data in actual operations and conducting specific demonstrations, the FAA recognized that wet runway occupancy times do not significantly differ from dry runway times and this requirement was eliminated.

3.7. Parallel Approach Separation Standards

In 1962, the FAA approved a minimum spacing between parallel-runway centerlines of 5000 feet to conduct independent instrument approaches. According to a 1971 FAA paper⁴:

⁴ Internal FAA paper, “Executive Summary – The establishment of a more definitive basis for the determination of lateral spacing criteria for IFR approaches to multiple runways”, received by MITRE on May 13, 1971.

“In 1962, data was recorded and analyzed of the lateral deviations of aircraft conducting IFR approaches to the Chicago O’Hare airport. The current lateral spacing criteria for conducting independent simultaneous IFR approaches to parallel runways [i.e., 5000 feet runway spacing] were based on the results of that data.”

A MITRE briefing⁵, circa 1973, recommended reducing the minimum spacing to 4300 feet. MITRE’s recommendation was based on increasing the No Transgression Zone (NTZ) between the runways from 2000 ft to 2700 ft and decreasing the size of the Normal Operating Zone (NOZ) around the localizer path, due to improved navigation performance. The NOZ is sized so that the likelihood of any normally operating aircraft being observed outside the NOZ is very small. However, the FAA decided to retain the 2000 feet NTZ. In 1975, MITRE refined its analysis⁶ and calibrated it to the FAA’s implementation of 4300 ft “as the accepted standard of system performance and safety.” The FAA approved 4300 feet in October 1974, presumably based on MITRE’s input as well as a report by Resalab⁷ (1972) that justified assuming smaller navigational errors.

The “MITRE Model” for parallel runway spacing calculated the required runway spacing based on providing a safe separation in the event of a “worst case” blunder, a sudden 30-degree turn towards the other approach. The blundering aircraft is assumed to not respond to controller intervention. Because surveillance and navigational errors increase with distance from the radar and or localizer antennas respectively, it was assumed that the blunder occurred far from the airport, when the aircraft first lost altitude separation.

More recently, real-time simulations and mathematical analysis were employed to calculate the overall risk of a collision due to a blunder, sudden deviation from the planned approach. A blunder is an extremely rare event. Even though simultaneous parallel approaches have been conducted for more than forty years, the FAA has no official data on the causes, the frequency, or other characteristics of blunders. However, there was a decision that the ATC system needed to protect against a 30-degree non-responsive blunder: an aircraft that turns 30 degrees towards the other approach, whose pilot does not respond (or cannot respond) to commands to return to course.

Finding 2. Most current separation standards have been developed empirically based on judgment, extrapolation of past experience, and limited analysis. In recent years, a more analytical approach has been applied. The current standards are not based on a consistent philosophy, varying from one part of the airspace to another, using varied analytical approaches and assumptions about behavior.

Finding 3. Some separation standards are strongly influenced by the possibility of gross deviations, or blunders. However, little is known about the occurrence of such blunders: their frequency, their magnitude, under what circumstances they are most likely to occur. Existing information about blunders is primarily anecdotal.

3.8. Lessons Learned from Historical Record

There are many difficulties associated with deriving an absolute measure of risk. The U.K. Air Registration Board, in its deliberations in the 1950’s, was aware that the mathematical risk and collision risk analysis that it imposed had little or no value in offering guidance as to the absolute safety to be achieved. It was valuable in evaluating several

⁵ The MITRE Corporation, ca. 1973, *Reduction of the Separation Standard for Simultaneous ILS Approaches to Parallel Runways*, unpublished briefing.

⁶ Haines, A.L., January 1975, *Requirements for 3500 Foot Spacings for Simultaneous Parallel IFR Approaches*, MTR-6841, The MITRE Corporation, McLean VA.

⁷ Resalab, Inc. July 1972, *Lateral Separation*, FAA-RD-72-58, Volumes I & II.

alternatives as to their comparative safety value. Nonetheless, while applying it was difficult and easy to misuse in the wrong hands, the idea of Target Level of Safety (TLS) was, and still is, attractive.

Absolute measure of risk is difficult because most risks in aviation are extremely rare events. As a consequence,

- the probability of a risk event cannot be easily described by standard statistical distributions
- separate risks may not be completely independent, since a risk event may have an underlying cause that would affect the probability of a different risk event
- defining a meaningful TLS is difficult

Consideration of separation standards must of necessity make assumptions about the performance of people and systems. But while experts can use judgment about the validity and value of assumptions, mathematical models and processes need absolute values if a result is to be derived. Because there is frequently little data available to support assumptions about extremely rare events or new systems (e.g. aircraft deviation due to blunders on a final approach to parallel runways, or blunder deviation data in over-ocean operations), many assumptions are open to question and possibly invalid. It is therefore essential that analysts clearly state the assumptions that are used in their safety/risk analysis and state the basis of the assumptions.

There has been much debate about the uses and limitations of mathematical risk analysis and collision risk modeling. An important point is that the requirement to conduct such analysis imposes a discipline on designers and system evaluators. It requires that designs and procedures be critically examined in a structured way for potential failure paths. The value of such discipline in testing designs and procedures is far more important than the fact that the analysis methods and models may not be perfect.

The attempt to assess the safety of aircraft operations and innovative ATC procedures by depending primarily on analytical means is attractive and convenient and seems sound. But there are serious difficulties. The catastrophes that might be predicted by a simple probability analysis simply have not happened. Some of the reasons that simple analysis has proven to be overly conservative are:

- navigation error assumptions are conservative, even perhaps pessimistic
- obstacles and adjacent route boundaries in the past were frequently represented in computations as neat geometrical shapes such as "walls" or sloping surfaces when often they are single or discontinuous protuberances
- supplemental methods of navigation or other cross checks are used which can catch blunders or large deviations before they can cause harm
- radar observations often exist and affect the situation
- pilots recognize the existence of and take special care to give a wide berth to obstructions known to them
- simple representation of overlapping distribution curves for aircraft navigation implies that collisions will occur if one or both aircraft on adjacent air routes drift into the adjacent route area. This does not consider that aircraft on the routes are not flying in solid nose-to-tail streams: aircraft are spaced longitudinally as well as laterally.

The important conclusion is that while the simple probability computation has proven useful and valid in the combination of navigation system error elements, the relation of such errors to actual collision risk when other factors are also at work is not yet completely understood.

While drawing conclusions from *experience* in purely probabilistic terms may be difficult, reasonable people can, will, and have drawn valid inferences from such experience. Experience on a valid sample in a practical operational environment has been a useful guide to decision-makers.

As noted above, it has been a common practice to try to develop probability numbers to show the safety of systems and procedures in aviation. The British Air Registration Board was very cautious about the meaning of such numbers (10^{-7} as their 'acceptable' landing accident figure). FAA describes 10^{-7} as an "extremely remote" event, but recognizes the difficulty of attempting to prove such values.

Finding 4. Mathematical analyses require substantial data to accurately characterize reality. Historically, sufficient data has not been available. The result of insufficient data is overly conservative separation standards.

Section 4

Current State of the Art to Establish Separation Standards

Over the years, the FAA has established safe separations standards for many operations and has introduced new procedures to take advantage of new technology. The safety of these operations was established using analyses that have grown increasingly more detailed and sophisticated, also taking advantage of new technology for modeling and simulation. IFR Separation Standards are described in Appendix 5 along with the critical factor that sets the standard.

4.1. ICAO Guidance on Separation Standard Analysis

A good general discussion of the current understanding of separation minima may be found in ICAO Doc 9689-AN/953, *Manual on Airspace Planning Methodology for the Determination of Separation Minima*. Although this overview tends to emphasize oceanic operations in its examples, many of the principles are generally applicable.

ICAO sets forth a general process for developing a new separation standard or any revision to the air traffic system. The steps in this process are:

- Identify the need for change
- Describe the current system
- Determine the proposed system
- Identify method of safety assessment
- Evaluate risk
- Determine changes to the proposed system, if safety criteria are not satisfied, and re-evaluate
- Implement and monitor the new system

In addition, two general techniques for evaluating risk are presented:

- Comparison with a reference system
- Evaluation of system risk against a threshold

4.1.1. Comparison with a Reference System

The first technique provides a *relative* measure of risk. The proposed system is compared to a substantially similar system that has already been judged to be acceptably safe. In order to be “substantially similar” for this purpose, ICAO presents four criteria that ensure that the risk of the new system will be no worse than the existing system. Most significantly, “separation minima must not be less in the proposed system.”

This criterion would seem to eliminate the comparative technique from consideration for evaluating any possible reductions to separation standards. However, ICAO acknowledges the proposed system may not always be “sufficiently similar,” and allows for a trade-off between parameters, such as navigation performance and separation minima, in such cases. Nonetheless, this comparative process tends to produce overly conservative results.

4.1.2. Evaluation Against a Threshold

The second technique identified by ICAO produces an *absolute* measure of risk, by explicitly evaluating every relevant risk associated with the proposed system. Such an approach is required when the new system is radically different from any existing system.

Parts of the proposed system that are little changed from the existing system may be excluded from the evaluation of risk, under the assumption that the risk level has not changed. This is feasible if the target level of safety (TLS) to be achieved also does not consider the excluded part of the system.

4.2. Examples of Successful Separation Reductions

4.2.1. 2.5 Nautical Mile Separation on Final Approach

In the analysis of reduced longitudinal separation on final approach, various potential hazards were identified. However, it was determined that most of these hazards did not present an increased risk at 2.5 NM separation compared to 3.0 NM and the two procedures would be “substantially similar.” Thus, this separation reduction was achieved by general conformance with the first method set down by ICAO: comparison with a reference system. (A more detailed description of the reduction can be found in Section 3.6.)

4.2.2. Simultaneous Parallel Approaches using a Precision Runway Monitor (PRM) Surveillance System

The approach used to develop runway spacing requirements for simultaneous parallel approaches using a PRM surveillance system followed the second ICAO method: evaluation of system risk against a threshold. Real-time simulations and mathematical analysis based on field measurements were employed to calculate the overall risk of a collision due to a sudden deviation from the planned approach, commonly referred to as a *blunder*.

PRM and the Final Monitor Aid, used in Denver, are designed to prevent a collision when one aircraft deviates into the adjacent approach path, an event termed a blunder. PRM testing included both 15-degree and 30-degree blunders initially, but it was quickly determined that the 15-degree blunder could consistently be resolved successfully. The overall risk analysis therefore focused on the 30-degree blunder, which might occur at various points along the final approach path.

The PRM was assessed using three methods, now believed to be essential for future initiatives that propose separation reductions. The three methods were:

- Mathematical analyses, based on field data, to estimate how well PRM would prevent a collision due to a rare deviation from the approach course
- Simulations that included real-time cockpit simulators to understand pilot responses, and focused on discovering unanticipated procedural or training issues.
- Field demonstration flights for airline pilots and controllers.

These are further described in Appendix 6.

ICAO and FAA have accepted closely spaced parallel approaches with the PRM as meeting the TLS. Extensive demonstrations and tests, consultations among the concerned parties, and sound judgments by operations experts finally led to reductions in the required spacing between parallel runways. The required spacing has now reached 3400 feet for parallel approaches, or 3000 feet if one of the approaches is offset by 2.5 degrees.

4.3. Introduction of Required Navigation Performance (RNP) operations

The current effort to integrate Required Navigation Performance (RNP) operations into busy terminal areas illustrates how the Comparison to a Reference Method, when applied to new technology, does not take advantage of the new capability. A full description can be found in Appendix 7, ILS/RNP Separation Standard.

4.4. FAA Safety Risk Management Process

The Safety Risk Management (SRM) process is part of the Safety Management System (SMS) being implemented by the FAA. SRM parallels the ICAO steps for evaluating risk. At the highest level, the SRM process consists of five steps:

- **Describe System:** including scope and objectives, stakeholders, and the risk evaluation criteria

- **Identify Hazards:** a structured review of the system to produce an understanding of everything that might go wrong
- **Analyze Risk:** estimate the frequency and consequences of the hazards, and the overall risk of the system, together with ways to control the risks
- **Assess Risk:** review the hazards and identify those that can or should be addressed
- **Treat Risk:** including risk treatment plans and monitoring of the system after implementation

As part of the SMS, an SRM analysis is required for any reduction in separations, and must be recorded in a Safety Risk Management Document (SRMD). The explicit consideration of risks and hazards in the SRM process has not always been quite as prominent in previous changes to the separation standards. Nevertheless, the FAA has attempted to manage the risk associated with new or revised procedures through careful analyses, demonstrations, and reviews, as in the PRM program summarized above.

Finding 5. New separation standards may be developed by comparison with a reference system or by evaluating system risk against a threshold level. Comparing to a reference system is an appropriate method to support incremental changes to the current system. To evaluate the major changes in separation standards that will be required for the Next Generation Air Traffic System (NGATS), the evaluation against a threshold methodology may be necessary.

A disciplined process for identifying and analyzing risk when developing or revising separation standards is of vital importance. Analytical and probabilistic studies are essential to the determination of safe standards, but, by themselves, are not enough. They should be used together with judgment. Their role is to inform and quantify judgment. Guarding against unrealistic or diabolical phenomena should not be a basis for the establishment of separation standards.

Section 5

Discussion

This section contains discussions of relevant topics. The individual topics, though disparate, are linked by their applicability to the problem at hand: reduction of separation standards.

5.1. Influence of New Technologies on Separation Standards

Separation standards are influenced by a number of factors, including the accuracy of the navigation system in use, the ability of the aircraft to adhere to the desired course, the ability of the air traffic service provider to monitor the aircraft's adherence to its intended track, and the ability of the air traffic service provider to intervene if a hazardous situation is developing.

Technological advances have provided improved capabilities in all of these areas.

Electronic navigation systems have evolved from low frequency ranges to VOR/DME augmented with Inertial Reference Units, and most recently to GPS-based satellite navigation. Instead of the miles or fractions of a mile accuracy of VOR/DME positioning, flight paths can now be defined with an accuracy of a few feet, or at most a few 10's of feet, i.e. within the dimensions of most aircraft. In addition, GPS signals provide essentially perfect time information to each user. Additionally aircraft alerting tells the pilot when the navigation or total system error has exceeded the Required Navigation Performance (RNP).

The real power of RNP is its independence from an extensive ground-based infrastructure and the fact that its performance distributions are not Gaussian. For example, the monitoring and alerting capability that is required in all RNP systems truncate the distribution at the 10^{-5} level, which means that the crew has high confidence that the error is less than $1 * RNP$ when the system is operating normally. The crew also knows when the performance is inadequate, and at that time, can apply the appropriate operational procedures, thereby truncating the distribution at that level.

Electronic flight management systems currently allow the pilot to program in and adhere very closely to the intended course. In the future, the intended course could be transmitted to the air traffic service provider so that there is no uncertainty as to the aircraft's intent. Not only does the FMS enable closer adherence to the specified flight track, including time along track, but a data link could transmit the selected flight track to the controller, confirming the aircraft's intent.

The ability of the controller to maintain track of the aircraft position has evolved from voice position reports to high-precision monopulse radars. The implementation of ADS-B will further enhance the surveillance capability, providing the controller with more precise aircraft position information, and other aircraft state parameters. In addition, other suitably equipped aircraft will be able to receive the ADS-B reports, giving them knowledge of the position and intent of the other ADS-B-equipped aircraft.

Using the more precise monitoring of aircraft position and intent afforded by ADS-B and enhanced automation aids; the controller will be able to more rapidly sense and react to deviations of an aircraft from its intended flight path. Eventually the ground-based computer will itself be able to take over the task of resolving routine separation issues. In addition, ADS-B will allow other aircraft to also monitor aircraft positions and deviations from intent, and so participate in the separation process.

Fundamental to these capabilities is reliable digital communication between aircraft and between aircraft and the ground-based control system. The limited data link capability inherent in ADS-B will be augmented with a general-

purpose link to provide connectivity between the computers on board the aircraft (especially the FMS) and the ground-based automation system.

The combination of these enhanced capabilities will allow aircraft to be routinely spaced more closely than they have in the past, because their flight paths can be more precisely defined and adhered to, and the control system will more quickly be able to sense and respond to deviations.

Finding 6. New technologies (e.g. GPS, ADS-B, CDTI, Datalink) offer the potential for reducing required separations. In particular, GPS-based RNP, together with the concept of containment, provides much more precise control and knowledge of an aircraft's intended trajectory, and ADS-B permits the pilot of other aircraft, as well as the air traffic controller, to monitor the flight path of a proximate aircraft and rapidly sense deviations from its intended path.

5.2. Potential Impact of Automation

It is generally agreed that humans will have a significant role in managing traffic within NGATS. This role will, however, be fundamentally different than in today's system. The human controller function will shift from tactical separation of aircraft to strategic management of traffic flows. "Overall objectives for increased capacity, safety, predictability and efficiency are met through two primary transformations: implementation of trajectory-based operations in concert with application of performance-based services" (page 2-1, NGATS CONOPS, V-0.2, July, 2006). "The NGATS capitalizes on human and automation capabilities to increase airspace capacity, improve aviation safety, and enhance operational efficiency. This is based on building processes and systems that support humans in doing what they do best—choosing alternatives and making decisions, while automation accomplishes what it can do best—the acquisition, compilation, monitoring, evaluation, and exchange of information. Research and analysis will determine the appropriate functional allocation of tasks between Air Navigation Service Provider (ANSP), Flight Operators, and automation. It will determine when decision support tools are necessary to support humans (e.g., identify conflicts and recommend solutions for pilot approval) and when functions should be completely automated without human intervention." (page 1-9, NGATS CONOPS, V-0.2, July, 2006).

NGATS will be a 4D trajectory-based system with a Trajectory Agreement between the aircraft operator and the ANSP. The trajectory is defined with only the level of specificity necessary to meet the performance requirements of the proposed operation. A "flexibility volume is assigned by" the ANSP "represents the extent to which an aircraft is authorized to deviate from the assigned path laterally, vertically, and in time. The flexibility volume defines the operator's flexibility to maneuver without negotiating a new Trajectory Agreement, and is assigned based on the density and complexity of traffic in the volume of airspace plus the operations being performed by the aircraft." (page 2-8, NGATS CONOPS, V-0.2, July, 2006).

"Performance-based services align ATM assets with user demand. New kinds of flight operations such as autonomous operations in which aircraft manage their own tactical separation from each other, and ANSP flow operations in which precise execution of agreed trajectories permit much higher traffic throughput than is possible today dramatically improve en-route productivity and capacity. Even with two to three times today's traffic, trajectory-based operations enables control of the number and complexity of conflicts, ensuring safe separation can always be maintained, whether separation assurance is the responsibility of the ANSP or the flight crew. Conflict detection and resolution, both airborne and ground-based, is highly automated, allowing for reduced and encounter-specific separation standards." (page 2-2, , NGATS CONOPS, V-0.2, July, 2006).

Clearly, there will be instances when things go wrong, when equipment or software fails on the ground, in the aircraft, or in space. In the current ATC system, human intervention to resolve problems happens quite naturally because the system relies on air traffic controllers who maintain a continuous internalized understanding of the airspace situation. When something goes amiss, they can intervene quickly based on that understanding. In NGATS, such a backup mechanism for providing separation assurance will no longer be possible since the controller no longer has a picture of all aircraft in his or her head. Also, since airspace is less structured in NGATS,

it may be more difficult for humans to intervene during malfunctions than in a more structured system. As research begins to identify roles and responsibilities for humans and for automation in NGATS, the research will also have to identify what potential failures might occur and how people and machines work together to deal safely with failures. If appropriate recovery mechanisms cannot be shown to be safe and effective, proposed roles and responsibilities during normal operation will have to be redefined.

Any proposed IFR separation standard in the NGATS environment must provide a safe distance between aircraft during normal operations, when automation, pilots, and controllers are exercising due care and diligence. The separation standard must also provide a margin of safety in the event of failures by providing enough time for some automated system to sense and successfully resolve the situation.

Finding 7. The next generation air transportation system will have:

- **new roles and responsibilities for pilots and controllers and the automation that supports them,**
- **increased shared situational awareness on board the aircraft that will provide more timely and accurate information including intent of nearby vehicles,**
- **the potential, through good system design, for fewer unexpected deviations, and**
- **new backup systems to deal with system/subsystem failures, possibly accepting lesser performance capability than the system being backed up.**

As surveillance, navigation, and communication performance increases, including communication of intent, separation standards will be driven more by failure analysis rather than system performance.

5.3. TCAS and other alerting system implications

The Traffic Alert and Collision Avoidance System (TCAS) is designed to reduce the risk of mid air collisions by sensing when aircraft are likely to violate existing separation standards and providing flight crews with situational awareness and, where necessary, vertical maneuver advisories. It is also an independent backup for any failure of the ATC system to ensure safe separation.

The TCAS threat logic operates using only surveillance data, e.g., the range to and altitude of other aircraft, and its own altitude to achieve a balance between maintaining separation while minimizing nuisance alarms. It does not have access to intent, nor air traffic control procedures. It also uses azimuth estimates for displaying traffic advisories.

As new procedures, involving further reductions in separation are implemented, TCAS will produce more unnecessary or nuisance alerts if left in the Resolution Advisory (RA) mode. Further, there will be an increased chance that the multi-aircraft logic within TCAS will be exercised as well, causing additional false or nuisance advisories.

In order to insure that TCAS does not become such a nuisance that flight crews ignore it, the use of TCAS and the design of its threat logic must be examined with respect to each new procedure that reduces aircraft separation. It is also recommended that new procedures be reviewed to insure they do not needlessly provoke TCAS RAs.

In addition to TCAS, Terrain Awareness and Warning Systems (TAWS), Minimum Safe Altitude Warning (MSAW), and Conflict Alert (CA) function, should be initiated to minimize false alerts as separation standards are reduced and revised.

Finding 8. In designing NGATS, an air-based independent (from ATM system) backup collision avoidance system (similar to TCAS or perhaps a modified TCAS) will be required.

Back-up safety systems in the aircraft and air traffic control facilities have been set to prevent collision while minimizing false alerts when aircraft are operating at today's separation standards. As separation standards are reduced, procedures and alerting logic must be reexamined to optimize the balance between collision avoidance and false alerts.

5.4. Stochastic Separation Standards

Currently controllers are held to a set of minimum landing separations. If the controller's action results in a separation that is less than the stated minimum, this is considered to be a violation. This encourages the controllers to work at an average separation larger than the minimum to ensure that natural variations will not produce a violation. A stochastic approach would hold the arrival controller to a distribution of arrival separations (during a shift or a push, say) that had an appropriate mean and standard deviation. If the actual means are too small or the deviations too large, then the controller would be faulted. The threshold mean and standard deviation are chosen to achieve the required level of safety.

Research into the use of stochastic control in terminal operations (specifically landing spacing) has shown a capacity benefit (i.e. the controllers can give up the "cushion" that protects them from a violation), but there is still the question of practicality. What unintended consequences are likely to emerge? This is an interesting area for research not only because it offers the prospect of some near term improvement in landing rates, but also because stochastic control is more appropriate than deterministic control in automated systems such as NGATS.

There is anecdotal evidence that the stochastic approach is in informal use at some heavily utilized airports.

Finding 9. Evaluating the controllers' performance by distribution (stochastic control) rather than a hard limit could increase capacity and effective throughput without compromising safety.

5.5. Wake Vortex

Interest in potential capacity gains from Wake Vortex research has increased in recent years, as traffic congestion has increased. Although current standards have proven to be safe it is thought that these separation distances may be over-conservative and thereby unnecessarily reduce capacity. There is not, at this time, an acceptable way to mitigate wake-vortex constraints and obtain the desired increases in airport capacity.

There are at least four approaches being considered for increasing capacity while mitigating the vortex encounter risk.

One approach for closely spaced parallel runways relies on wake observations to build a solid statistical basis to validate the assertion that vortices do not travel from one runway to the other under any operational wind conditions. This approach is being pursued for St. Louis now, for Cleveland in the near future, possibly followed by a national rule change.

A second approach is to determine safe distances for an aircraft to trail behind a leading aircraft as a function of wind conditions. This approach can be applied to single runway or multiple runway operations.

Another approach being considered for approaches to parallel runways is to apply a stagger between the aircraft so that the trailing aircraft on the adjacent approach stays in front of the leading aircraft's vortices.

A fourth approach considers static reductions of wake separation under the premise that there is some agreed-upon wake severity that would allow harvesting of potential capacity with better knowledge of wake vortex/aircraft encounter behavior.

NASA, working with the FAA, has a research program to enable an increase in NAS capacity through novel concepts for wake vortex constrained terminal area operations. The project is following a three-phase approach.

1. Procedural Approach

The first phase determines the feasibility of reducing current standards under certain conditions. The objective is to safely increase capacity without the need for infrastructure changes. The FAA is leading the procedural changes while NASA is responsible for providing data and data analysis to validate that the proposed procedures do not lead to an unacceptable risk of a vortex encounter.

2. Wake Transport Approach

The second phase addresses the feasibility of safely increasing capacity by accounting for knowledge of the winds and the effect that winds have on moving a vortex out of the path of a trailing aircraft for single runway operations, or, ensuring the vortices can not move into the path of a trailing aircraft on a parallel runway. This is a joint activity between FAA and NASA.

3. Application of Advanced Technologies

The third phase will examine the application of new technologies to provide improved awareness of the presence of vortices and methods for mitigation of vortex encounters thereby reducing the risk of a vortex encounter while attaining a substantial increase in capacity. The third phase is being led by NASA but followed by the FAA. Technologies being considered include improved wake vortex prediction algorithms, wind persistence and prediction algorithms, wake vortex detection technologies, and weather measurement and forecasting technologies. The third phase will also address integration of ground and airborne systems for dynamic spacing, the development of flight deck visualization systems, and wake mitigation technologies. Safety analysis will be included throughout the effort.

Although the community generally supports the current program, the importance of this work for separation reductions requires that it be periodically reviewed for technical content, progress and support from NASA and the FAA.

Finding 10. In considering the possibilities for reducing separations standards, wake turbulence becomes the driving consideration. For NGATS, wake turbulence could become the primary limiter of capacity.

Section 6

Findings⁸ and Recommendations⁹

Finding 1. The current system, based on the separation standards that have evolved over the last 50 years, is safe, but still unable to meet projected demand. The separation standards (and the approach to establishing separation standards) now need to be reconsidered in order to meet the demand for increased capacity.

Finding 2. Most current separation standards have been developed empirically based on judgment, extrapolation of past experience, and limited analysis. In recent years, a more analytical approach has been applied. The current standards are not based on a consistent philosophy, varying from one part of the airspace to another; using varied analytical approaches and assumptions about behavior.

Finding 3. Some separation standards are strongly influenced by the possibility of gross deviations, or blunders. However, little is known about such blunders: their frequency of occurrence, their magnitude, under what circumstances they are most likely to occur. Existing information about blunders is primarily anecdotal.

Finding 4. Mathematical analyses require substantial data to accurately characterize reality. Historically, sufficient data has not been available. The result of insufficient data is overly conservative separation standards.

Finding 5. New separation standards may be developed by comparison with a reference system or by evaluating system risk against a threshold level. Comparing to a reference system is an appropriate method to support incremental changes to the current system. To

⁸Findings 1 through 5 all deal with the historic establishment of separation standards, and the limitations of some of the methodology used. They are treated together in this section in order to establish a consistent set of recommendations.

⁹ Recommendations are presented in two time frames, Immediate and Longer Term. The Immediate recommendations are those that should or can be undertaken immediately. Some of them could increase efficiency, if applied, in the current National Airspace Space system. Longer Term recommendations are must be preceded by other work or do not apply to today's system.

evaluate the major changes in separation standards that will be required for the Next Generation Air Traffic System (NGATS), the evaluation against a threshold methodology may be necessary.

A disciplined process for identifying and analyzing risk when developing or revising separation standards is of vital importance. Analytical and probabilistic studies are essential in the determination of safe standards, but, by themselves, are not enough. They should be used together with judgment. Their role is to inform and quantify judgment. Guarding against unrealistic or diabolical phenomena should not be a basis for the establishment of separation standards.

Recommendation:

Establish an R&D program that will lead to consistent and safe reduction of separation standards and that will support NGATS. The process outlined below for setting separation standards should be adopted. This R&D program should include, but not be limited to:

- **Immediate**
 - Establish a research program to develop an understanding of the nature and frequency of blunders.
 - Performance Data Analysis & Reporting System (PDARS) appears to be a possible source for needed data.
 - Develop new systems, if needed, for automated reporting of such anomalies.
 - Establish data needs for establishment of separation standards early in NGATS development so opportunities, such as demonstrations, can be used collect data.
 - If conservative separation standards are put in place, such as RNP Parallel Approach Transition (RPAT), establish a data collection process early in the implementation so operational data collected to reduce separations in the future.
- **Longer Term**
 - Conduct research to develop consistent approaches for the development of separation standards with all assumptions stated concisely.
 - Conduct research to improve the methodology for evaluating separation standards against an absolute threshold (target level of safety). In particular, there needs to be a consistent, credible way to take into account the response of humans to rare events.

Process for Separation Standard Reduction

The PRM program was only one example of the successful implementation of a new ATC procedure through a process of careful analysis and testing. Based on this experience, the following general process should be the guideline for evaluating and implementing future separation reductions. An evaluation of the overall system risk is necessary when the proposed system is much different from the current system – as is frequently the case when new technologies are introduced.

Mathematical Analysis. Such analyses may be simple at first, considering only the most common scenarios for the proposed procedure. Based on actual data wherever possible, such analyses could help to refine the procedure and identify scenarios wherein the proposed procedure would not produce satisfactory performance (a collision being only one example of a negative outcome). More sophisticated analyses, such as Monte Carlo simulations, should be employed when well constructed models describing the performance of systems and humans, derived from field measurements, are available.

Real Time Simulations. The refined procedure should be given an operational evaluation through real-time, human-in-the-loop simulations that are as realistic as feasible. Mathematical analyses will have identified the

factors, which most affect the probability of unsatisfactory performance; these factors should be incorporated into the simulation with the highest degree of realism. In the process, it is likely that additional factors will be identified as potentially significant.

Performance data collected during the real-time simulations can be used to refine and extend the mathematical analyses. Also, insights obtained during the simulations provide important data for the later risk assessment of the procedure.

Field Demonstrations. Additional realism is provided by field demonstrations, clearly. But the expense involved necessitates that the procedure be thoroughly tested prior to the demonstration phase. Demonstrations can help to identify additional operational concerns, as well as help to validate the simulation results for a sample of conditions. Demonstrations are not a substitute for the simulations, but can provide confidence that the simulations provided valid results.

Risk Assessment. The FAA SRM process should form the basis for such assessments. The results of the analyses, simulations, and demonstrations should inform the risk assessment process. All assumptions that are part of a system risk assessment should be stated, all assumptions should be accepted by consensus, and the sensitivity of the results to the assumptions should be evaluated. Here the different risk elements and their consequences are evaluated and a determination is made whether or not to proceed with development or implementation of the procedure. The risk assessment should be transparent and involve a range of users and operators.

Evaluation against a threshold or application of the target level of safety poses tough problems, but it is based on a solid premise: that any new design, whether it is an engine, flight control system, or wing structure, must be at least as good or better than its predecessors. This is primarily due to the fact that most risks in aviation are due to extremely rare events.

Judgment and Experience. Judgment and experience will be needed to address rare, unpredictable events. Attempting to compensate for “diabolical” threats or similar anomalies in the system is impractical.

A “diabolical” threat in the context of maintaining separation between two aircraft is a threat in which one of the aircraft begins to maneuver in such a manner as to maximize the probability of collision. Designing a system that would detect such a maneuver in time to effect a successful evasion by the burdened aircraft is extremely demanding. The concept is not a practical basis for designing a separation maintenance system but it is a useful construct for thinking about the vulnerability of various approaches to separation assurance.

Structured Introduction. Finally, the new procedure should be introduced to general usage in a stepwise manner, with opportunities to observe actual operations, review performance, and make modifications (or halt the procedure) if necessary. For example, a new approach could be demonstrated in visual conditions, then allowed in lower and lower weather conditions until the intended minima are achieved. For another example, one airline could pioneer the new procedure at an airport, and then the procedure could be implemented at other airports or by other carriers.

Such a process of analysis, testing, observation, and modification requires an extended commitment of time and resources. However, it is a necessary investment that can pay off in operational benefits while maintaining safety.

Finding 6. The next generation air transportation system will have:

- **new roles and responsibilities for pilots and controllers and the automation that supports them,**
- **increased shared situational awareness on board the aircraft that will provide more timely and accurate information including intent of nearby vehicles,**
- **the potential, through good system design, for fewer unexpected deviations, and**
- **new backup systems to deal with system/subsystem failures, possibly accepting lesser performance capability than the system being backed up.**

As surveillance, navigation, and communication performance increases, including communication of intent, separation standards will be driven more by the need to accommodate system failures than by variations in nominal system performance.

Recommendations

- **Longer Term**
 - Establish a research program to develop an understanding of the roles of the human and automation in dealing with failures and the implication of those roles on separation standards.
 - Managing failure gracefully is perhaps the most difficult design aspect of the NGATS. Specific and intense research into the human and automated alternatives will be required.

Finding 7. New technologies (e.g. GPS, ADS-B, CDTI, Datalink) offer the potential for reducing required separations. In particular, GPS-based RNP, together with the concept of containment, provides much more precise control and knowledge of an aircraft's intended trajectory, and ADS-B permits the pilot of other aircraft, as well as the air traffic controller, to monitor the flight path of a proximate aircraft and rapidly sense deviations from its intended path.

Recommendations

- **Immediate**
 - As more and more aircraft use RNP-based navigation, monitor their performance, and gather and analyze data to develop a statistical understanding of the performance of RNP-based systems in various flight regimes.
 - Re-examine the design of parallel and converging approaches and departures based on an appropriate probability distributions (may not be Gaussian) or on data gathered using RNP-based navigation.
 - The Performance-Based Advisory Rulemaking Committee (PARC) should redefine the definition of "established on approach" to include LNAV and VNAV. The requirement to be aligned with the runway centerline should be studied for possible elimination.
 - Research into potential reduction of Arrival/Departure and Departure/Departure separations due to RNP guided missed approaches and departures should be pursued.
- **Longer term**
 - Develop (recommendations for) new separations standards based on the improved navigation, surveillance, communication, control, and automation technologies, which will be part of NGATS. Utilize lessons learned during the analysis of other standards.
 - When the nature and frequency of blunders off an ILS course are better understood using data ILS/RNP parallel runway separation should be reevaluated. RNP/RNP parallel approach separation should be established.
 - The No-Transgression Zone (NTZ) role for ILS operations should be re-defined based on real blunder information. Then, if still required, appropriate dimensions and shapes should be established.
 - The role of the NTZ in RNP/RNP separations should be established. The NTZ may not be needed.

Finding 8. In designing NGATS, an air-based independent (from ATM system) backup collision avoidance system (similar to TCAS or perhaps a modified TCAS) will be required.

Back-up safety systems in the aircraft and air traffic control facilities have been set to prevent collision while minimizing false alerts when aircraft are operating at today's separation standards. As separation standards are reduced, procedures and alerting logic must be reexamined to optimize the balance between collision avoidance and false alerts.

Recommendations

- **Longer Term**
 - Research is required for the future independent airborne collision avoidance system in the context of the ATM system construct and the associated separation standards.
 - Research and analysis of alerting systems, such as Traffic Alert and Collision Avoidance System (TCAS), Terrain Awareness and Warning Systems (TAWS), Minimum Safe Altitude Warning (MSAW), and Conflict Alert (CA) function, should be initiated to minimize false alerts as separation standards are reduced and revised.

Finding 9. Evaluating the controllers' performance by distribution (stochastic control) rather than a hard limit may be able to increase capacity and effective throughput without compromising safety.

Recommendation

Immediate

Research into the practicality of stochastic control in terminal operations (specifically landing spacing) should be initiated. Research should pursue the question of practicality and unintended consequences. This is an important area for research because it offers the prospect of some near term improvement in landing rates, and because stochastic control is more appropriate than deterministic control in automated systems such as NGATS.

Finding 10. In considering the possibilities for reducing separations standards, wake turbulence becomes the driving consideration. For NGATS, wake turbulence could become the primary limiter of capacity.

Recommendations

- **Immediate**
 - Full support of existing research and implement program should continue.
 - Commission a team to conduct in-depth annual technical and programmatic reviews of the wake research and implementation program. The reviews should include the objectives, technical approach, schedule, and funding. The team should be composed of external experts knowledgeable in the areas of wake vortices in normal operating configurations, advanced Light Detection and Ranging (LIDAR) and other sensors that may be useable in detecting the strength of a wake vortex, aircraft behavior in the presence of wakes, and how this information can be used in the flight deck and air traffic facilities. This team should be structured along the lines of the Department of Defense Science Board and report to ATO leadership.
- **Longer Term**
 - Investigate advanced instrumentation such as LIDAR or other sensing methods to obtain direct measurements of vortex strength.

- Investigate the feasibility and practicality of wake vortex sensing/tracking to provide the flight crew an indication of encroaching wake vortex location, strength and upset risk.

Appendix 1

SWAG Members

- Sarah Dalton- Chair-Alaska Airlines
- Jim White -DFO - FAA
- Gloria Dunderman -Administration -FAA
- Bill Swedish - MITRE
- Dallas Denery - UCSC
- Dres Zellweger - JPDO
- Glenn Morse – Continental Airlines
- Jim Duke - ALPA
- John Fielding-Consultant/Raytheon
- Mark Cato - ALPA
- Michael Perie - Consultant
- Paul Drouilhet – Lincoln Labs
- Ray LaFrey-Consultant
- Siegbert Poritzky- Consultant

Appendix 2

Terms of Reference

FAA's Research, Engineering and Development Advisory Committee

Separation Standards Working Group

Established August 2005

- Establishing appropriate separation standards is an important element of achieving increased NAS capacity and flexibility, especially in terminal airspace. Two principal elements of required interaircraft separation, navigation accuracy and surveillance capability, have improved markedly since the current separation standards were established. It is important to understand how these improvements, plus other technology advances, can lead to adjustment in required interaircraft separation without any degradation of safety.
- The Working Group will examine the basis for current separation standards, and review past and ongoing studies of separation requirements. It will consider improved methodologies for establishing separation standards, and will outline a recommendation R&D program for the FAA to determine to what degree separation standards can be reduced using current and future technologies.

Appendix 3

Summary of Presentations and list of presenters

PRESENTATION LIST

DATE	PRESENTER	TITLE
10/18/2005	Brian Colamosca, FAA	The Reduced Vertical Separation Minimum (RVSM): Implementation Criteria
10/18/2005	John Andrews, MIT/LL	Validation of New Separation Standards: <ul style="list-style-type: none"> • Closely Spaced Parallel Runways • General Horizontal Separation Standards General Horizontal Separation Standards: Validation Issues
10/19/2005	Bill Swedish, MITRE	A Brief History of Separation Standards
10/19/2005	Dr. Andrew Zeitlin, MITRE	TCAS and Separation
10/19/2005	Suzanne Porter, MITRE	RNAV and RNP Track Spacing: Opportunities for Benefit
10/19/2005	S. R. Jones, MITRE	Determination of Requirements for ADS-B Separation Requirements
10/19/2005	Randy Bone, MITRE	Automatic Dependent Surveillance Broadcast (ADS-B) Applications Review ATO DRAFT ADS-B Separation Standards (3 NM Separation - Terminal Area) prepared by John Marksteiner, FAA
11/15/2005	Russ Paielli, NASA	Tactical Separation-Assisted Flight Environment (TSAFE)
11/16/2005	Steve Fulton, NAVERUS	Informal talk on position performance
11/16/2005	Tom Imrich, Boeing	Required Navigation Performance <i>Briefing not available</i>
1/10/2006	Sherry Borener, FAA	NGATS <i>Briefing not available</i>
1/10/2006	Don Pate, FAA	TERPS – Using Performance Modeling to Set Standards
1/10/2006	Steve Barnes	System Management System (SMS) – <i>briefings not available</i>
1/10/2006	David Lankford, FAA	History of Blunder Resolution

1/10/2006	Wayne Bryant, NASA	Joint FAA/NASA Wake Vortex
1/10/2006	Steve Lang, FAA	Research Program
1/10/2006	George Donohue George Mason University	Aircraft Separation Standards
1/11/2006	Irv Statler, NASA	Aviation System Monitoring and Modeling (ASMM) Project
1/11/2006	David Holl, ATAC Corp	Applications of the Performance Data Analysis & Reporting System to Separation Standards Development
1/11/2006	Kevin Corker, San Jose State University	Application of Human Performance Modeling to Separation Standards Developments and Hazard Assessment
1/11/2006	Steve Bradford, FAA	Required Surveillance Performance to Support 3-Mile Separation in the National Airspace System <i>Briefing not available</i>
1/11/2006	Dr. James Yates, ISI	Target Level of Safety (TLS)

Appendix 4

Current MITRE Research Related to Separation Standards

RNP/RNAV Track Spacing

POC: Walt Scales, wcales@mitre.org

MITRE CAASD is working with the FAA to develop the operating procedures and standards needed for RNP-2 and RNP-1 en route and terminal applications.

The current lateral separation criterion for en route RNAV routes (Q routes with radar separation) is 8 NM track-to-track. Even wider Q-route spacings have been applied in the Gulf of Mexico. The thrust of the current effort is to explore methods for reducing parallel route separations for Q-Routes, T-Routes, RNAV SIDs and RNAV STARs. Spacing reductions could potentially be based on RNP containment, on radar separation, or on combinations of the two (e.g., using RNAV and/or RNP to limit controller intervention rates while using radar for separation assurance).

Requirements for Simultaneous Parallel Approaches

POC: Vince Massimini, svm@mitre.org

MITRE CAASD is reviewing the major assumptions and analytical techniques used during previous simultaneous approach studies, and will provide the FAA an assessment of which ones potentially could be modified in light of new technology, procedures, testing or data availability. CAASD will also provide recommendations for data analysis, analytical techniques, and testing that could be accomplished to provide a basis for modifying current simultaneous approach standards.

As one specific example, CAASD will provide an analysis of the feasibility of substituting RNAV vertically-guided approaches (i.e., GLS, LPV, LNAV/VNAV and RNP) for ILS and MLS approaches during the conduct of simultaneous, dependent, SOIA, and RPAT approaches.

ADS-B Separation Standard

POC: Stan Jones, sjones@mitre.org

ADS-B provides an alternative to radar for aircraft surveillance. A single ADS-B position report is potentially more accurate than a radar-based position, depending on the radar type and location. The minimum aircraft separation based on ADS-B will be affected by this accuracy as well as by other characteristics of ADS-B such as the update rate, asynchronous updates, and the possibility of a GPS integrity failure.

MITRE has used the ICAO Close Approach Probability (CAP) model to evaluate proposed 3 NM and 5 NM separation standards when using ADS-B for surveillance. A separation less than the separation standard may result if one aircraft turns towards the other during the asynchronous reception time, or if there is an undetected GPS fault. The proposed standards would be acceptable if the minimum distance between aircraft for the ADS-B system was no greater than that of the SSR reference system at the same CAP risk level.

The analysis provided performance requirements for the ADS-B system that would allow use of the 3 NM and 5 NM separation standards. These requirements are likely to be met by an operational system. The CAP approach, combined with automated conflict detection for the controller, may support reduced separation standards in the future.

ADS-B Applications

POC: Randy Bone, bone@mitre.org

MITRE is working with the FAA to develop concepts and requirements for new advanced ADS-B applications that will improve overall operations, e.g., safety (improved traffic awareness), capacity, and efficiency. Such applications include Cockpit Display of Traffic Information (CDTI) Assisted Visual Separation (CAVS) and parallel approaches to closely spaced runways.

CAVS is intended to improve pilot traffic awareness during visual approaches in marginal visibility conditions. The pilot will use the CDTI to assist visual acquisition of other traffic, and then maintain separation using the CDTI even if visual contact is lost due to low clouds or haze. United Parcel Service (UPS) has formally requested operational approval for the use of CAVS. MITRE CAASD has been the lead in analyzing the technical and operational issues required for certification and operational approval, through concept development and real-time simulations.

Oceanic Separation Reductions

POC: Cathy Horton, chorton@mitre.org

As part of the continuing transition toward more stringent RNP operations, MITRE/CAASD has been working with the FAA to reduce horizontal separations in the Pacific. In FY05, MITRE CAASD developed the Safety Case Hazard Analysis for applying 30 NM lateral separation and 30 NM longitudinal separation (30/30) in the South Pacific. CAASD also collaborated with the FAA and industry to develop the 30/30 procedures. The implementation of these reduced separations for aircraft capable of this more stringent RNP capability, as well as other CNS elements is part of a worldwide ICAO coordinated effort. Such reduced separations provide more efficient use of airspace, more optimum wind efficient routings, accommodation of increased traffic, and greater flexibility.

Wake Turbulence Separation

POC: Jeff Tittsworth, allen@mitre.org

MITRE CAASD has been working with the FAA and NASA to reduce the separation requirements for alternating arrivals to runways spaced less than 2500 ft apart. Under current ATC procedures, consecutive arrivals to these runways are given full radar or wake vortex separation even if they are approaching different runways. An upcoming demonstration project at St. Louis Lambert Field (STL) will allow a smaller separation (1.5 NM) where the lead aircraft does not present a wake vortex hazard for the trailing aircraft. In FY05, CAASD evaluated the implementation risk of such a procedure and developed a prototype of a wake turbulence visualization tool for controller use. This year, CAASD will prepare the hazard analysis and benefits assessment for an enhanced procedure, where separations between departures are reduced when wind conditions deflect the vortex away from the path of the next departure.

Separation Standards Analysis

POC: Bill Swedish, swedish@mitre.org

This research project will investigate current separation standards and their basis, and attempt to develop a consistent analytical framework for developing new standards. Safety analysis (per Safety Management System requirements) is an integral part of this investigation. The analytical framework is intended to enable the FAA to analyze the effect of new technologies (e.g., ADS-B, GPS), new procedures (e.g., RNP), and new concepts (e.g., UAVs and very light jets) on operations. A comprehensive framework will support development of appropriate separation standards that expedite operations while maintaining or improving safety.

Current NASA Research Related to Separation Standards

Wake Vortex:

POC: Wayne Bryant, Wayne.H.Bryant@nasa.gov

Interest in potential capacity gains from Wake Vortex research has been of long term interest but has increased in recent years. Although current standards have proven to be safe it is recognized that these separation distances are often over-conservative and in some cases unnecessarily reduce capacity.

NASA working with the FAA has an active research program to enable an increase in terminal area capacity at an agreed upon level of safety for the National Airspace System through new standards for wake vortex operations. The project is following a three phase approach. The first phase is aimed at determining the feasibility of reducing current standards under certain conditions through the implementation of procedural changes. The objective is to safely increase capacity without the need for infrastructure changes. The FAA is leading the procedural changes while NASA is responsible for providing data and data analysis to validate that the proposed procedures do not lead to an unacceptable risk of a vortex encounter. The second phase is aimed at determining the feasibility of safely increasing capacity by accounting for knowledge of the winds and the affect that winds have on moving a vortex out of the path of a trailing airport. This is a joint activity between FAA and NASA. The third phase is aimed at the application of new technology to provide improved awareness of the presence of a vortex thereby removing the risk of a vortex encounter while attaining a substantial increase in capacity. The third phase is being led by NASA but followed by the FAA. Technologies being considered include improved wake vortex prediction algorithms, wind persistence and prediction algorithms, wake vortex detection technologies, and weather measurement and forecasting technologies. The third phase will also address integration of ground and airborne systems for dynamic spacing, the development of flight deck visualization systems, and wake mitigation technologies. Safety analysis will be included throughout the effort.

Aviation System Monitoring and Modeling Project:

POC: Irving Statler, Irving.C.Statler@nasa.gov

The Aviation System Monitoring and Modeling Project has not directly addressed the definition of separation standards but has included several activities that are relevant to this question.

One such activity is the Performance Data Analysis & Reporting System (PDARS) Project. The PDARS project collects, processes, and analyzes ATM operational data obtained from Center and TRACON radars. It is currently operational at all 20 Centers and 13 TRACONS. The project includes the collection, processing, and analysis of ATM operational data. It also includes tools to support explorative studies. The FAA has recently accepted full responsibility is continuing expansion of PDARS to include the 35 Operational Evaluation Plan (OEP) airports and associated TRACONS and the development of metrics for safety, capacity, and cost as a function of runway, airport, TRACON, and Center. PDARS could be a valuable source of information to gain insight into the nature and frequency of blunders and their impact on system safety in current operations.

Another activity that has direct relevance is the Modeling and Simulations Project. The Modeling and Simulations Project is aimed at the development of modeling tools that can be used to predict the system-wide impact and efficacy of interventions and the use of these models in simulation. It includes model interactions among multiple human and non-human agents (automation), use of these models to simulate scenarios for which there are no data or experience in order to identify systemic features conducive to human error. The methods appear to be extendable to the determination of the likelihood and hazard impact of off-nominal ("blunders") operations in human-system interactions.

Tactical Separation Assisted Flight Environment:

POC Russ Paielli; Russ.Paielli@nasa.gov

The Tactical Separation Assisted Flight Environment activity is a prototype system being developed by NASA for alerting air traffic controllers to imminent conflicts. Although this activity is directed towards assuring that current separation standards are not violated, the analysis has included the identification of the nature and cause of several “blunder” types that have led to operational errors. This analysis could be useful in defining the nature, frequency, and likelihood of hazardous operations. The work has focused on the En Route airspace.

Appendix 5

List of IFR Separation Standards

Table 1 is a listing of the IFR separation standards in the radar and Oceanic environments. These standards have been selected for this table because they have the greatest impact on the capacity of the NAS. The important characteristics of these separations are summarized in the table. A full description of the standards can be found in FAA Order 7110.65, Air Traffic Handbook (appropriate paragraphs indicated in the fourth column) and other FAA documents, as indicated.

The fifth column indicates the primary factor, or factors, affecting the separation standard.

Table 1: Critical IFR Separation Standards

Flight Phase	Separation Minima	Selected Requirements ¹	Reference ²	Controlling Factor
OCEANIC	LATERAL: 60-120 NM	Depends on speed and route (North Atlantic and Caribbean)	¶8-7-4 ¶8-8-4	Navigation accuracy, no radar
	or VERTICAL: 2000 ft	Above FL290 (non-RVSM)	¶8-7-2 ¶8-8-2	Altimetry accuracy
	1000 ft	Above FL290 (RVSM) or at or below FL290		
	or LONGITUDINAL: 10-60 minutes at track entry	Depends on speed and distance flown	¶8-3-3.e.	Navigation accuracy, no radar
EN ROUTE within the U.S.	LATERAL: 5 NM	Below FL 600, if multiple radar sensors (mosaic mode) radar or either aircraft more than 40 NM from antenna, and 60 NM for Mode S surveillance ³	¶5-5-4	Radar resolution and update rate

¹ For complete requirements, refer to FAA Order 7110.65 and other FAA documents.

² FAA Order 7110.65, unless otherwise indicated.

³ An FAA sponsored study determined that the increased accuracy of new Secondary Surveillance Radars permits increasing the range for 3 NM separation to at least 60 NM and FAA Order 7110.65R, Chapter 5, ¶5-5-4. MINIMA, has been changed accordingly.

Flight Phase	Separation Minima	Selected Requirements ¹	Reference ²	Controlling Factor
	3 NM	Below FL 180, if radar in single sensor mode and both aircraft within 40 NM of antenna, and 60 NM for Mode S surveillance ⁴		
EN ROUTE within the U.S. (continued)	or VERTICAL: 2000 ft	Above FL290 (non-RVSM)	¶4-5-1	Altimetry accuracy
	1000 ft	Above FL290 (RVSM) or at or below FL290		
SUCCESSIVE ARRIVALS – Same runway or parallel runways spaced <2500 ft apart	LONGITUDINAL: 3.0 NM	Radar in single sensor mode and both aircraft within 40 NM of the antenna, and 60 NM for Mode S surveillance ⁵	¶5-5-4	Radar resolution ⁶ and update rate
	2.5 NM	On final approach, if runway occupancy is 50 sec or less and no wake turbulence effect	¶5-5-4.g.	Runway occupancy time
	4/5/6 NM	Behind a Heavy aircraft or B757 (depends on trailing aircraft type)	¶5-5-4.f.	Wake turbulence
PARALLEL APPROACHES – Independent ILS approaches to dual runways	Simultaneous operations once established on final approach	Runways < 4300 ft apart ⁷	¶5-9-7	Blunder recovery Radar resolution ⁸ and update Localizer resolution
		Runways 3400-4300 ft apart ⁹	¶5-9-8	
		Runways 3000-3400 ft apart ¹⁰		

⁴ Ibid.

⁵ Ibid.

⁶ Current SSR range and azimuth accuracies, 1.1 mrad RMS and 60 ft RMS respectively, are not available because of limitations in the CD data formats.

⁷ Requires operational ASR radar system.

⁸ See footnote 5.

⁹ Requires high accuracy / high update rate system and Final Monitor Aid (high resolution display and alerting logic), i.e., Precision Runway Monitor system

¹⁰ Requires Precision Runway Monitor system and 2.5 degrees localizer offset.

Flight Phase	Separation Minima	Selected Requirements ¹	Reference ²	Controlling Factor
PARALLEL APPROACHES – Dependent ILS approaches to dual runways	2.0 NM diagonal between aircraft on adjacent runways	Runways < 4300 ft apart	¶5-9-6	Blunder recovery
	1.5 NM diagonal between aircraft on adjacent runways	Runways 2500-4300 ft apart		Wake turbulence is an issue below 2500 ft spacing
CONVERGING APPROACHES – Independent	Simultaneous operations once established on final approach	Missed Approach Points separated by 3.0 NM, and TERPS surfaces for turning missed approaches do not overlap (TERPS + 3 criteria)	FAA Order 7110.98	Simultaneous missed approaches
CONVERGING APPROACHES – Dependent	Alternating arrivals with specified separations based on runway geometry	Converging Runway Display Aid (CRDA)	FAA Order 7110.110A	Simultaneous missed approaches
SUCCESSIVE DEPARTURES – Same runway or parallels spaced <2500 ft apart	1.0 NM	Courses diverge by 15 degrees or more (not behind Heavy/B757)	¶5-8-3	Radar separation Wake turbulence
	2.0 NM increasing to 3.0 NM	Courses do not diverge	¶5-5-4	Radar separation
	Wake vortex separation - distance (see above) - time (2 minutes)	Behind a Heavy/B757	¶5-5-4 ¶3-9-6	Radar separation Wake turbulence
SIMULTANEOUS DEPARTURES – Parallel or non-intersecting runways	Simultaneous operations	Parallel runways separated by 2500 ft or more and courses that diverge by 15 degrees or more	¶5-8-3.c.	Radar separation Wake turbulence
		Non-intersecting runways that diverge 15 degrees or more	¶5-8-3.b.	
DEPARTURE	2.0 NM increasing to 3.0 NM	Within 40 NM of the antenna ¹¹	¶5-8-4	Radar separation

¹¹ See footnote 5.

Flight Phase	Separation Minima	Selected Requirements¹	Reference²	Controlling Factor
AND ARRIVAL – Same runway	2.0 NM increasing to 5.0 NM	Not within 40 NM of the antenna		Radar resolution and update rate
DEPARTURE AND ARRIVAL – Parallel or non-intersecting runways	Simultaneous operations	Thresholds are even ¹² Runway thresholds are at least 2500 ft apart Missed approach and departure courses diverge by at least 30 degrees Missed approach by a heavy jet can not overtake departing aircraft	¶5-8-5	Radar separation Wake turbulence

¹² Staggered thresholds increase or decrease the runway separation required.

Appendix 6

PRM for Simultaneous Parallel Approaches

The approach used to develop runway spacing requirements for simultaneous parallel approaches using a Precision Runway Monitor (PRM) surveillance system followed the second ICAO method: evaluation of system risk against a threshold. Real-time simulations and mathematical analysis based on field measurements were employed to calculate the overall risk of a collision due to a sudden deviation from the planned approach, commonly referred to as a *blunder*.

PRM and the Final Monitor Aid, used at Denver, are designed to prevent a collision when one aircraft deviates into the adjacent approach path, an event termed a blunder. Even though simultaneous parallel approaches have been conducted for more than forty years, the FAA has no official data on the causes, the frequency, or other characteristics of blunders. However, there was a decision by an industry committee that the ATC system needed to protect against a 30-degree non-responsive blunder: an aircraft that turns 30 degrees towards the other approach, whose pilot does not respond (or cannot respond) to commands to return to course.

PRM testing included both 15-degree and 30-degree blunders initially, but it was quickly determined that the 15-degree blunder could consistently be resolved successfully. The overall risk analysis therefore focused on the 30-degree blunder, which might occur at various points along the final approach path.

The PRM was assessed using three methods, now believed to be essential for future initiatives that propose separation reductions. The three methods are:

- Mathematical analyses, based on field data, to estimate how well PRM will prevent a collision due to a rare deviation from the approach course
- Simulations that include real-time cockpit simulators to understand pilot responses, and focus on discovering unanticipated procedural or training issues.
- Field demonstration flights for airline pilots and controllers.

ICAO and FAA have accepted closely spaced parallel approaches with the PRM as meeting the TLS. Extensive demonstrations and tests, consultations among the concerned parties, and sound judgments by operations experts finally led to reductions in the required spacing between parallel runways. The required spacing has now reached 3400 feet for parallel approaches, or 3000 feet if one of the approaches is offset by 2.5 degrees.

Mathematical Analysis of PRM Effectiveness

To estimate PRM effectiveness, the Monte Carlo method was used. This consisted of selecting a blunder scenario (10 NM final, 15 degree deviation for example), and creating a trial blunder situation using randomly selected conditions: initial aircraft positions, radar antenna position, monitor controller response, radio activity, and pilot and aircraft response. The resulting aircraft trajectories for each aircraft were then calculated and it was noted whether adequate separation was maintained; this process was repeated for one hundred thousand trials, and the results used to estimate the effectiveness of PRM in maintaining a 500-foot minimum separation. The Monte Carlo process was then repeated for other blunder scenarios.

To enable this analysis the following field data was collected:

- The response of twenty five pairs of FAA monitor controllers to blunder scenarios was collected at a Memphis Experimental Facility during a six month effort.¹ Additional data was collected at a second test facility at the Raleigh-Durham experimental facility. This work and the pilot response studies were designed and overseen by an experienced human factors scientist.
- The response of FAA and ALPA pilots to blunders and the breakout scenarios was collected using full motion B727, DC-10², B747³ and A320⁴ simulators.
- Final approach lateral deviations for 7000 approaches at Memphis were recorded and the Total System Navigation Error analyzed. This included coupled and non-coupled approaches.⁵
- The accuracy of a 2.4 second scan secondary surveillance radar (SSR) at the Memphis airport and a 1.0 second scan SSR at Raleigh-Durham airport.⁶
- Estimates of radio channel blockage statistics from VHF radio recordings at Memphis and Chicago O'Hare airports.

Simulations

Data was collected during real-time simulations at Raleigh Durham and the FAA Technical Center near Atlantic City, NJ. Controllers used prototypes of the PRM digital displays to monitor aircraft on final approach. Traffic was a combination of computer-generated targets and flight data from full-motion aircraft simulators being "flown" by airline pilots. Selected aircraft would blunder towards the other approach course, and the controllers would then act to return the blundering aircraft to its approach path and to turn the other aircraft out of harm's way

Data collection included how quickly the controller responded after the blunder began, how quickly the flight crew responded to the controller's instructions, and the minimum separation between the two simulated aircraft. Less than 500 feet horizontally or vertically was considered to be a collision.

During these tests it was discovered that pilots flying an MD80 had difficulty disabling the autoland, delaying their response. In other tests, pilots attempted to use the go-around mode, but switch to the autopilot heading mode. This delayed the start of the evasion maneuver. Since safety is enhanced by rapid response (the risk analysis assumed a hand-flown, standard rate evasion turn), this indicated the need to address flight technique and pilot training.

During the B727, B747 and A320 pilot response studies, pilot preferences on breakout phraseology, flight procedures, and training were solicited.

Field Demonstrations

Three hundred flight demonstrations were provided by fifty airline pilots at MEM and RDU. The airline pilots flew the FAA B727 (N40) and experienced staged blunders and breakout maneuvers in visual conditions, with PRM radar monitoring provided by FAA controllers. The results of those flight

¹ FAA Research and Development Services, *Precision Runway Monitor Demonstration Report Final Report* DOT/FAARD-91/5, February 1991

² Ibid

³ Hollister et al, *Evaluation of Boeing 747-100 Performance During ATC-Directed Breakouts on Final Approach*, MIT Lincoln Laboratory Project Report ATC-263, 7 January 1998

⁴ Hollister et al, *Airbus A320 Performance During ATC-Directed Breakouts on Final Approach*, MIT Lincoln Laboratory ATC Project Report ATC-265, 20 November 1998.

⁵ Owen, *The Memphis Precision Runway Monitor Program Instrument Landing System Final Approach Study*, MIT Lincoln Laboratory Project Report ATC-194, 24 May 1993.

⁶ Reference 1.

demonstrations and the subsequent pilot surveys indicated that the majority of pilots accepted PRM operations.

The real-time demonstrations also identified potential issues that had not been previously considered. One of these was the possibility that the controller's evasion instructions to the pilot could be blocked or garbled by other pilot transmissions. This led to the current requirement for a second communications frequency, to be monitored by the pilot but used only for transmissions by the monitor controller, to ensure that the evasion instructions are received promptly.

Overall Risk

A Target Level of Safety for PRM approaches was set prior to the simulations. The FAA decided that the introduction of PRM should add a collision risk of no more than one in twenty-five million approaches, which is one-tenth that of the perceived ILS accident risk.⁷

The risk analysis considered such factors as:

- the rate of blunders on final approach
- the probability that the blunder will involve a turn of 30 degrees or more
- the probability that the aircraft will be non-responsive
- the probability that another aircraft is aligned with the blundering aircraft (in other words, the two aircraft will collide if there is no evasion)
- the probability that the collision is not averted by pilot/controller action

Based on the Monte Carlo assessment, real-time simulations and other analyses, it was concluded that the Target Level of Safety would be met even if the blunder rate were as high as one 30-degree blunder per 2000 pairs of simultaneous ILS approaches. There is no official FAA data on the rate of blunders. However, in the opinion of controllers familiar with operations at airports like Chicago O'Hare and Atlanta, where simultaneous ILS approaches have been conducted for many years, blunders occur less frequently than this threshold rate. Therefore, closely spaced parallel ILS approaches with the PRM were accepted by the FAA. These approaches were also accepted by ICAO, after a thorough review of the simulation methodology and analyses.

⁷ See reference 1, page v.

Appendix 7

ILS/RNP Separation Standard

The Comparison with a Reference System method is being used to establish the lateral separation between an ILS course and a RNP course in the RNP Parallel Approach Transition (RPAT) concept. The purpose of RPAT is to increase capacity to closely spaced parallel runways (typically 750-4300 ft apart). It allows a dual aircraft stream to closely spaced parallel runways in weather conditions that currently allow only a single stream.

Figure 2 illustrates the RPAT concept. One aircraft flies the straight-in ILS course, which is aligned with the runway centerline. The second flies a parallel RNP approach, offset by 5000 ft. At the PFAF point, the RNP aircraft executes a guided sidestep towards the other approach to align with the second runway. This concept is similar to the PRM Simultaneous Offset Instrument Approach (SOIA), in that the aircraft fly instrument procedures through the clouds and then visual procedures to the runways.

While flying through the clouds, the ILS and RNP courses are monitored by controllers in the same way as standard simultaneous parallel approaches. Prior to the PFAF, the pilot of the RNP aircraft must visually acquire the ILS aircraft; once the aircraft are clear of the clouds, they are separated visually. This allows dual approach streams to closely spaced parallel runways when ceilings are as low as 2000 ft. Typically such dual approach streams must be halted and only a single stream can be used when the ceilings are 4500 ft or below.

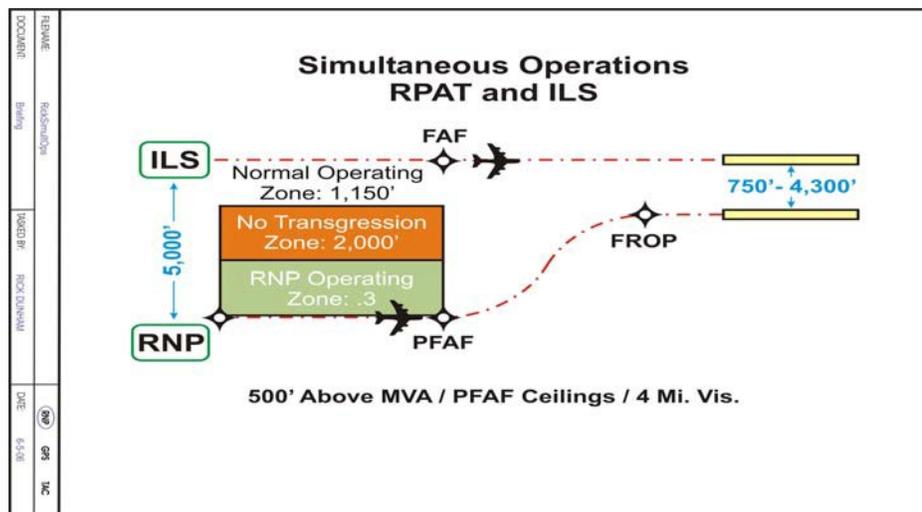


Figure 2. Simultaneous Operations – RPAT and ILS

The minimum separation between ILS and RNP courses has not previously been established. The preliminary RPAT concept separates these two courses by 5000 ft. The minimum separation between parallel ILS courses for simultaneous approaches is 4300 ft (with standard radar), so the RPAT concept provides 700 ft more separation.

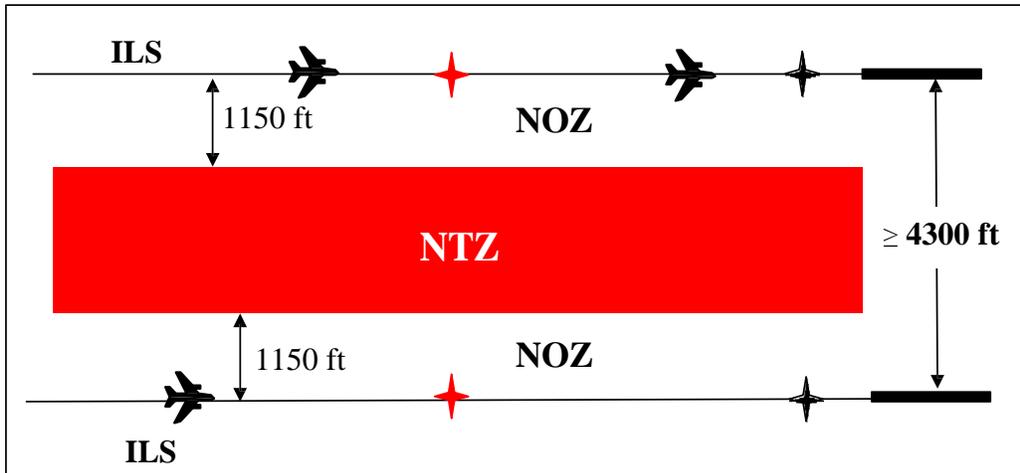
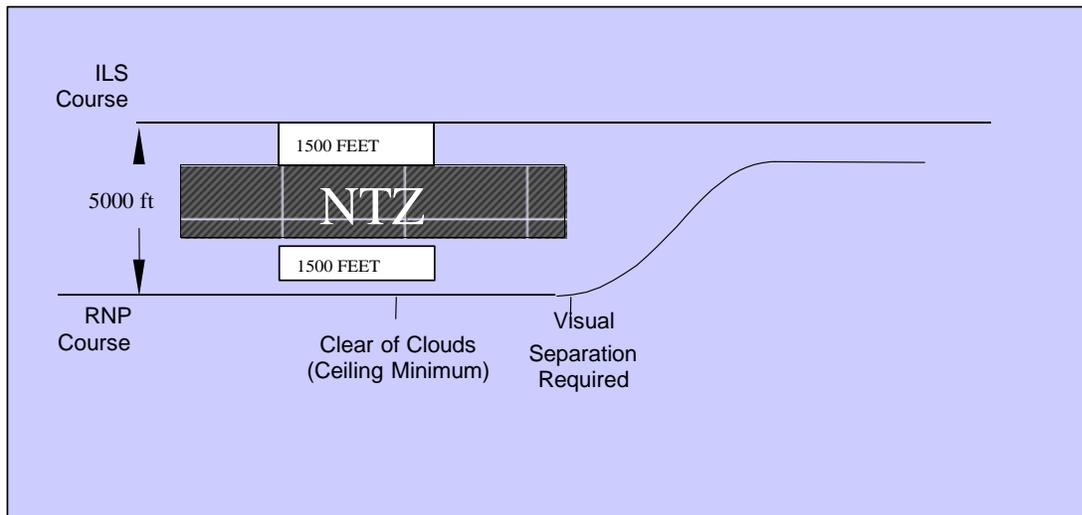


Figure 3. Parallel ILS Runway Spacing

The preliminary RPAT concept is based on the 4300 ft minimum runway spacing for parallel ILS approaches. The ILS aircraft is protected by the standard ILS Normal Operating Zone (NOZ), 1150 ft wide, and the standard 2000 ft wide No Transgression Zone (NTZ). The NOZ for the RPAT aircraft is assumed to be one times RNP, or 1800 ft for a navigational performance of RNP .3⁸. The total separation between the two courses is thus nearly 5000 ft, so 5000 ft is the proposed standard.

The preliminary RPAT concept placed the NTZ closer to the ILS course than to the RPAT course. This is inconsistent with the standard for parallel ILS approaches, which states that the NTZ should be equidistant between the approaches. Therefore, the latest RPAT proposal retains the total 5000 ft separation but centers the NTZ between the courses. This increases the NOZ for the ILS, and decreases the NOZ for the RPAT course, to 1500 ft.



⁸ RNP .3 is equivalent to .3 nautical miles or 1800 ft. In other words, the aircraft is expected to be within .3 NM of the course centerline 95% of the time.

Figure 4. Current proposed Simultaneous ILS/RPAT separation

This is an application of the Comparison with a Reference System method. Some members of industry have largely accepted the proposed course separations because they are greater than the equivalent ILS course separations. However others are concerned that this course separation is larger than it needs to be, so the maximum benefits of the procedure will not be realized. In general, the Comparison with a Reference System approach to safety results in conservative standards that will not produce the dramatic capacity increases needed to support NGATS, because it limits the new procedure to be similar to an existing, accepted procedure.