Project Report
ATC-258

Terminal Area Separation Standards: Historical Development, Current Standards, and Processes for Change

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16 January 1997

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Prepared for the Federal Aviation Administration,
Washington, D.C. 20591

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
ATC-258		

4. Title and Subtitle Terminal Area Separation Standards: Historical Development, Current Standards, and Processes for Change	5. Report Date 16 January 1997 6. Performing Organization Code
7. Author(s) Steven D. Thompson	8. Performing Organization Report No. ATC-258
9. Performing Organization Name and Address MIT Lincoln Laboratory 244 Wood Street Lexington, MA 02173-9108	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFA01-93-Z-02012
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, DC 20591	13. Type of Report and Period Covered ATC / January 1997 14. Sponsoring Agency Code

15. Supplementary Notes

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, under Air Force Contract F19628-95-C-0002.

16. Abstract

This paper gives an overview and summary of the separation requirements for air traffic control in the U.S. National Airspace System with emphasis on those relevant to terminal landing operations. These requirements are documented in the Federal Aviation Administration's (FAA's) Air Traffic Control Order 7110.65J, as amended, and various national and local Orders. These requirements are also addressed in the Aeronautical Information Manual, the International Civil Aviation Organization's Standards and Recommended Practices, and the Federal Aviation Regulations (FARs). The purpose of this paper is to assist those people involved with the introduction of new technologies and procedures in the terminal airspace by providing them with an understanding of the separation requirements, the need for those requirements, and the processes used to change the requirements.

17. Key Words	18. Distribution Statement
	This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

FORM DOT F 1700.7 (8-72) Reproduction of completed page authorized

FOREWORD

This report represents work done by MIT Lincoln Laboratory for the Federal Aviation Administration's (FAA) Office of System Safety, Safety Analysis Division, ASY-200, under support by the National Aeronautics and Space Administration's (NASA) Terminal Area Productivity (TAP) Program. The goal of the TAP Program is to provide the technology and operational procedures for safely increasing terminal area capacity in instrument meteorological conditions. This report details the terminal separation standards for air traffic control that are now in use, the historical development of those standards, and the studies now underway that may influence changes to the standards. A review of the standards change process, both nationally and internationally, is presented. The report is intended to serve as a baseline from which new technologies and procedures can progress. The role of collision risk analysis in setting standards is reviewed.

EXECUTIVE SUMMARY

This report gives an overview and summary of the separation requirements for air traffic control in the U.S. National Airspace System with emphasis on those relevant to terminal landing operations. These requirements are documented in the Federal Aviation Administration's (FAA's) Air Traffic Control Order 7110.65J, as amended, and various national and local Orders. These requirements are also addressed in the Aeronautical Information Manual, the International Civil Aviation Organization's Standards and Recommended Practices, and the Federal Aviation Regulations (FARs). The purpose of this report is to assist those people involved with the introduction of new technologies and procedures in the terminal airspace by providing them with an understanding of the separation requirements, the need for those requirements, and the processes used to change the requirements.

The basic procedural and radar separation requirements are presented for visual and instrument flight rules. The specific requirements for horizontal, vertical, and wake vortex separation are examined as are the separation requirements for runway occupancy. Next, the longitudinal requirements for single runway precision approaches are presented followed by the lateral and longitudinal requirements for independent and dependent multiple runway approaches.

The historical development of the current standards is reviewed as well as the processes that are in place to change these standards. The change process is presented for both national and international standards. The role of collision risk analysis in setting and changing standards is reviewed.

Current studies in the Precision Runway Monitor (PRM) Program, the Multiple Parallel Approach (MPAP) Program, Free Flight, Wake Vortex, the Terminal Air Traffic Control Automation (TATCA) Program, and Automatic Dependent Surveillance Broadcast (ADS-B) using the Global Positioning System (GPS) and data link are reviewed. The data and results generated by these studies may provide justification for the future reduction of separation standards in the U.S. National Airspace System.

The current radar separation standards were established based on radar accuracy, display target size, and controller and pilot confidence. Documentation of any specific analysis leading to these standards was not found. Other factors, such as human reaction time, seem to be implicitly included in these standards.

As traffic in the terminal area continues to increase, it needs to be determined if and how parallel and longitudinal separation reductions can be safely accommodated. New surveillance systems, such as Automatic Dependent Surveillance Broadcast (ADS-B) using the Global Positioning System (GPS), will require a review of the basis for establishing surveillance separation standards.

Although operational judgment will continue to play an important role in evolving separation standards, improvements to the objective measurement of risk represents a critical element in developing new standards.

ACKNOWLEDGMENTS

The careful review and helpful comments of Walter Brown and William Joss of MIT Lincoln Laboratory are gratefully acknowledged. The time and effort they spent is appreciated. Their corrections, comments and suggestions were, almost without exception, incorporated. The review of the final draft by Robert Dye, Don Streeter, and Jack Wojciech of the FAA Office of System Safety, Bill Swedish of the MITRE Corporation, and Gene Wong with the FAA's Integrated Product Team for Surveillance and Weather was quite helpful and appreciated. Their efforts certainly contributed to the correctness of this report. Any errors that may remain, in spite of their efforts, must be attributed to the author. Finally, the programmatic support and comments of Mary Connors from NASA Ames is gratefully acknowledged.

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1. INTRODUCTION

The purpose of this report is to give an overview and summary of the separation requirements for air traffic control in the U.S. National Airspace System with emphasis on those relevant to terminal landing operations. These requirements are documented in the Federal Aviation Administration's (FAA's) Air Traffic Control Order 7110.65J [1] as amended, and various national and local Orders. The requirements are also addressed in the Aeronautical Information Manual [2], the Federal Aviation Regulations [3] (FARs), and, with a few exceptions, contained in the International Civil Aviation Organization's Standards and Recommended Practices. The goal is to review and present the terminal separation requirements in a format that aids in understanding the current application of the standards and facilitates the introduction of new technologies and procedures into the terminal airspace. The historical development of the current standards is presented as well as the processes that are used to change these standards, both nationally and internationally. The role of collision risk analysis in setting and changing standards is also reviewed.

An overview of air traffic control operations is presented in Section 2 which includes the necessary terminology for understanding the separation requirements. A convention followed in this report is that terms important to the understanding of separation requirements are listed in **bold** type as they are introduced. Their meanings should be clear from the context. This is followed in Section 3 by a general background and history of air traffic control separation and the use of radar for separation. The basic separation requirements for visual and instrument flight rules are presented in Section 4. These include the specific requirements for horizontal, vertical, and wake vortex airborne separation and the requirements for separation on the runway. Section 4 also includes the longitudinal separation requirements for single runway landing operations. Section 5 presents the lateral and longitudinal requirements for independent and dependent multiple runway operations. Section 6 summarizes current studies in the Precision Runway Monitor (PRM) Program, the Multiple Parallel Approach (MPAP) Program, Free Flight, Wake Vortex, the Terminal Air Traffic Control Automation (TATCA) Program, and Automatic Dependent Surveillance Broadcast (ADS-B) using the Global Positioning System (GPS) and data link. These studies all have the potential of affecting separation standards in the future. Section 7 is a review of the process in place to change both national and international standards. The role of collision risk analysis in setting and changing standards is included in this section.

2. OVERVIEW OF AIR TRAFFIC CONTROL OPERATIONS

2.1 AIRSPACE CLASSIFICATION

The airspace above the United States is divided into six classes for air traffic purposes. The services provided by **Air Traffic Control (ATC)**, the requirements for separation of aircraft, the weather minimums necessary for operation in the airspace, and the rules of flight are all defined in terms of the airspace classification. **Class A, Class B, Class C, Class D, and Class E airspace** are **controlled airspace**. Controlled airspace is airspace within which all aircraft operators are subject to certain pilot qualifications, operating rules, and equipment requirements. Generally speaking, Class A airspace has the most ATC services and the most stringent requirements for entry, and Class E airspace has the least requirements. Class G airspace is uncontrolled airspace. Class F is defined by the International Civil Aviation Organization (ICAO), but is not used in the United States. Figure 1 is a depiction of the airspace classes. The descriptions that follow are taken from the Pilot/Controller Glossary in the Federal Aviation Administration's (FAA's) Air Traffic Control Order 7110.65J [1].

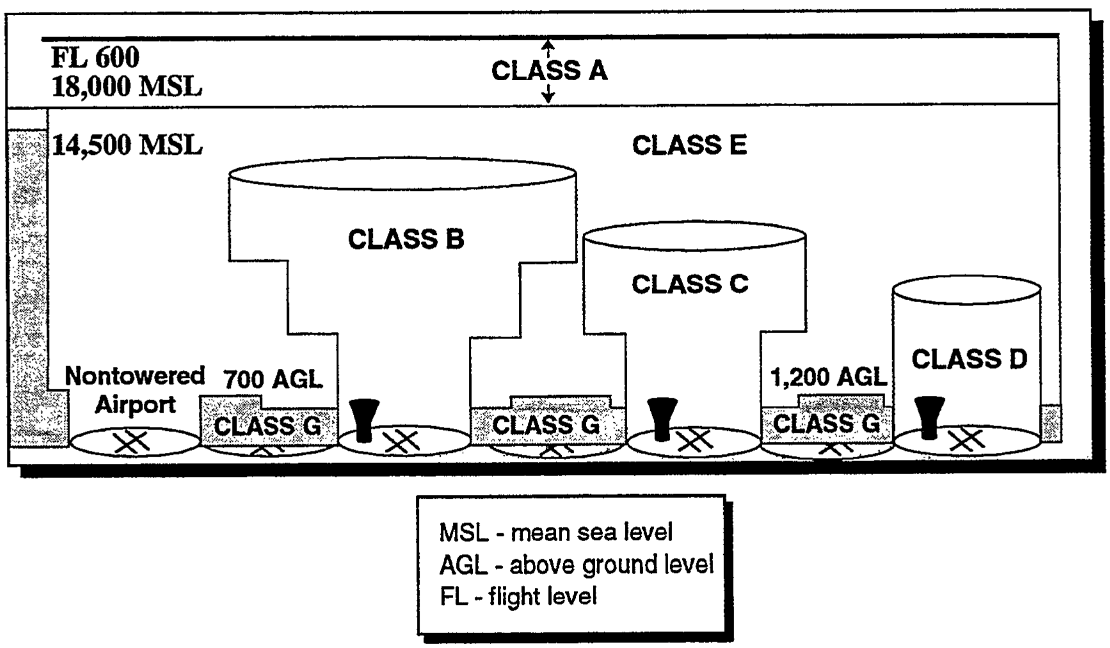

Figure 1. Airspace classification in the United States.

The airspace from 18,000 feet **mean sea level (MSL)** to **Flight Level (FL)** 600 (60,000 feet) is Class A Airspace. Below 18,000 feet, altitude is expressed as feet above mean sea level and the aircraft's altimeter is set to the local altimeter settings. At and above 18,000 feet, all aircraft set their barometric altimeter to a datum of 29.92 inches of mercury and the altitude is expressed in terms of flight levels, FL390 being 39,000 feet, for example.

Class B airspace surrounds the largest and busiest major airports. The Class B airspace extends from the airport's surface in a tiered "upside-down wedding cake" fashion to

10,000 MSL. The airspace is individually tailored for each location and may have corridors through the airspace. As of August 1996, there were 29 Class B airspaces in the United States containing 33 primary civilian airports. Two military airfields are also contained in Class B airspace.

Class C airspace surrounds airports that have operational towers and radar approach control, but are not as busy as the primary airports under Class B airspace. Class C is also individually tailored, but usually consists of an inner circle of airspace with a 5-nautical mile radius extending from the surface to 4,000 feet above the airport elevation and an outer circle of airspace with a 10-nautical mile radius that extends from 1,200 feet above the airport elevation to 4,000 feet above the airport elevation.

The remainder of the airports with operational control towers are surrounded by Class D airspace extending from the surface to 2,500 feet above the airport elevation. The airspace generally is a circle with a 5-nautical mile radius, but it is tailored to contain airspace needed for instrument approach procedures.

Generally, if the airspace is not Class A, Class B, Class C, or Class D, and is controlled airspace, it is Class E airspace. Class E airspace extends upward from either the surface or a designated altitude to the overlying controlled airspace. When not extending upward from the surface, Class E is generally designated to begin at either 700 feet above the surface or 1,200 feet above the surface.

Uncontrolled airspace, Class G, generally lies under Class E airspace extending from the surface to 700 or 1,200 feet above ground level.

2.2 FLIGHT RULES AND WEATHER

Aircraft conduct flight operations under either **Visual Flight Rules (VFR)** or **Instrument Flight Rules (IFR)**. Visual Flight Rules are the rules that govern the procedures for conducting flight under visual conditions but the term "VFR" is also used to indicate weather conditions that are equal to or greater than the minimum VFR requirements. In addition, it is used by pilots and controllers to indicate a type of flight plan [2]. Under VFR, aircraft are responsible for their own separation from other VFR and IFR traffic ("see and avoid"), and terrain clearance, although in certain airspace VFR traffic will receive separation services as described below. Instrument Flight Rules are the rules governing the procedures for conducting flight solely by reference to the aircraft's instruments. It is also a term used by pilots and controllers to indicate a type of flight plan. Under IFR, ATC is responsible for the separation of aircraft on IFR flight plans. Aircraft operating under IFR are assured terrain clearance if they are in compliance with the minimum altitudes on published instrument routes and approach procedures. ATC uses minimum vectoring altitudes to assure terrain separation when aircraft are off of published routes. Aircraft operating under VFR in controlled airspace (except Class A airspace as described below) can, under certain restrictions, operate together with aircraft operating under IFR and ATC will, to the extent possible, provide traffic advisories.

In order for aircraft to operate under VFR, **Visual Meteorological Conditions (VMC)** must exist. Visual Meteorological Conditions are expressed in terms of visibility, distance from clouds, and **ceiling** equal to or better than a specified minimum [2]. The ceiling is the height above the ground of the lowest layer of clouds (or other obscuring phenomena) that covers more than half the sky. The specified minimum conditions are sometimes referred to as basic VFR weather minimums. If conditions are less than the minimums specified for Visual Meteorological Conditions, then **Instrument Meteorological Conditions** (IMC) exist and aircraft must operate under IFR. The presumption is that VMC provides sufficient flight visibility conditions for aircraft operating under VFR to accomplish visual separation. Visual Meteorological Conditions are not defined for Class A airspace since no VFR operations are authorized. VMC in Class B airspace requires 3 statute mile flight visibility and that the aircraft stay clear of the clouds, however all VFR aircraft in Class B airspace are operating with an ATC clearance, are under radar surveillance, and will receive separation services. See Section 2.3 and Table 2. VMC below 10,000 feet MSL in Class C, D, and E controlled airspace requires a flight visibility of at least 3 statute miles and that the aircraft remain a distance of at least 500 feet below, 1,000 feet above, and 2,000 feet horizontally from clouds. Above 10,000 MSL in Class E airspace, the VMC flight visibility must be at least 5 statute miles and the cloud clearance requirements are 1,000 feet below, 1,000 feet above, and 1 statute mile horizontal.

"**Special VFR**" weather minimums allow a flight visibility of only one mile (FAR 91.157). The Special VFR requirement of one mile visibility and clear of clouds is possible in the airspace below 10,000 MSL within the airspace contained by the upward extension of the lateral boundaries of the controlled airspace designated to the surface for an airport. Special VFR must be specifically requested by the pilot, is allowed only during the hours between sunrise and sunset, and requires an ATC clearance. A significant number of airports with Class B and Class C airspace prohibit Special VFR operations and these airports are listed in Appendix D of Part 91 of the FARs. The basic VFR weather minimums are contained in FAR 91.155 and these minimums are reproduced in Table 1 for Class A, B, C, D, and E airspace.

Table 1.
Basic VFR Weather Minimums

Airspace	Flight Visibility	Distance from Clouds
Class A	Not Applicable	Not Applicable
Class B	3 statute miles	Clear of Clouds
Class C	3 statute miles	500 feet below 1,000 feet above 2,000 feet horizontal
Class D	3 statute miles	500 feet below 1,000 feet above 2,000 feet horizontal
Class E Less than 10,000 feet MSL	3 statute miles	500 feet below 1,000 feet above 2,000 feet horizontal
Class E At or above 10,000 feet MSL	5 statute miles	1,000 feet below 1,000 feet above 1 statute mile horizontal

Note: Special VFR within Class B,C,D, or E airspace may be conducted, if approved by ATC, with a flight visibility of 1 statute mile and clear of clouds

The effects of weather on terminal operating procedures make it advantageous to describe the terminal weather with more descriptive categories than just VMC and IMC. A typical categorization was used by Owen [4] in her report on the Memphis Precision Runway Monitor Program. It was adopted from the standard categorical outlook descriptions used in pilot weather forecasts as listed in the AOPA Handbook for Pilots [5] and is the same as the categorical outlook description in the Aeronautical Information Manual [2]. Note that the categories are in terms of flight rules (VFR and IFR) rather than meteorological conditions. In this system, the terminal weather is described as **Low IFR** if the ceiling is below 500 feet and/or the visibility is below 1 mile, **High IFR** if the ceiling is between 500 feet and 1,000 feet and/or the visibility is between 1 and 3 miles, **Marginal VFR** if the ceiling is between 1,000 and 3,000 feet and/or the visibility is between 3 and 5 miles, and **Good VFR** if the ceiling is above 3,000 feet and the visibility is greater than 5 miles. This is illustrated in Figure 2. Note that visibility requirements are always listed in **statute miles**. All ATC separation requirements are specified in **nautical miles**. A statute mile is 5280 feet while a nautical mile is 6,076 feet, a 15% difference.

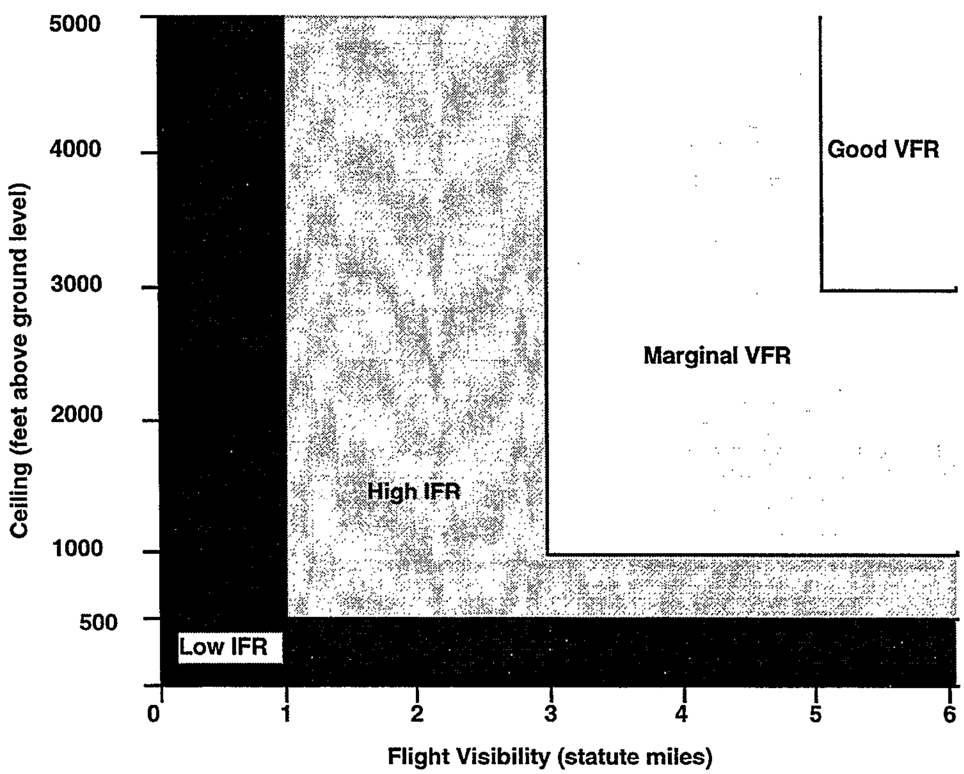

Figure 2. Categorical weather outlook descriptions.

The effects on terminal operations is as follows: During periods of Good VFR, aircraft can accept visual approaches to the runways and assume responsibility for visual separation from other aircraft (see Section 2.3). The net effect is to allow a more flexible airport operation including the potential use of additional parallel and intersecting runways. This in turn will affect the **Airport Acceptance Rate (AAR)** which is the maximum number of airplanes an airport can accommodate in a fixed period of time. In areas of Marginal VFR, aircraft may have to begin an instrument approach until the pilot reaches a point where he or she is able to land by visual references. At that point, the pilot may accept visual separation from other aircraft. There is, therefore, less flexibility in Marginal VFR than in Good VFR. In High IFR and Low IFR, aircraft must conduct instrument approaches and, depending on the airport's ability to conduct simultaneous approaches to two or more runways, the airport acceptance rate may be reduced. In Low IFR, runway occupancy time and missed approaches become a concern which may reduce the airport acceptance rate even further.

2.3 SEPARATION SERVICES AND PROCEDURES

Separation of aircraft can be accomplished visually, procedurally (non-radar), or with radar. **Visual separation** can be provided by ATC in the event both aircraft are visible from the tower cab, or it can be provided by the pilots flying outside of Class A airspace. If ATC is providing visual separation from the tower cab, it is not necessary for the pilots to see each other. If the pilots are in visual contact in VMC and visual separation is assigned by ATC and agreed to by the pilots, then the responsibility for separation can be accepted by the pilots even though they are operating under Instrument Flight Rules. In that case, visual separation is assigned by ATC and accepted by the pilot only after the pilot has visual contact with the other aircraft. Visual separation is never allowed in Class A airspace, regardless of the weather. For aircraft that are **in-trail** (one lined up behind another), only the "following" aircraft has to have the preceding traffic in sight. If the pilot agrees to visual separation, he or she accepts responsibility for maintaining separation. In the event visual contact is lost, the pilot must notify ATC immediately.

Non-radar separation is the term used when ATC provides separation service based on position reports and estimates given by pilots over radio voice communications. Enroute separation may be accomplished with flight progress strips and the use of different altitudes, but in the terminal area non-radar separation generally translates into one aircraft at a time having the clearance to use a block of airspace for an approach and that airspace being closed to other aircraft until the first aircraft reports landing. Timed approaches can be used in a non-radar environment if the weather is sufficient to allow circling at the airport and if the missed approach procedure does not involve a course reversal. In a timed approach, an aircraft is cleared to depart the **approach fix** (a defined geographic point where the approach procedure begins) at a specified time before the preceding aircraft has landed.

In busy terminal areas, **radar separation** is provided by ATC and all aircraft are under positive control. The only exceptions would be in the case of loss of radar or in the more common procedure of the aircraft providing visual separation in VMC. Radar separation in ATC parlance means exactly that; the separation between aircraft as shown on the radar display and *not* necessarily the actual separation between the aircraft, the difference being due to radar system inaccuracies. The difference between actual aircraft position (and separation) and radar position will depend on the radar system being used, the distance of the aircraft from the radar site and the update rate of the system and display.

The radar target that depicts the aircraft's position on the radar display can be a **primary target** or **secondary target.** A primary target is generated by the reflected radar signal off of the aircraft while the secondary target is generated by the response of a **radar beacon transponder** on board the aircraft. All aircraft operating in Class A or B airspace are required to have transponders. These transponders reply to the radar's interrogation signal by broadcasting a **beacon identity code**, assigned by ATC, and the aircraft's encoded altitude. ATC computers, if they have a stored **flight plan**, can usually link the beacon code to the aircraft identification and display that information, along with altitude, aircraft type, and ground speed, in a **flight data block**, sometimes referred to as a **full data block**. The alphanumeric data block appears on the radar display and is associated with the target through a **leader line**.

For both terminal and enroute radar displays, primary radar targets appear as small dots or blobs and secondary targets as short straight lines or slashes. Either the primary, the secondary, or both can be displayed. If both are displayed, the secondary slash will overlay the primary target. The computer-generated target displays are different for enroute and terminal radar displays. On terminal displays the slash is perpendicular to the radar site. Enroute displays have diagonal slashes. The direction of the diagonal slash depends on whether or not the target is **correlated**. Correlated means that the radar position data is associated with the computer projected track of an identified aircraft. Radar separation is defined as between the centers of primary targets and between the ends of transponder generated beacon control slashes of secondary targets. Most major **Terminal Radar Control** facilities **(TRACONS)** use **Automated Radar Terminal Systems (ARTS)** equipment to track aircraft and to associate aircraft ID with targets on the **Data Entry and Display System (DEDS)**. Separation on the DEDS displays or the newer **Full Digital ARTS Displays (FDADS)** is defined as between the centers of the digitized targets.

The term "radar separation" is generally used to mean horizontal separation based on radar position reports as opposed to **vertical separation** although, technically, aircraft can be separated horizontally or vertically while within radar coverage. Note however, that vertical separation is based on aircraft reports (either verbal or via **Mode C** transponder), not independent information from radar. Altitudes in the terminal area under IFR are assigned in 1,000-foot increments above mean sea level and vertical separation requires assigned altitudes at least 1,000 feet apart. Either vertical or horizontal (generally 3 miles in the terminal airspace) separation must be maintained except that vertical separation between aircraft may be discontinued before horizontal separation is achieved if the aircraft are on opposite/reciprocal courses (and have passed!) or the aircraft are on crossing courses at least 15 degrees apart and one aircraft has crossed the projected course of the other.

Separation service is provided between aircraft according to the Class of controlled airspace within which they are operating. All aircraft operating in Class A airspace must operate under IFR and are therefore provided positive separation by ATC. Positive separation is also provided in Class B airspace around the largest and busiest major airports. Although aircraft may operate under VFR or IFR in Class B airspace, VFR aircraft must obtain an ATC clearance to do so and will be separated from other VFR and IFR traffic. All aircraft receive radar separation service and terrain separation service. Pilots can only accept responsibility for visual separation in Class B airspace if weather conditions permit.

VFR aircraft in Class B airspace must be separated from other VFR or IFR aircraft that weigh more than 19,000 pounds and any turbojet by 1 1/2 miles horizontal or 500 feet vertical or by visual separation. VFR aircraft in Class B airspace are separated from VFR or IFR aircraft weighing 19,000 pounds or less by radar display target resolution or 500 feet vertical separation or visual separation. Aircraft operating under VFR in Class C airspace are only separated from IFR traffic, not other VFR traffic.

Table 2 summarizes the basic separation services provided in Class A through E airspace. The details of IFR radar separation requirements are contained in Section 4. There are no ATC separation services provided in Class G airspace.

Table 2.
Separation Services by Airspace Classification

	Class A	Class B	Class C	Class D	Class E
Operations Permitted	IFR only	IFR & VFR	IFR & VFR	IFR & VFR	IFR & VFR
Entry Requirements	ATC Clearance	ATC Clearance	IFR-Clearance VFR-Radio Contact	IFR-Clearance VFR-Radio Contact	IFR-Clearance VFR-none
Aircraft Separation	All	All	IFR and Runway Operations	IFR and Runway Operations	IFR
VFR Separation Services	N/A	<u>from VFR/IFR</u> • from aircraft weighing more than 19,000 lb. 1 1/2 mile lateral *or* 500 feet vertical *or* visual separation • from aircraft weighing 19,000 lb. or less: target resolution *or* 500 feet vertical *or* visual separation	<u>from IFR</u> target resolution *or* 500 feet vertical (except beneath heavy jet) <u>from VFR</u> traffic advisories	None except traffic advisories, workload permitting	None except traffic advisories, workload permitting

Separation is maintained through the use of **radar vectors** (headings), speed control, and altitude assignments. Once established on an instrument approach, ATC discontinues vectoring. At a predetermined point, generally at the final approach fix, ATC discontinues speed control and altitude assignments. All control must be relinquished inside the final approach fix or at a point 5 miles from the runway, whichever is closer to the runway. A controller may *request* a speed for the aircraft to fly during the approach such as a "best" (meaning fastest) speed on the approach, but there is no requirement for the pilot to fly this speed during the approach and, in fact, it may not be possible for the aircraft to fly too high a requested speed. This has the effect of making it more difficult for ATC to maintain a specified separation for two aircraft in-trail on an instrument approach.

The controller will often add a **buffer** or additional separation distance at the beginning of the approach in order to assure separation throughout the approach. One of the reasons controllers need to add a buffer is the natural effect of **compression** as aircraft near the final approach fix and slow down to a landing configuration and speed. Aircraft with a given in-trail separation distance and traveling at a high speed will compress, or reduce in separation distance, as the aircraft sequentially slow down upon reaching a common geographic point such as an approach fix. Controllers will assign speeds to fly to a predetermined point, normally the final approach fix, in order to minimize compression on the final approach course.

2.4 LANDING APPROACH PROCEDURES

Aircraft operating under VFR in VMC may land at an airport using visual references to guide the airplane to the runway. The pattern around the landing runway consists of a **downwind** leg parallel to the runway and flown in a direction opposite landing, a **base** leg perpendicular to the runway, and a **final** leg leading to the landing. All or only a portion of the pattern might be flown depending on traffic and the direction from which the aircraft is arriving.

Aircraft operating IFR in VMC may conduct a **visual approach**. A visual approach is defined as an approach conducted on an IFR flight plan which authorizes the pilot to proceed visually and clear of clouds to the airport [2]. The pilot must, at all times, have either the airport or the preceding aircraft in sight. The approach must be authorized and under the control of the appropriate air traffic control facility. Reported weather at the airport must be ceiling at or above 1,000 feet and visibility of 3 miles or greater.

Aircraft operating IFR in IMC will conduct an **instrument approach procedure**. An instrument approach procedure is a series of predetermined maneuvers that provide obstacle clearance and lead to a point from which a landing may be made visually. If a landing cannot be made visually, a **missed approach** procedure guides the airplane to a holding point back in the enroute system.

Instrument approach procedures are either **precision approaches** or **non-precision approaches**. A precision instrument approach, by definition, provides an independent electronic vertical guidance signal. Note that the difference between a precision approach and non-precision approach is not defined in terms of a limit to any navigational service accuracy, although precision approaches do offer more navigational accuracy. The types of precision approaches currently available are the **Instrument Landing System (ILS)**, the **Microwave Landing System** (MLS) and the **Precision Approach Radar (PAR)** approach. MLS and PAR are not in common enough usage to be important for the purposes of this report. Descriptions of these systems can be found in the Aeronautical Information Manual [2] or Noland [6].

The ILS provides right/left guidance through an electronic **localizer** signal and vertical guidance through an up/down **glide slope** signal. The localizer signal emanates from an antenna centered at the opposite end of the runway and fanned out such that full scale deflection of the **course deviation indicator** (CDI) in the aircraft typically corresponds to 350 feet either side of the centerline of the runway at the approach end of the runway threshold. The glide slope descends at approximately a three degree slope intercepting the runway approximately 1,000 feet from the threshold and is sited to provide a runway threshold crossing height of between 50 and 60 feet. Also part of the ILS are the **approach lighting system (ALS)** and the **marker beacons.** The ALS is designed to aid aircrews in locating the runway and conducting the landing during periods of low visibility and at night. The marker beacons are 75 MHz transmitters that transmit directional signals received by aircraft flying overhead and mark locations along the localizer. The **outer marker (OM)** is located four to seven miles from the runway threshold and is usually, but not always, near where the aircraft intercepts the glide slope and begins the descent. The fix which identifies the beginning of the final approach segment is known as the **Final Approach Fix (FAF)** and, for an ILS approach, is generally the point at which the aircraft intercepts the glide slope. Sometimes a low frequency **non-directional beacon (NDB)** providing a relative bearing to the marker is co-located with the outer marker and in that case the marker is referred to as a **locator outer marker (LOM)**. The **middle marker (MM)** is located along the localizer near the point where the aircraft's altitude reaches the **decision height (DH)**. The aircrew must make the decision to land (if the runway or ALS are in sight) or execute a missed approach. The DH is normally 200 or 250 feet **above ground level (AGL)**. The distance from the runway threshold at the decision height will vary depending on the glide slope angle and runway intercept point, but for a decision height of 200 feet it will be approximately one-half mile from the threshold.

For runways equipped for **Category II** operations (normal ILS systems are **Category I**) there is an **inner marker (IM)** located closer to the runway (less than one thousand feet from the threshold) with a decision height of 100 feet or 150 feet. Below that, **Category IIIA** approaches can be conducted with no decision height and visibility as low as 700 feet. The International Civil Aviation Organization (ICAO) categories define **Category IIIB** down to 150 foot visibility although in the United States all Category IIIB approaches are limited to visibility down to 600 feet, very little different from Category IIIA. **Category IIIC** is for weather down to zero visibility. There are no Cat IIIC approaches authorized in the United States. Aircraft and aircrews must receive special certification to conduct Cat II or Cat III approaches. LaFrey [7] provides a more complete description of the ILS in his report on the Parallel Runway Monitor.

The **Global Positioning System (GPS)** is a satellite navigation system designed to provide accurate continuous coverage all over the world. Navigation is accomplished by triangulating on the distance or **range** from four or more satellites. This is accomplished by comparing receiver generated time based pseudo-random codes with the same codes received from the satellites. The time differences in the codes can be converted to distance measures. Four satellites are necessary because of the limits of accuracy available in the receiver clocks. An introductory level explanation of the principles of GPS can be found in Thompson [8] or Hurn [9]. GPS augmented by pseudo-range corrections broadcast to the aircraft from a ground station or a satellite, is known as **differential GPS**, and is expected to be capable of meeting the requirements for precision approaches. Although none have been certified yet, precision approaches using differential GPS have been demonstrated in air carrier aircraft including approaches followed by automatic landings.

The major non-precision approach systems in use today are the **VOR** approach using the signal from a **Very High Frequency Omnidirectional Range**, the low frequency non-directional beacon (NDB) approach, the area navigation (**RNAV**) approach using VOR and **Distance Measuring Equipment** (**DME**), and approaches based on the Global Positioning System (GPS). There are currently no approved Loran-C approaches. Some Loran-C approach procedures still appear in approach procedures publications, but they are all listed as not usable in the **Notices to Airmen (NOTAMS)**.

VORs form the backbone of the current air traffic control route structure. VORs are ground stations that transmit two VHF signals such that a receiver, by comparing the time difference or phase between the two signals, can determine the aircraft's position relative to a given **radial** or direction from the VOR. VOR radials are linked together to form the low altitude **victor airways** and high altitude **jet airways** that comprise today's route structure. Some VORs known as **VORTACS** have DME that allow suitably equipped aircraft to measure their **slant range** distance (direct line distance from the airborne aircraft to the station) to the VOR. NDBs transmit a low frequency signal that allows aircraft equipped with an **Automatic Direction Finder** (**ADF**) to provide the **relative bearing** to the station. The relative bearing is the direction to the station relative to the aircraft's current heading. As pointed out above, NDBs are sometimes co-located with the outer marker of an ILS approach. Nolan [6] presents a more detailed description of the principles of operation of the VOR, DME, and NDB.

During non-precision approaches, aircraft "step-down" to lower altitudes based on their horizontal position. The lowest altitude allowed during the approach is the **Minimum Descent Altitude** (**MDA**). The aircrew can proceed up to a **Missed Approach Point** (**MAP**) where a decision must be made to continue to a landing if the airport is in sight and the airplane in a position to land, or to execute a missed approach. Recently, there have been a large number of new GPS non-precision approaches approved. Most of these "overlay" existing VOR or NDB approaches but "stand-alone" GPS approaches have been approved. The GPS overlay approaches use GPS to fly the VOR or NDB approach; none of the area navigation features of GPS are used. The stand-alone GPS approaches are "true" area navigation approaches in that they are not restricted to following ground tracks relative to VORs or NDBs. These procedures are not listed as RNAV approaches but as GPS approaches.

The requirements for pilots and controllers during arrival are available in Section 5, Section 4 of the Aeronautical Information Manual [2]. Noland [6] and Mundra [10] give more details describing the operation of the air traffic control system including approach procedures.

2.5 AIRCRAFT CLASSES, CATEGORIES, AND GROUPS

For the purposes of wake vortex separation, aircraft are divided into **Weight Classes** according to their maximum certificated gross takeoff weight. The maximum gross takeoff weight is the maximum weight for which the aircraft is certificated (approved by the FAA) for take off. This is not the aircraft's actual weight which will depend on the amount of fuel, number of passengers, and cargo on board. In fact, the aircraft's actual weight in flight will necessarily be less than the maximum certificated gross takeoff weight as fuel is burned during the flight.

On July 16, 1996, the FAA issued Notice N7110.157 which redefined the Weight Classes and added additional wake vortex separation requirements. The effect of the change was to transfer more than fifty models of commuter turbo-prop and corporate jet and turbo-prop aircraft from the Large weight class to the Small weight class. This had the effect of increasing the wake vortex separation for these aircraft when following Large or Heavy weight class aircraft. Two commuter turbo-prop aircraft models, the Saab Fairchild 340 and the ATR-42 were exempted from the Small weight class and were classified as Large aircraft for separation purposes. Ongoing studies by NASA may exempt other aircraft in the future.

Aircraft are now classified as **Heavy** if the aircraft's maximum gross takeoff weight is more than 255,000 pounds, **Large** if the aircraft's maximum gross takeoff weight is more than 41,000 pounds up to 255,000 pounds, and **Small** if the maximum gross takeoff weight is 41,000 pounds or less. Small aircraft of 41,000 pounds or less are further broken down into aircraft weighing 12,500 pounds or less and aircraft weighing more than 12,500 pounds up to and including 41,000 pounds. This is for the purposes of wake turbulence separation departure restrictions for intersection departures. The Boeing 757, nominally a Large Weight Class aircraft, is now treated as a separate Weight Class for wake vortex separation requirements because of concerns over strong vortices generated by that aircraft.

The wake vortex separation standards are presented in matrix form in Section 4.4. The following aircraft are given as examples: the Weight Class for a Boeing 747, Boeing 767, and McDonnell-Douglas DC-10 is Heavy; for a Boeing 727, Boeing 737, and McDonnell-Douglas DC-9 is Large; and for a Dornier Do 228-100 commuter, Embraer Brasilia EMB 120-commuter, and light single engine or twin engine aircraft is Small. Corporate jets and turboprops can fall into either the Small or Large classification.

For the purposes of the pilot determining minimums (descent altitudes and visibility) for conducting instrument approach procedures, aircraft are grouped into **Aircraft Approach Categories** according to their computed **Calibrated Air Speed** (**CAS**) during approach at maximum gross landing weight. This speed is computed as 1.3 times the stall speed in the landing configuration (V_{SO}). **Category A** is for speeds less than 91 knots, **Category B** for speeds91-120 knots, **Category C** for speeds 121-140 knots, **Category D** for speeds 141-165 knots, and **Category E** for speeds of 166 knots or more. An aircraft can fit into only one category and if it is necessary for the aircraft to maneuver at speeds in excess of the computed category, then the approach minimums for the higher category apply. As examples, the computed reference speed for a Boeing 727 based on a V_{so} with 40 degrees of flaps is 138 knots and for a Beech 1900 turbo-prop commuter is 113 knots [11].

For the purposes of **same runway separation** (**SRS**) at airports with an operating control tower, aircraft categories are specified as **Category I** for small (12,500 pounds or less) single-engine, propeller-driven aircraft and all helicopters, **Category II** for small (12,500 pounds or less) twin-engine, propeller-driven aircraft, and **Category III** for all other aircraft. The following aircraft are given as examples: the single engine Mooney or Beechcraft Bonanza are SRS Category I, the twin-engine Beechcraft Baron and Cessna 310 are SRS Category II, as are the lighter turbo-prop commuters, and anything heavier, such as the larger commuter or jet airliners, are SRS Category III.

For the purposes of simultaneous operations on intersecting runways (**SOIR**) at airports with an operating control tower, aircraft are categorized into **SOIR Group 1, 2, 3, 4**, or **5**, based on their ability to land and stop in a short distance. SOIR Group 1 aircraft can land and stop in a very short distance but Group 5 aircraft take a long distance. The criteria can be found in FAA Order 7210.3, Section 12. As examples, the requirement for an airport at sea level to conduct land and hold short operations for a Group 1 airplane is a distance of at least 1650 feet from the landing threshold to the intersecting runway edge, and for a Group 5 airplane is at least 8400 feet. The following aircraft are given as examples: the Helio Courier is a SOIR Group 1 airplane, the Beechcraft Bonanza and Cessna 152 are SOIR Group 2 airplanes, the Cessna Citation and Beech Starship are SOIR Group 3 airplanes, the Boeing 727 and McDonnell-Douglas DC-9 are SOIR Group 4 airplanes, and the Lockheed L1011 and Boeing 767 are SOIR Group 5 airplanes.

In addition, many terminals use locally defined categories of aircraft not published in 7110.65 to facilitate procedures. These categories are published in local Letters of Agreement between facilities and generally group aircraft for the purposes of runway assignments and approach routes.

3. BACKGROUND OF SEPARATION REQUIREMENTS

Before the introduction of radar, enroute separation under IFR was accomplished by **procedural separation**. Lateral separation was provided through different routing or by ensuring sufficient spacing along a route. The spacing along a route was calculated based on aircraft speed and updated with pilot position reports. The amount of separation that was sufficient was not clearly defined. Vertical separation was also used. Aircraft traveling in the same direction along a route were generally separated by two thousand feet. Traffic traveling in the opposite direction were assigned the thousand foot altitudes in between and thus were separated from on-coming traffic by one thousand feet.

The first radio routes were established in the late 1920's and were known as "four course radio ranges." [6] A low frequency ground station was used to transmit overlapping Morse code letters A (dot-dash) and N (dash-dot) in four quadrants. The four ranges or directions relative to the station were determined by the pilot aurally when the A and N signals overlapped thus producing a steady tone. The routes or "airways" were established using a network of stations connecting from two to four ranges from each station. Low powered radio beacons were used to mark points along an airway. Longitudinal separation along routes was time based and depended on position reports and estimated times of arrivals at fixes provided by pilots and updated as they progressed along the route.

Aircraft arriving in the terminal area in IMC were required to conduct instrument approach procedures in order to land. This required maneuvering and descending in a block of airspace reserved for the approach. Procedural separation consisted of reserving that airspace for one aircraft at a time. Other arriving aircraft would have to hold in a holding pattern outside of the reserved airspace until it was clear. Generally, holding was conducted in a specified quadrant relative to a radio range and the let down for the approach was started over the range out bound. Timed approaches could be used if there was a missed approach procedure that did not involve a course reversal and the ceiling and visibility were high enough to allow circling around the airport. In the case of a timed approach, a succeeding aircraft was cleared to descend to the altitude vacated by the preceding aircraft and given a specified time to depart the approach fix. Aircraft were then separated by time as they crossed the final approach fix and were protected by a non-conflicting route in the event of a missed approach.

The Radio Technical Commission for Aeronautics (RTCA) Special Committee 31 recommended in 1948 that the development of the air traffic control system proceed around the use of the VHF omnidirectional range (VOR) and distance measuring equipment (DME) as the primary navigation system. In that same report the RTCA also recommended the use of airport surveillance radar at busy airports and air traffic control centers. The report recommended the development and use of a radar beacon transponder system capable of reporting aircraft identification and altitude as well as location when interrogated by ground radar [6].

Rockman [12, 13] citing Briddon et al. [14], original radar air traffic control procedures manuals, and conversations with those involved with the introduction of radar control, gives an excellent overview on the origin of the radar separation minimums. Rockman points out that shortly after the opening of the first radar-equipped control tower in Indianapolis, the *Radar Procedures Manual* specified "the aircraft may be turned toward the desired course by the radar controller and given headings which will keep it at least three miles laterally from all holding aircraft until past the pattern." Rockman found that 2-mile longitudinal separation for aircraft on final approach was initially allowed, but was changed with the adoption of a 3-mile horizontal separation criteria agreed to by the Civil Aeronautics Administration (CAA) and industry sometime in 1949 or 1950. The 3-mile separation criteria was apparently a consensus of interested users of Washington's National Airport. The current 5-mile separation requirement for aircraft more than 40 miles from a radar site shows up in the *Third Edition of Radar Procedures for Airport Control Towers* in 1953.

In addition, Rockman [12, 13] states

> *The choice of 5 miles was almost certainly influenced by the fact that radar target arcs of more distant targets appear wider on the radar screen, and this is almost certainly why a larger separation minimum was deemed necessary for targets sufficiently far from the radar site. However, to the author (and to many other observers) there does not appear to have been a precise rationale, at the time, for the 3- and 5-mile figures.*
>
> *In fact, an unpublished FAA staff study from the early 1970's flatly asserts "no rationale exists for the broadband radar minima."*

In summary, the current three and five mile radar separation standards were apparently established based on radar accuracy, display target size, and controller and pilot confidence and represent a consensus of the users at the time radar was introduced. There appears to be no specific analysis leading to these standards. Other factors, such as human reaction time, seem to be implicitly included in these standards.

An aircraft in flight will produce a cyclonic sustained **wake vortex** trailing from each wing tip due to the pressure differences on the wing. The problems with encountering wake vortices were not considered to be important until 1969 and were generated by concerns over the introduction of the new jumbo Boeing-747, and military Lockheed C-5A. In addition, the B-707-300 and DC-8-63 had attained maximum gross takeoff weights of around 300,000 pounds. In January 1970 an interim standard was introduced, based on analysis, which required all aircraft within 60 degrees either side and 2,000 feet below, to be at least 10 miles behind a Boeing 747 or Lockheed C5-A Galaxy [14]. By February, the requirement had been amended to 5 miles based on experimental studies, but it was applied to various other large jet aircraft as well. Before 1970, the 3 mile radar separation standard was used for all classes of aircraft. The first wake vortex separation standards using the Heavy, Large, Small weight categories were introduced in 1970 [15]. In 1972, a DC-9 two miles behind a DC-10 crashed at Fort Worth and it was concluded that this was due to a wake vortex encounter [6]. The standards were revised in 1975 and again just recently when the B-757 was separated out to a new category that requires a 4-mile spacing behind it for all classes of aircraft.

In June of 1970, the concept of a Terminal Control Area (TCA) was introduced which required positive separation of aircraft in the busiest (Group I) TCAs. There were initially 10 Group I TCAs and 14 Group II TCAs. These terms were recently dropped in favor of the International Civil Aviation Organization (ICAO) classification of airspace. Group I TCAs corresponded roughly to Class B airspace and Group II TCAs to Class C airspace.

By the end of 1970, the first operational Automated Radar Terminal System (ARTS) III system was delivered to Chicago's O'Hare International Airport. The system went operational in

June of the next year and was commissioned in October 1971 [14]. The ARTS III system could detect, track, and predict secondary radar targets and uses computer generated symbols and alphanumeric characters to display flight data on the radar display screen. The data include aircraft ID, altitude, ground speed, and flight plan data. In late 1971, positive control airspace was lowered from 24,000 feet to 18,000 feet. This airspace, from 18,000 to FL600, is now called Class A airspace.

In the late 1980's the three mile radar and wake vortex separation minimums were reduced, at approved airports, to two and one half miles between certain aircraft established on the localizer of the same runway and inside the outer marker. Section 4.5 details the specific conditions that must be met. The analysis to support this reduction was done by Swedish [16]. The reduction to two and one half miles was later expanded to include aircraft within ten miles of the runway. There are restrictions in the use of the two and one half mile separation (see Section 4.5), however it is approved at many major terminals. The major operational advantage is at airports that have a high percentage of Large weight class aircraft. However, note that this is a minimum separation allowed during the final approach, a period of time that the controller does not have speed control over the aircraft. Therefore, the separation is generally three miles at the start of the approach and the two and one half mile limit makes up the buffer for the case where the second aircraft overtakes the first aircraft. This compression effect, as explained in Section 2.3, is due to speed reductions that take place during final approach.

4. CURRENT SEPARATION REQUIREMENTS

4.1 GENERAL SEPARATION REQUIREMENTS

As stated earlier, separation is accomplished by either visual separation, non-radar procedural separation, or radar separation. Visual separation puts the responsibility for maintaining separation on the pilots and provides no specific limits, either vertically or horizontally. Visual separation may also be applied by the controller when both aircraft are in sight. Procedural separation and radar separation have a complicated set of requirements and quantitative limits. These require *either* vertical separation *or* horizontal separation with the exception that vertical separation can be discontinued before horizontal separation is attained when aircraft have crossed headed in divergent directions. In this report we are primarily concerned with radar separation and especially with radar separation in the terminal area. Separation standards are concurrent constraints and the largest separation requirement applies. That is, there are horizontal separation requirements based on radar target returns, there are wake vortex separation requirements which depend on aircraft weight categories, and there are runway separation requirements for arrivals behind arrivals or departures to the same runway. In the event radar separation requirements would allow a 3-mile separation, but wake vortex requirements would dictate a 6-mile separation, then the wake vortex requirement would be the active constraint. Similarly, an in-trail longitudinal separation of two and one half miles might be allowed for two aircraft during the final portion of an approach, yet the runway separation requirements would still be active and may preclude use of the two and one half mile separation. The remainder of this section is concerned with summarizing and explaining the separation requirements for the National Airspace System with a focus on terminal landing operations at major airports. These requirements are specified in Air Traffic Control Order 7110.65J [1]. Note that separation requirements specified in *miles* in 7110.65J always means *nautical miles.* This is different than the use of miles in weather reports which report visibility in statute miles.

4.2 RADAR SEPARATION

The requirement for radar separation in en route airspace is 5 miles below FL600 and 10 miles at or above FL600 for Stage A **Direct Access Radar Channel (DARC)** and **En Route Automated Radar Tracking System (EARTS)** Mosaic Mode radars. If both aircraft are within 40 miles of the radar antenna and below FL180, then facility directives may specify 3 mile separation. The radars that feed an **Air Route Traffic Control Center (ARTCC)** may be located at up to 15 different sites. The airspace at an ARTCC is divided into "**radar sort boxes**" and each sort box is tied to a radar site. The display at a given **sector** (all airspace "belonging" to an ARTCC is divided into contiguous sectors) may contain input from more than one radar site depending on the sector and sort box geography. This is called a **mosaic** display. The result is that it is not usually reasonable for an en route controller to know whether a target is within 40 miles of the radar site that is tracking that aircraft, therefore all targets in a Center are assumed to be more than 40 miles from a radar site and the 5-mile criterion is adopted. Notwithstanding the general rule, if there is a significant operational advantage to be obtained by modifying a radar site adaptation so that a particular control area will know when targets are within 40 miles of the radar site, then the separation requirement can be reduced to 3 miles in en route airspace when both targets are within 40 miles of the radar site and operating below FL180. EARTS in the

Sensor Mode (as opposed to the Mosaic Mode described above) displays information from the radar input of a single site and the separation requirement is then 3 miles when both aircraft are less than 40 miles from the antenna and 5 miles if either aircraft is 40 miles or more from the antenna.

Note that Class A airspace stops at FL600. Presumably, airspace above FL600 is outside of positive controlled airspace, however, in practice, separation service is provided as needed. Often the operations in this airspace are military and the military may assume responsibility for separation. In any event, the 10 mile separation standard applies above FL600.

Airport Surveillance Radars (ASRs) are found at approach control facilities and used to separate aircraft in the terminal area. The older broadband radars are ASR-7 and ASR-8. The ASR-9 is a new full digital terminal radar system. When using broadband systems or ASR-9 the radar separation requirement is 3 miles when both targets are less than 40 miles from the antenna and 5 miles when either target is 40 miles or more from the antenna site. When transitioning from terminal to en route airspace the separation requirement increases from 3 to 5 miles. While there is no specific requirement (as in the en route case) for the traffic to be below FL180 for the 3-mile separation, the ASR-9 and Broadband Radar Systems are normally found at Terminal Radar Control Facilities and the airspace under their control is usually within approximately 60 miles of the airport and below FL180.

4.3 VERTICAL SEPARATION

The vertical separation limits below FL290 are 1,000 feet for IFR traffic. At FL290 and above, the assigned altitudes are 2,000 feet apart. VFR traffic are interspersed in 500 foot increments between the IFR 1,000 foot levels, however, there is no VFR traffic above 18,000 MSL. Vertical separation can be used in lieu of horizontal separation in a radar environment provided valid altitude reporting of the encoded altitude is provided by the Mode C transponder or the altitude is reported by the pilot. The controller must verify the Mode C altitude report with the pilot when radar contact is initially established. The pilot can provide the altitude over the radio if the Mode C altitude is not provided. In a non-radar environment, altitude separation is based on pilot reporting.

While under radar control, the full 1,000-foot separation must exist or vertical separation is lost and horizontal separation must exist. Vertical separation may be discontinued without regard to horizontal separation under certain conditions when aircraft have passed and are diverging. Vertical separation for aircraft on opposite courses may be discontinued as soon as the aircraft pass and their targets do not touch on the radar screen ("green between"). Vertical separation for aircraft on the same or crossing courses may be discontinued after one aircraft has crossed the projected course of the other, and the angular difference between their courses is at least 15 degrees, and the radar targets do not touch.

4.4 WAKE VORTEX SEPARATION

Wake vortex or wake turbulence procedures specify separation criteria based on the Weight Classes of the aircraft. The Weight Classes were changed by the FAA on July 16, 1996, by Notice 7110.157, which also specified additional wake vortex separation requirements. The new requirements are reflected in this seciton. The Weight Classes are defined in Section 2. The general separation requirements apply to any aircraft operating directly behind or directly behind and less than 1,000 feet below the leading aircraft. They also apply to aircraft following an aircraft conducting an instrument approach. When aircraft are following each other on approach, the wake vortex separation requirements must be maintained to the runway threshold. Wake vortex strength is a function of aircraft weight, speed, wing shape, and configuration (flap setting and the deployment of other wing configuring devices). The greatest vortex strength occurs when the generating aircraft is heavy, clean, and slow. The general wake vortex separation criteria can be expressed in terms of the Weight Classes of the leading and following aircraft as follows:

General Wake Vortex Separation Standards

1. Heavy behind Heavy	4 miles
2. Large, or Heavy behind a Boeing 757	4 miles
3. Small or Large behind a Heavy	5 miles
4. Small behind a Boeing 757	5 miles

There are more stringent wake vortex separation requirements that apply to Small Weight Class aircraft landing behind Large or Heavy aircraft on the same runway or on a parallel runway that is less than 2,500 feet away. These apply whether the lead aircraft is landing, doing a touch and go, or a low approach. Parallel runways less than 2,500 feet apart are considered as a single runway because of the possibility, in certain wind conditions, of the wake vortex from the aircraft on one runway traveling across to the adjacent runway. The low airspeeds used during approach to landings create stronger vortices that dictate the more stringent wake vortex separation standards for Small aircraft following Large or Heavy aircraft during a landing. The additional separation provided to Small aircraft is measured at the time the preceding aircraft is over the runway threshold.

Landing Wake Vortex Separation Standards for Small Aircraft

1. Small behind Large	4 miles
2. Small behind a Boeing 757	5 miles
3. Small behind Heavy	6 miles

The general and landing wake vortex separation requirements can be combined with the normal 3-mile (sometimes 2.5-mile under conditions explained in Section 4.5) radar separation requirement to produce the landing wake vortex separation requirements matrix shown as Table 3. This applies to aircraft following aircraft landing on the same runway or a parallel runway less than 2,500 feet away. This table is often cited as the wake vortex separation matrix but the reader should note that the matrix in Table 3 does not appear anywhere in the regulations. It is a compilation of requirements with subtle differences as to their application as explained above.

Also note that there is a separate category for aircraft following a single type of aircraft, the Boeing 757. This was prompted by recent concerns over the strength of the vortex behind the B-757. Although the B-757 is in the Large category, the maximum certificated gross takeoff weight of the B-757 puts it very near the dividing point between the Large and Heavy categories. Because wake vortex strength is primarily a function of weight, the new distance requirements for following a B-757 were instituted.

Table 3.
Landing Wake Vortex Separation Standards At Threshold

Lead Aircraft -> / Following Aircraft	Heavy	B-757	Large	Small
Heavy	4 miles	4 miles	3 (2.5) miles	3 (2.5) miles
Large	5 miles	4 miles	3 (2.5) miles	3 (2.5) miles
Small	6 miles	5 miles	4 miles	3 (2.5) miles

There are also wake vortex separation requirements for departing aircraft. There is a 2-minute separation requirement for all aircraft departing behind a Heavy jet when departing on the same or parallel runway separated by less than 2,500 feet. There is a requirement to separate aircraft from a Heavy jet by 2 minutes when operating on a runway with a displaced landing threshold if projected flight paths will cross for any departure following a Heavy jet arrival or any arrival following a Heavy jet departure. The pilot of the departing aircraft can initiate a request to deviate from the 2-minute interval. A Small aircraft must be separated by 3 minutes behind a Large aircraft taking off or making a low/missed approach when utilizing opposite direction takeoffs on the same runway. The pilot may also initiate a request to waive this requirement. All aircraft must be separated behind a Heavy jet departing or making a low/missed approach in the opposite direction on the same or parallel runways separated by less than 2,500 feet by 3 minutes.

There are different wake turbulence criteria for intersection departures. Small aircraft weighing 12,500 pounds or less taking off from an intersection in the same or opposite direction behind a preceding Small departure weighing more than 12,500 pounds must not start the takeoff roll until 3 minutes after the preceding aircraft has taken off. All Small aircraft (41,000 pounds or less) making an intersection takeoff (same or opposite direction) behind a preceding Large aircraft must wait 3 minutes. Any aircraft taking off (same or opposite direction) from an intersection on the same runway or parallel runway separated by less than 2,500 feet must not start the takeoff roll until at least 3 minutes after a Heavy aircraft has taken off. Aircraft conducting touch and go and stop and go operations are considered to be departing from an intersection. Air traffic controllers will not approve pilot requests to deviate from the required wake turbulence time interval/distance if the preceding departing aircraft is a Boeing 757 or a Heavy aircraft.

4.5 TERMINAL RADAR SEPARATION REQUIREMENTS FOR APPROACH

If the ceiling is at least 500 feet above the minimum vectoring altitude or minimum IFR altitude and the visibility is at least 3 miles, aircraft *may* be vectored (given heading and altitude assignments) for a visual approach. If the reported weather is less than that specified above, then the aircraft must be vectored to a final approach fix for an instrument approach. If the approach is an ILS, then the aircraft must be vectored onto the localizer at a point at least 2 miles outside the approach gate, which itself is located at least one mile outside the outer marker. Additionally, the aircraft must be vectored so that the intercept angle to the final approach course is no more than 30 degrees. If the weather is 500 feet above the minimum vectoring altitude or minimum IFR altitude and visibility 3 miles or better and the aircraft is vectored for an ILS approach, then it may be vectored to intercept the localizer less than 2 miles outside the approach gate. In that case the intercept angle must be 20 degrees or less. Vectoring to intercept the localizer inside 2 miles of the approach gate can only be done if the weather is at least as good as specified above or the pilot specifically requests such, however the intercept can be no closer than the final approach fix.

Unless visual separation is provided by the tower or by the pilots, radar controllers are required to maintain the 3-mile radar separation and meet wake vortex separation standards during the approach. In certain cases, the separation is allowed to decrease to 2.5 miles within 10 miles of the runway threshold. The requirements for the 2.5-mile reduced separation on final are as follows:

1) the leading aircraft's weight class is the same or less than the trailing aircraft.

2) the leading aircraft is not a Heavy weight class or a Boeing 757.

3) the average runway occupancy time is a documented 50 seconds or less.

4) radar displays are operational in the tower.

5) runway turnoff points are visible from the control tower.

Note that the 3-mile or 2.5-mile radar separation is only an in-trail separation requirement during approach. During instrument approaches to parallel runways, as described in Section 5, the lateral separation between aircraft is less than 3 miles. This is allowed because vertical separation is maintained until the aircraft are established on the localizer and inbound to the runway, after which the precise guidance provided by the localizer during the final approach and the special monitoring by controllers are justification for reduction of the 3-mile separation standard in the lateral spacing.

4.6 RUNWAY SEPARATION

The runway separation requirement for SRS Category III aircraft (everything except light single and twin engine propeller aircraft) is that the lead arriving aircraft must have landed and be clear of the runway before the following arriving aircraft crosses the landing threshold. For the case of an arriving aircraft landing on the same runway behind a departing aircraft, the departing aircraft must have crossed the runway departure end before the arriving aircraft crosses the landing threshold. There is an exception if the controller can determine distances by reference to suitable landmarks, and the departing aircraft is airborne. In that case, it need not have crossed the other end of the runway as long as it is at least 6,000 feet beyond the runway approach threshold when the arriving aircraft crosses the threshold.

If the same runway is being used for departures between successive arrivals, the runway separation requirements may be the active constraint for arrival separation. After an arrival aircraft crossed the runway threshold, the departure aircraft may be cleared to taxi into position and hold for takeoff, but the takeoff cannot begin until the preceding arrival has cleared the runway. And, as explained above, the next arrival cannot cross the threshold until the departing aircraft is airborne and at least 6,000 feet beyond the runway approach threshold.

Light single (SRS Category I) and twin-engine (SRS Category II) piston-powered aircraft have less stringent requirements for landing behind a previous arrival or departure to the same runway. Between sunrise and sunset, if the controller can determine distances by reference to suitable landmarks, a landing Category I aircraft can cross the runway threshold behind a preceding Category I or II arrival that is at least 3,000 feet beyond the runway threshold, and a Category II aircraft can cross the threshold behind a Category I or II aircraft that is at least 4,500 feet beyond the runway threshold. Note that the separation requirements apply to the landing aircraft as it crosses the runway threshold and that the separation may decrease as the landing aircraft overtakes the preceding arrival aircraft on the runway. Similarly, Category I aircraft need only have 3,000 feet when landing behind a departing Category I or II aircraft and Category II aircraft need 4,500 feet when landing behind a departing Category I or II aircraft. If either aircraft is Category III, then the standards described in the paragraph above apply.

An aircraft arriving to a runway with arriving or departing traffic on an intersecting runway may not cross the arrival threshold until the aircraft arriving or departing on the intersecting runway has passed through the intersection. This restriction may not apply if special land and hold short procedures are approved and in use.

4.7 SUMMARY OF TERMINAL ARRIVAL SEPARATION REQUIREMENTS

The requirements for separation of arrival traffic in Class B terminal airspace can be summarized as follows:

1. Traffic must be separated visually, or under radar control. If separated visually, there are *no* requirements for horizontal or vertical separation or for wake vortex separation, but the runway separation requirement (see #5 below) still exists.

2. If separated under radar control, the aircraft must be *either* 3 miles apart horizontally (if both targets are within 40 miles of the radar site), or else 5 miles apart, *or*, separated vertically by 1,000 feet. Vertical separation is dependent on the aircraft's reported altitude from a Mode C transponder or by the pilot, and is not measured directly by the radar. Vertical separation may be discontinued before horizontal separation is achieved if the aircraft flight paths have crossed and are diverging. Aircraft can close to within two and one half miles in-trail separation within 10 miles of the runway during landing but there are specific requirements (see Section 4.5).

3. In addition to the horizontal separation standards listed above, wake turbulence applications require that aircraft operating directly behind or directly behind and less than 1,000 feet below, or following an aircraft conducting an instrument approach be separated by:

1)	Heavy behind Heavy	4 miles
2)	Large/Heavy behind Boeing 757	4 miles
3)	Small/Large behind Heavy	5 miles
4)	Small behind Boeing 757	5 miles

In addition, the following are requirements for a Small aircraft landing (or making a low approach) behind another aircraft on the same runway. These requirements exist at the time the preceding aircraft is over the landing threshold:

1)	Small behind Large	4 miles
2)	Small behind Boeing 757	5 miles
3)	Small behind Heavy	6 miles

Parallel runways less than 2,500 feet apart are considered an single runway for the requirements listed down.

4. If the ceiling is at least 500 feet above the minimum vectoring altitude or minimum IFR altitude and the visibility is at least 3 miles, aircraft may be vectored for a visual approach. Aircraft vectored for an ILS approach must be vectored to intercept the approach course at least two miles outside of the approach gate (unless the pilot requests otherwise) and at an intercept angle of no more than 30 degrees. If the leading aircraft is not of a heavier weight category than the following aircraft and not a Heavy or Boeing 757, and the average runway occupancy time is documented as 50 seconds or less, and there is a radar display in the tower, and the tower cab personnel can see the landing aircraft clear the runway, then the separation is allowed to decrease to 2.5 miles in-trail within 10 miles of the runway.

5. An arriving air carrier (SRS Category III) aircraft may not cross the runway threshold until the preceding arrival has exited the runway except that, between sunrise and sunset, a Category I aircraft can land behind a preceding Category I or II aircraft that is at least 3,000 feet beyond the runway threshold and a Category II airplane can land behind a preceding Category I or II aircraft that is at least 4,500 feet beyond the threshold. Similarly, an arriving air carrier aircraft cannot cross the arrival threshold of the runway until the preceding departing aircraft has crossed the departure end or is airborne and at least 6,000 feet beyond the runway approach threshold and this can be determined visually from the Tower Cab. Category I landing aircraft need only have 3,000 feet behind a departing Category I or II aircraft and Category II aircraft need 4,500 feet landing behind a Category I or II departing aircraft.

An excellent tutorial on air traffic control operations in the terminal area is provided by Mundra [10]. Some of the standards have changed since the 1989 edition and the use of the ICAO system of airspace classification has since been adopted, but otherwise this gives a good overall view of how the terminal air traffic control system works.

5. SIMULTANEOUS ILS OPERATIONS

5.1 VERTICAL SEPARATION DURING ILS OPERATIONS TO PARALLEL RUNWAYS

In the case of parallel runway ILS operations, vertical separation during vectoring to approach is maintained until the aircraft are established in-bound on the localizer. This is accomplished by having the aircraft using one runway maintain an altitude at least 1,000 feet higher than aircraft using the other runway. Once an aircraft is established on the localizer, that aircraft begins its descent when the glide slope is intercepted. Obviously this will occur further from the runway for the aircraft at the higher altitude. Denver International Airport sometimes uses three runways for simultaneous independent instrument approaches. In that case, the aircraft are kept at three different altitudes until established on the localizer. Figure 3 illustrates this procedure.

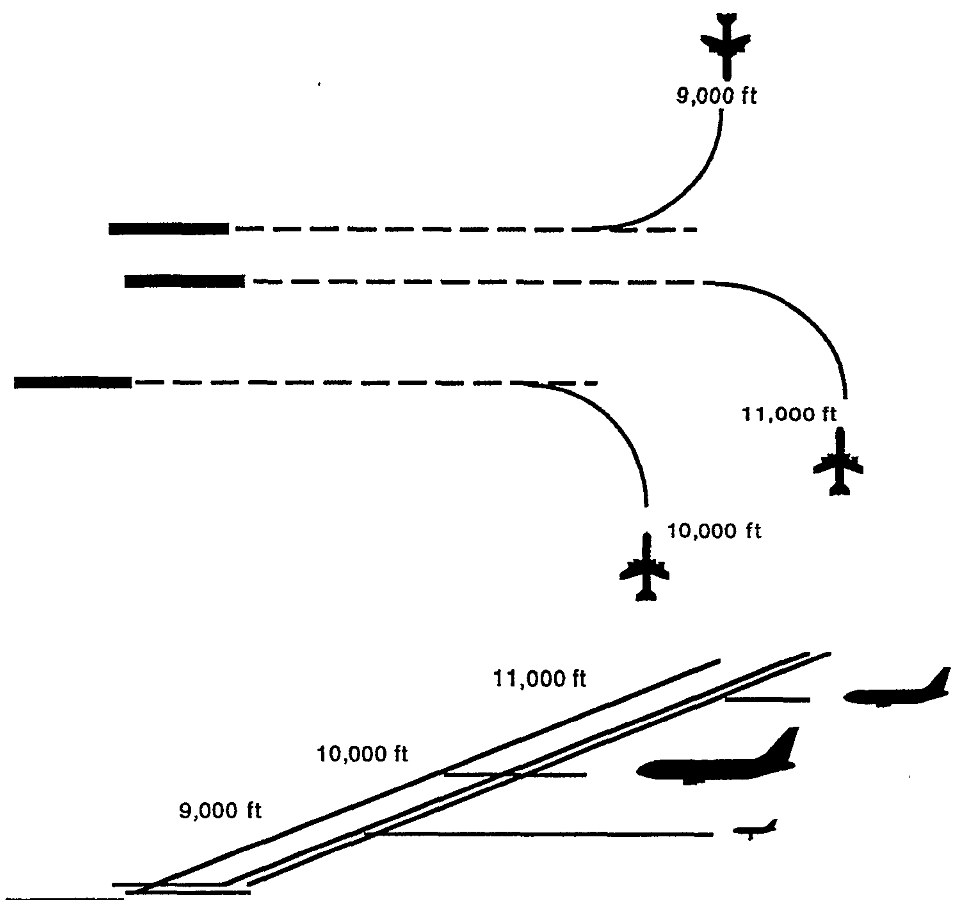

Figure 3. Procedure for maintaining vertical separation during turn-on for simultaneous triple parallel runway approaches at Denver International Airport.

5.2 DEPENDENT PARALLEL ILS OPERATIONS

Dependent parallel runway operations means that separation requirements exist between aircraft on the adjacent approaches as well as between aircraft on an approach to the same runway. When an airport is conducting dependent operations to two parallel runways in IMC and the runways are not greater than 9,000 feet apart, then separation requirements exist diagonally between the aircraft on the parallel runways as well as between the aircraft in-trail to the same runway. The separation requirements are 1.5 miles diagonally between successive aircraft on adjacent courses when the runway centerlines are at least 2,500 feet, but no more than 4,300 feet apart and 2 miles diagonally when the runway centerlines are more than 4,300 feet but no more than 9,000 feet apart. This is illustrated in Figure 4. A minimum of 1,000-foot vertical separation or 3-mile horizontal separation must be maintained during turn on of aircraft to the parallel approaches. These requirements are in addition to the in-trail wake vortex separation requirements shown in Table 1. The diagonal separation requirement is applied only after the aircraft are established on their parallel final approach courses. In order to conduct parallel runway operations in IMC, it is also a requirement that only straight-in landings be made, missed approach procedures do not conflict, and that the aircraft are informed that approaches to both runways are in use. The information that parallel operations are being conducted can be supplied through the pre-recorded **Automatic Terminal Information Service** (ATIS).

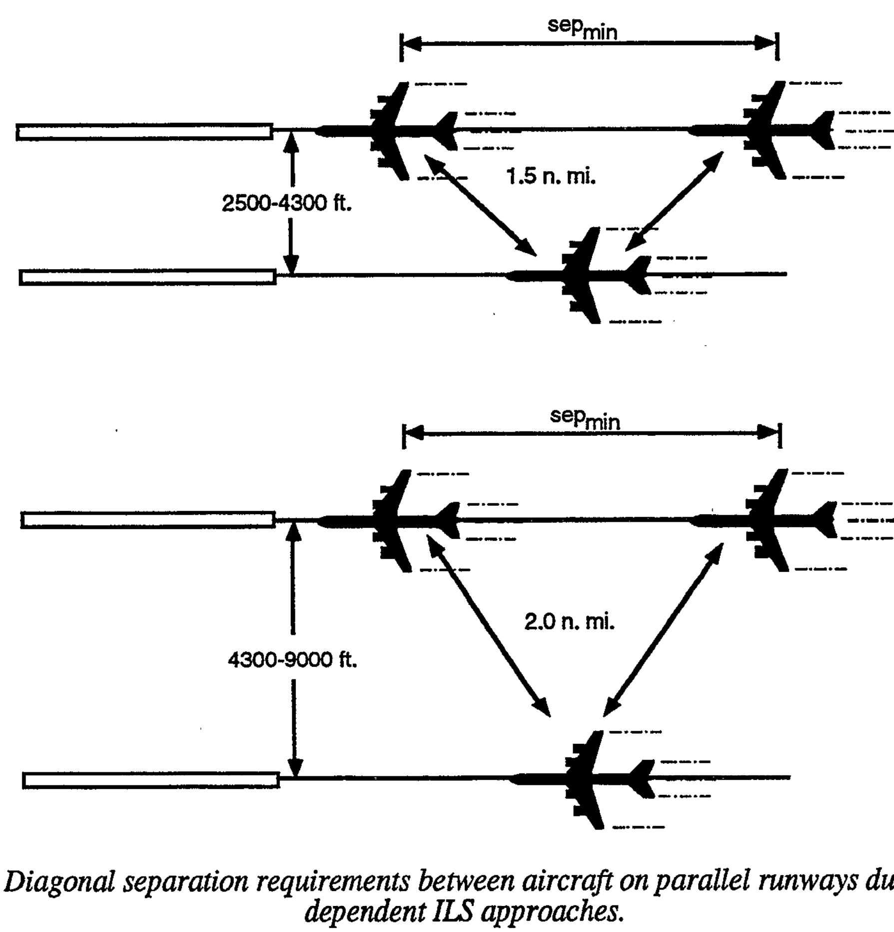

Figure 4. Diagonal separation requirements between aircraft on parallel runways during parallel dependent ILS approaches.

The diagonal separation requirement between aircraft on parallel runways results in an implicit *minimum* allowable separation distance between the aircraft on the same runway according to:

$$sep_{\min} = 2\sqrt{(1.5)^2 - (d/6076)^2}$$

for runways at least 2,500 feet but no more than 4,300 feet apart. d is the distance between the runways expressed in feet and sep_{min} is the implicit separation minimum in nautical miles.

For runways more than 4,300 feet apart but no more than 9,000 feet apart the minimum separation is:

$$sep_{\min} = 2\sqrt{(2.0)^2 - (d/6076)^2}$$

Note that this minimum may not be achieved unless the aircraft on the adjacent runways are perfectly spaced and wake vortex separation requirements do not supersede. These implied minimum same-runway separation requirements are illustrated in Figure 5.

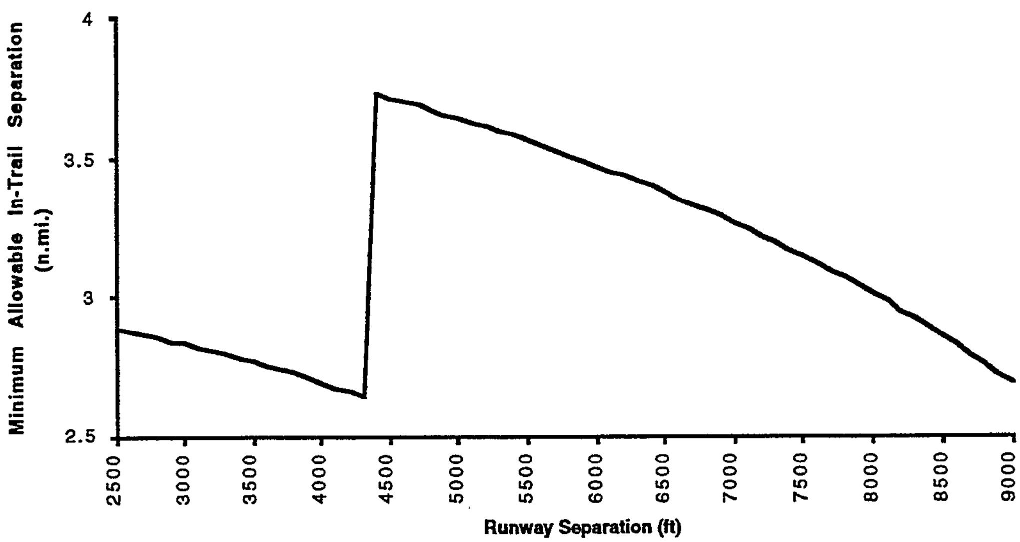

Figure 5. Minimum allowable in-trail separation distance during dependent parallel instrument approach operations as a function of lateral runway separation distance.

One of the consequences of the rule being "segmented" at 4,300 feet is apparent from Figure 5; an airport with runways 4,000 feet apart is allowed to space aircraft closer than one with runways 5,000 feet apart.

5.3 INDEPENDENT PARALLEL ILS OPERATIONS

Simultaneous independent ILS approaches to *dual* parallel runways can be conducted using the airport surveillance radar (ASR) provided the runway centerlines are at least 4,300 feet apart. Simultaneous independent operations to *triple* parallel runways can be conducted if the runway centerlines are at least 5,000 feet apart *and* the airport field elevation is less than 1,000 feet mean sea level. A **no transgression zone** (**NTZ**) at least 2,000 feet wide must be established equidistant between the extended runway centerlines and depicted on a final monitor display. All approaches must be monitored by a final monitor controller regardless of the weather. The approach controller must provide 1,000-foot vertical or 3-mile horizontal separation between aircraft during the turn on to parallel finals and until the aircraft are established on the localizer. Only straight-in landings are allowed and the aircraft must be informed that simultaneous ILS approaches are in use. This may be done on the ATIS. The aircraft must be cleared to descend to the glide slope intercept altitude soon enough to provide enough distance to dissipate any excess speed. This means that the aircraft should be established at the correct altitude before the turn to base leg (perpendicular to the final approach course). The vertical separation requirements as described in Section 5.1 apply.

Simultaneous independent dual ILS approaches to parallel runways separated by 3,400 feet are authorized when a **Precision Runway Monitor** (**PRM**) system is utilized. A PRM system is comprised of a radar with an update rate of 2.4 seconds or less, and a **Final Monitor Aid** (**FMA**). The FMA is a high-resolution expanded scale display used at the final monitor control position and includes alerting algorithms to aid in the early detection of aircraft that violate the NTZ. The requirements for 1,000-foot vertical or 3-mile horizontal separation during turn on, straight-in landings, informing the aircraft of the dual operation, and descending the aircraft in time to lose excess speed, still apply.

If a "high-resolution, color monitor with alert algorithms, such as the Final Monitor Aid or that required in the Precision Runway Monitor program" [1] is in use, then independent triple parallel runway operations can take place when the triple parallel runway centerlines are at least 4,300 feet apart and the field elevation is less than 1,000 feet mean sea level. Triple parallel approaches to airports where the field elevation is 1,000 feet MSL or more (Denver International Airport is currently the only airport in this category) require "the high resolution colormonitor (sic) with alert algorithms and an approved FAA aeronautical study." [1]

Figure 6 is a summary of the requirements for dual and triple dependent and independent approaches as a function of distance between the runway centerlines. Note that the runway centerline separation depiction is not to scale.

Notice that for the case of independent dual parallel runways, there is no differentiation between airports whose field elevation is below 1,000 feet MSL and those at or above 1,000 feet MSL as is the case for independent triple operations. This is according to the requirements listed in paragraphs 5-9-7 and 5-9-8 of Order 7110.65J [1]. The issue is that at airports with higher field elevations, aircraft ground speeds will be higher (due to the less dense atmosphere) and violations of the NTZ may occur more quickly. One explanation for why there is a differentiation of airports above and below 1,000 feet in one case and not the other is that for triple operations, a violation of the NTZ by one airplane could cause the diversion of two other airplanes. In any event, the requirements listed for independent triple parallel runway operations for airports with field elevations above 1,000 MSL came into being after the design of Denver International Airport, and it is likely that the current requirements for independent dual operations would be reviewed in the event approvals were sought for independent dual operations at an airport with a high field elevation.

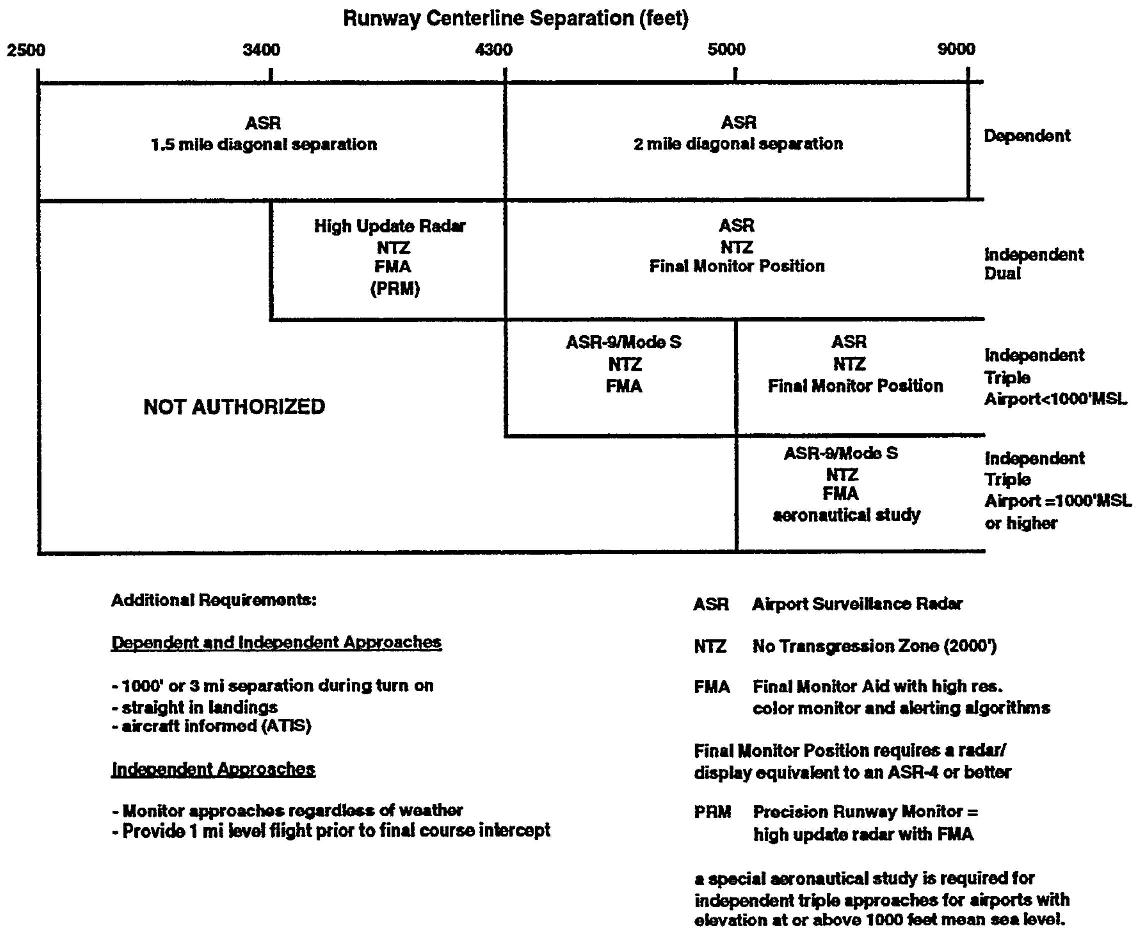

Figure 6. A summary of the requirements for conducting dependent and independent instrument approach operations to dual and triple parallel runways.

5.4 ILS OPERATIONS TO CONVERGING AND INTERSECTING RUNWAYS

The FAA's Air Traffic Control Order 7110.65J [1] lists no requirements for converging ILS approaches. Thus, as Mundra [10] points out, simultaneous operations to converging or intersecting runways may be conducted by providing basic radar separation until visual separation can be assumed by the aircrew. Mundra's research showed that most airports conducted simultaneous approaches to converging or intersecting runways in VFR conditions. Only a few airports conduct simultaneous converging approach operations in IFR conditions. The requirements for **Simultaneous Converging Instrument Approaches (SCIA)** are covered in Order 7110.98. Two significant requirements are that the missed approach points be separated laterally by at least three miles and that the obstacle free missed approach areas do not overlap.

The procedures and requirements for designing instrument approach procedures are contained in the **Terminal Approach Procedures (TERPS)** manual published by the FAA and the two requirements listed above for SCIA operations are sometimes known as "TERPS plus three." These requirements mean that many airports cannot use Order 7110.98 procedures below decision heights of 1,000 feet due to the airport layout.

Dependent Converging Instrument Approaches (DCIA) were developed to permit the use of lower decision heights while protecting for possible consecutive converging missed approaches. The requirements for conducting Dependent Converging Instrument Approaches in IMC were developed by Smith and Mundra [17] and others and implemented by the FAA in the form of a National Order, 7110.110A. The procedures for implementing DCIAs at a specific airport are detailed in an FAA Order for that airport based on the requirements in 7110.110A. The local Order will specify the criteria for conducting Dependent Converging Instrument Approaches, such as the staffing of the Control Tower and the runway configurations that are approved for the operation. In general, this Order will require an operating surveillance radar and operational **Converging Runway Display Aid**, or **CRDA**. The CRDA utilizes existing computers and displays to show actual targets along with a virtual image or "ghost target" [18] of aircraft from a converging approach stream. Ghosts are displayed the same distance from a common reference point as the actual aircraft targets. This common reference point will be the runway intersection when runways cross or will be the point of intersection of the extension of the two runways.

The CRDA aids the controllers in maintaining the required stagger, defined as the difference in range from the common point between two aircraft on converging approaches. For non-Heavy aircraft, this stagger distance will normally be 2 or 2.5 nautical miles depending on the runway configuration, and for Heavy aircraft and Boeing 757s, 5 nautical miles. The Order states that the stagger is applied when the leading aircraft is over the landing threshold, although the stagger and a buffer will normally be applied during the approach. Aircraft with final approach speeds of 160 knots or greater are not authorized to participate in the procedure. When an aircraft has an approach speed of 100 knots or less, the associated slot must be skipped by approach control. The controller must vector to follow the next ghost target or standard separation must be used.

Aircrews are informed by ATIS that dependent converging approaches are in use and will use a special approach procedure chart designated as a converging approach procedure. The only difference will, in general, be that the minimums are higher and there may be a different missed approach procedure than the standard ILS approach to that same runway. These weather minimums will be specified in the facility Order and on the approach procedures. One reason for the higher minimums is that the missed approach points for the two approaches have to be located at least 3 nautical miles apart, so the missed approach points may be located further away from the runway threshold.

The runway separation on intersecting and non-intersecting runways provided under FAA Order 7110.65 as described above still applies.

6. CURRENT STUDIES RELATED TO SEPARATION

6.1 PRECISION RUNWAY MONITOR PROGRAM

The Precision Runway Monitor (PRM) Program was a successful project completed in 1992 that demonstrated the requirements for extending authorization for simultaneous independent parallel ILS approaches to runways separated by as little as 3,400 feet [4, 19]. The requirements call for a high update radar and a Final Monitor Aid (FMA) that depicts a color display of a 2,000-foot wide no transgression zone (NTZ) and has automatic alerting algorithms to alert controllers if an aircraft "blunders" into the NTZ. A good overall description of the program is provided by LaFrey [7]. He lists the major terminals using parallel runway operations and the distance between those runways showing the current dividing line between independent and dependent operations.

Shank and Hollister [20] reported on the risk assessment model used for the PRM system that was instrumental in evaluating the safety of independent operations of runways separated by less than 4,300 feet. This is a three-dimensional Monte Carlo simulation model that evaluates the separation requirements for preventing an accident in the event of a blunder event. This approach is adaptable to other studies that would be necessary for reducing the separation requirements below 3,400 feet. Additional work is on-going using the PRM risk analysis methodology to assess further reductions in runway separation and the impact of modern "glass cockpit aircraft" on lateral separation requirements.

6.2 MULTIPLE PARALLEL APPROACH PROGRAM

The Multiple Parallel Approach Program (MPAP) Technical Work Group (TWG) is comprised of FAA organizations charged with evaluating the use of triple, quadruple, and closely spaced dual parallel runway configurations. Real-time simulations are conducted at the FAA Technical Center in Atlantic City, New Jersey, in an effort to develop and evaluate procedures and technologies that will increase airport capacity and safety. The MPAP program has the capability to simulate proposed operations against test criteria that have been developed over the course of many real-time simulations. Among the simulations being conducted are evaluations of the effectiveness of new and novel glass cockpit displays. It was the MPAP TWG that evaluated and approved the triple runway operation at Denver's new airport. The MPAP TWG determined the need for a Final Monitor Aid at Denver International Airport to conduct simultaneous independent operations to three runways. The airport's elevation and resultant high density altitudes result in high ground speeds that allow less time for corrective action to blunders.

6.3 TERMINAL AIR TRAFFIC CONTROL AUTOMATION PROGRAM

The Terminal Air Traffic Control Automation Program (TATCA) is an FAA administered program with the goal of near-term implementation of automation tools designed to increase airport capacity. The potential benefits of properly engineered tools integrated into today's ATC system include reduced delays, fuel savings, and reduced pilot and controller workload. The TATCA Program is comprised of the Converging Runway Display Aid (CRDA) Program and the Center/TRACON Automation System (CTAS) Program.

6.3.1 Converging Runway Display Aid Program

The Converging Runway Display Aid (CRDA) is a MITRE Corporation developed automation tool designed to assist controllers in spacing aircraft on final approach to converging runways. Previously, airports had been restricted to single or parallel runway operations in IMC. The use of CRDA, in conjunction with approved converging instrument approach procedures, permits operations to two converging runways in IMC.

CRDA makes use of a "ghosting" or imaging concept [18] that projects the location of an aircraft on one approach over to the approach path for the converging runway. This depiction appears as a "ghost" target at a point equally distant from the reference point. The reference point is the intersection of the two runways or their extended centerlines. This aids the controller in maintaining the required dependent spacing to the two runways. CRDA has proved to offer significant capacity improvements to some airports during IMC.

6.3.2 Center/TRACON Automation System Program

CTAS was developed at NASA-Ames[21] and uses workstations external to the ATC Host and ARTS computers that interact with the Host and ARTS to provide three traffic management tools. The Traffic Management Advisor (TMA) provides efficient arrival sequences and runway assignments, the Descent Advisor (DA) provides conflict-free fuel-efficient descents into the terminal area in conjunction with the schedule developed by TMA, and the Final Approach Spacing Tool (FAST) provides terminal approach controllers with speed and vector advisories to aid in attaining the maximum airport capacity. TMA, DA, and FAST are designed to work as one integrated traffic management planner. CTAS is designed to act as an aid to air traffic controllers, not as a replacement, and will adjust to their actions. This is true even if the controller decides to implement a sequence or runway assignment different than that suggested by CTAS. A prototype of the system is being field tested at Denver Air Traffic Control Center and the new Denver airport and at the Dallas-Fort Worth airport. Traffic Management Coordinators in an Air Traffic Control Center's Traffic Management Unit input dynamic airport and airspace restrictions that TMA will schedule to meet. TMA allows the manual rescheduling of any aircraft and will adjust to changes in airport acceptance rates, arrival gate closures, and weather impacts. Work by Spencer, Andrews, and Welch [22] shows that large capacity increases are achievable through precise scheduling and control of traffic in the terminal area.

6.4 FREE FLIGHT

The FAA, through RTCA Inc. (formerly the Radio Technical Commission on Aeronautics), established a Select Committee on Free Flight. The Board of Directors of the Select Committee produced a report in January of 1995 that defines the committee's view of free flight and its incorporation into the National Airspace System [23]. The goal is to develop a system that will allow the user the freedom to choose flight route, altitude, and speed in real time. ATC will provide tactical (short term) resolutions of conflicts. It is envisioned that by the year 2000, the free flight system will be integrated with CTAS in a concept that utilizes direct digital communications between CTAS and the aircraft's flight management system. A final report that will outline the operational concept and steps necessary to achieve free flight is due in 1996. It is not clear yet what effect free flight might have, if any, on separation standards. This will depend on the detailed operational concept that is finally adopted.

6.5 WAKE VORTEX STUDIES

As can be seen from Table 1, the wake vortex separation requirements have a strong impact on airport capacity in the terminal airspace. The Integrated Wake-Vortex Program Plan [24] gives an overview of the wake vortex testing program sponsored by the FAA. The testing was undertaken to better understand the behavior of wake vortices as a function of weather. The goal is to understand those conditions that impose a safety concern and to also understand those conditions that might allow a safe reduction in the wake vortex separation requirements. Reducing these restrictions would provide significant capacity increases and consequent cost savings. The thrust of the research is aimed at developing weather condition standards that might allow a reduction in the current standard, resulting in a dynamic wake vortex separation matrix.

6.6 GPS AUTOMATIC DEPENDENT SURVEILLANCE BROADCAST

The Global Positioning System (GPS) Automatic Dependent Surveillance Broadcast (ADS-B) concept [25, 26, 27, 28] proposes to make use of a data link (Mode S is one candidate) to broadcast GPS derived position. This system offers the potential for surveillance in locations not covered by radar and could eventually replace radar as the primary source of position information for meeting separation requirements. There is also the possibility that, since the aircraft is broadcasting its position, the data could be used by other aircraft to achieve "self-separation" with the proper display of traffic information in the cockpit. A data-link is also proposed to receive differential satellite corrections from the FAA's Wide Area Augmentation System (WAAS) to improve position accuracy. Research in this area is being funded by the FAA. It is anticipated that the augmented GPS system will allow precision approaches, although, as pointed out earlier, the current requirement for a precision approach includes an independent electronic signal for vertical guidance. Certification of GPS for precision approaches may require a change in the current definition of precision approach depending upon the interpretation of "independent" signal. Using the Mode S transponder "squitter" feature, GPS altitude and position information can be broadcast along with aircraft ID approximately once per second. This may be sufficient to support independent parallel runway operations for runways separated by between 3,400 and 4,500 feet. This program will affect surveillance and separation standards in at least two ways. First, by offering increased surveillance accuracy and update rate, the contribution of the radar surveillance system errors to separation standards will be reduced. Second, the broadcast mode of the squitter makes cockpit display of traffic information feasible which may fundamentally change the concept of the current ground based separation system.

7. SEPARATION REQUIREMENTS CHANGE PROCESS

Separation standards are defined both internationally and nationally. The process for changing international standards is more formal and generally takes longer than the process for changing national standards. The following sections detail the change processes and give examples of the analysis needed to support a change in the standards.

7.1 ICAO CHANGE PROCESS

The United States is a member state of the **International Civil Aviation Organization (ICAO)**, and United States FARs and ATC rules must, in general, be in compliance with ICAO requirements. One of the goals of ICAO is to standardize international requirements and systems to facilitate a seamless flight environment throughout the world. ICAO publishes the standards adopted by the member states (there are approximately 183 member states) as **International Standards and Recommended Practices.** They are published as **Annexes to the Convention on International Civil Aviation.** The Convention referred to was held in Chicago in 1944. The ICAO Annexes can be amended during International Conferences held at the ICAO headquarters in Montreal, Canada. During these Conferences, any changes to the International Standards and Recommended Practices are published in the appropriate Annex. Annex 2, Rules of the Air, and Annex 11, Air Traffic Services, are the documents most appropriate to separation standards. The ICAO "Procedures for Air Navigation Services; Rules of the Air and Air Traffic Services" [29] documents separation requirements. There are some differences between the ICAO requirements and those in Air Traffic Control Order 7110.65J. For instance, ICAO provides for Cat III landing minimums lower than those instituted in the United States. ICAO standards also call for four weight classes of aircraft and somewhat more stringent wake vortex separation criteria than is used in the United States domestic airspace. The United States has to deviate from ICAO standards from time to time because of the amount and complexity of its air traffic and because of the airport capacity problems unique to the United States. The United States has, as a member state, the right to have different standards in its sovereign airspace, but these differences are filed with ICAO through the Interagency Group on International Aviation which supports the Department of State. Article 38 of the Convention on International Civil Aviation requires this notification. These differences must be made available to other member states so that they can comment and because aircraft from other states may operate in U.S. airspace. To change a separation standard in the United States, either the ICAO standard itself must be changed, or a difference filed with ICAO and published in the appropriate ICAO Annex.

ICAO lists the factors that should be considered in setting separation standards in ICAO Document 9426-AN/924, Air Traffic Services Planning Manual [30]. The process for changing a standard is involved and takes a considerable length of time. The change must be adopted by a Convention of ICAO and only after extensive review by member states. Appendix A is a reproduction of an ICAO paper entitled "Making A Standard", which was obtained through the Interagency Group on International Aviation [31]. This outlines all of the steps and procedures required to amend a standard and recommended operating practice and defines all of the appropriate terms.

7.2 U.S. DOMESTIC CHANGE PROCESS

The FAA organization that approves standards in the domestic United States airspace is the Flight Standards Service. However, Flight Standards works closely with the Office of Air Traffic in coordinating separation requirements. In effect, both organizations must agree to the change. Within the FAA, there is not the same clear certification/approval process that is present in ICAO. Rockman [12] outlines his concept of the FAA's internal certification process as having three go/no-go decision points.

1. The original proposal results in a feasibility analysis and a costs/benefits analysis. The feasibility analysis considers safety, environmental, and procedural issues. The results of these two analyses are presented in a preliminary operational review at which a go/no-go decision is made for further development.
2. The next step consists of "human-in-the-loop" simulations and demonstrations feeding data back and forth in an effort to establish precise procedures. This results in an updated feasibility and costs/benefits analysis and another go/no-go decision point.
3. The final step starts with a higher-level operational review that generates a strawman specification and sets up procedures for validation and verification. This in turn results in an operational evaluation and a decision for certification and deployment.

If there are outside interested parties, as is usually the case, the FAA will often call upon the Radio Technical Commission on Aeronautics (now known as RTCA Inc.) to set up a Special Committee to look into the requirements for changing standards. Interested parties may include users such as the Air Transport Association (ATA) and Regional Airlines Association (RAA) representing the airlines, the Aircraft Owners and Pilots Association (AOPA) representing general aviation, groups representing business aviation, the Air Line Pilots Association (ALPA) representing the air line pilots, and potential avionics and airframe manufacturers. The process usually involves a mathematical model that calculates a level of safety. If there is a proposal to reduce a current separation standard , then it must be shown that the level of safety will not be reduced. This may be possible by showing that the introduction of a new technology will reduce the contributions from the sources of errors. Alternately, it may be possible to reduce errors through a change in operating procedures or from a combination of procedures and technology. If the proposed change is a significant change to the FARs or procedures that drive separation requirements, a Notice of Proposed Rule Making will be issued to formally allow users an opportunity to comment. For less significant changes, the Office of Air Traffic will issue a Change Proposal. An analysis of the comments may create changes in the proposal or even stop the process. Depending upon the nature of the change, an operational demonstration at one or more sites will be performed before system wide implementation.

7.3 COLLISION RISK MODELS

Usually, some form of analysis is needed to support a reduction in separation standards to prove that the proposed reduction can be implemented without decreasing safety. The seminal work on modeling collision risk and separation standards is probably that of Reich [32] reported in 1966. Reich, in a series of three papers, describes the work of the Royal Aircraft Establishment on analyzing the air collision risk rate and separation standards. Reich used observed error distributions in aircraft assigned positions and then calculated the exposure risk for "all possible directions from which one aircraft can come into collision with another..." Two subsequent approaches to risk analysis methodology are reported here. These are examples of methods used to demonstrate the safety of separation reductions, emphasizing in the first instance the spacing between parallel runways and in the second a collision risk analysis of en route aircraft.

7.3.1 Precision Runway Monitor Program

In the Precision Runway Monitor (PRM) Program, a Blunder Risk Model (BRM) based on Monte Carlo simulations was developed and used to model blunders and determine the probability distribution function of the minimum separation distance between a blundering aircraft and one on an adjacent parallel approach. A blunder occurs when an aircraft on final approach turns towards the adjacent parallel course. The blunder aircraft must be detected and directed back to the original course or else any aircraft on the adjacent course must be directed away from the blunder aircraft. A summary of the history of blunder analysis is contained in Fain [33]. In their analysis for the PRM Program, Shank and Hollister [20] used the accepted definition of a Worst Case Blunder (WCB) as one in which the errant aircraft suddenly deviates thirty degrees towards the adjacent course and does not return to course. The minimum separation which occurs during this event depends upon many factors including the runway separation distance, the relative initial geometry of the aircraft, sensor errors and delays, alerting algorithms, communication delays, human (controller and pilot) response times, and aircraft dynamics. For modeling purposes, a collision was presumed if the centroid positions of the two aircraft came within 500 feet of each other. The BRM model used specified parameters, such as the geometry of the aircrafts' initial positions, and calculated or estimated probability distribution functions, such as pilot and aircraft response times, as inputs to determine the probability of a collision given a Worst Case Blunder.

In this approach, a target fatal accident rate was chosen of one accident per 25 million IMC approaches. This number was derived from accident statistics and selected so as to not significantly increase the overall ILS approach risk as calculated by Yates [34]. The output of the BRM was used to estimate the probability of a collision given a Worst Case Blunder. The probability of a Worst Case Blunder (or any blunder for that matter) is not known since it is such a rare event and there are no statistics available. No blunder has ever resulted in an accident. The approach taken was to use the target collision rate and the BRM results to compute the maximum allowable 30-degree blunder rate. The system was judged acceptable if the calculated 30-degree blunder rate was greater than anyone's intuitive sense of how often a blunder occurs. The value of 4×10^{-3} was used for the probability of a collision given a Worst Case Blunder. This was derived from the BRM for a radar update rate of 2.4 seconds. The value of 4×10^{-6} was used for the target accident rate. This resulted in an acceptable probability of a 30-degree blunder per approach of 1×10^{-3}. To put this in perspective, this equates to about ten 30-degree blunders per year at Chicago's O'Hare airport or fourteen per year at Atlanta Hartsfield. This was deemed much higher than the actual number of any blunders. Shank and Hollister estimate only one out of one hundred blunders is a WCB. Based on these assumptions, the value of 4×10^{-3} for a probability of a collision given a Worst Case Blunder was deemed acceptable.

The PRM work showed that independent operations can be safely conducted for runways separated by 3,400 feet. A requirement that resulted from this study was the need for a high update radar system. The Allied Signal system tested at Raleigh Durham has been approved for operational use and is being installed at Minneapolis-St. Paul International Airport.

This methodology was subsequently extended by Shank, Hollister, Yates, and others for the FAA's Multiple Parallel Approach Program to support the analysis of simulations of triple and closely-spaced dual parallel runways.

7.3.2 Reduced Vertical Separation Minima

Studies by the FAA to develop requirements for safe operation of aircraft with 1,000-foot vertical separation above FL 290 in the domestic U.S. airspace have been underway for over ten years. This is now known as the Reduced Vertical Separation Minima (RVSM) Program. The RTCA established a Special Committee (SC-150) at the request of the FAA to lead this effort. SC-150 broke down, in tree-like fashion, all of the contributing factors that might lead to differences between assigned altitude and the actual altitude for an aircraft. The initial report of SC-150 [35] contains, in its Appendix I, an analysis of the altitude error components; there are over twenty individual contributing factors. The Collision Risk Methodology adopted by SC-150 is reported by Rigolizzo [36]. An extensive data-taking program was undertaken to determine the distribution of actual altitudes around assigned altitudes for aircraft under actual flight conditions. Because of observed errors in altitude, a reduction in vertical separation standards was deemed to be less safe unless there was some change in the accuracy of the altimetry calibration and reporting systems or some change in operational procedures such as requiring autopilots with altitude hold to be engaged. The probability of a collision due to loss of vertical separation is the probability that two aircraft are simultaneously at the same altitude and that they are in the same horizontal location. Since aircraft traveling in opposite direction on an airway can be separated by the minimum altitude separations, the probability of a collision may be looked at as the number of opportunities for a collision (crossings) times the probability that both aircraft are sufficiently far from their assigned altitudes so as to overlap. Clearly, reducing the separation will increase this possibility unless requirements are instituted to reduce the tails of the distribution of aircraft about their assigned altitude.

The target level of safety reported in Rigolizzo's paper was based on ICAO deliberations and is expressed as no more than one midair collision for every 100 million flying hours. This level was used to determine performance specifications. The collision risk methodology is reported in detail in Rigolizzo's paper as well as the procedures used to estimate the input parameters.

7.3.3 The Role of Collision Risk Analysis in Setting Standards

The FAA has formally recognized the role collision risk analysis plays in setting standards. The FAA's position was coordinated for presentation to the Review of General Concepts of Standards Panel and reproduced as an Appendix in Rigolizzo's paper. The FAA endorsed collision risk analysis as a valuable tool stating:

> *Collision risk analysis, used as an aid to establishing conformance to target levels of safety, of necessity, requires use of assumptions which are not readily validated. Nevertheless, it is a valuable analytical tool to support operational judgment in consideration of the integrated effect of navigational performance (lateral, longitudinal, and vertical) separation minima, and traffic density/occupancy on estimated levels of risk. Operational judgment must be used to assure that system changes are made either to improve safety, improve efficiency, or both. Collision risk analysis is particularly useful in assessing the relative impacts of alternative system parameter changes on system safety.*

Although operational judgment will continue to play an essential role in evolving separation standards, improvements to the objective measurement of risk represents a critical element in developing new standards.

7.4 SUMMARY

In summary, there is no formal documented process for implementing a change in separation standards within the FAA, although the process would almost certainly involve the creation of a forum of the FAA (especially Flight Standards, Air Traffic, and Safety), all concerned users, and potential manufacturers. Normally some form of collision risk methodology is necessary to assess that there is no reduction in safety. Although Flight Standards is closely involved in setting the minimum separation standards, it is up to Air Traffic to make sure that the new standards can be safely implemented in an operational environment. Notwithstanding the United States' rights to set separation standards in the U.S. domestic airspace, there is an incentive to be consistent with ICAO Standards and Recommended Practices. There is a formal process for changes to those standards, and the United States must file exceptions if the standards in U.S. airspace are different from those set by ICAO. It should be pointed out that the FAA is an active participant in initiating the analysis and testing that leads to setting ICAO standards. The FAA has formally recognized the role of collision risk analysis in setting standards.

APPENDIX
MAKING A STANDARD[1]

A DOCUMENT OF THE INTERNATIONAL CIVIL AVIATION ORGANIZATION

International standardization is essential to the safe and efficient operation of aircraft. Standardization affects the airworthiness of aircraft and the numerous facilities and services required in support of aircraft operations throughout the world. These facilities and services include such things as aerodromes, communications, navigational aids, meteorology, air traffic services, search and rescue, aeronautical information services and many others. Were it not for uniform rules and procedures, worldwide civil aircraft operations would be chaotic and inefficient to the degree that they would be virtually impractical. These factors and particularly the environment in which an airplane flies anywhere in the world are the chief concern of the International Civil Aviation Organization.

ICAO's headquarters are in Montreal, Canada, with regional offices throughout the world. From its official beginning in 1947 it has grown to an organization of over 140 member States. ICAO's aim is the safe and orderly development of all aspects of international civil aeronautics. It provides the forum whereby requirements and procedures in need of standardization may be introduced, discussed, studied and resolved. It is these technical specifications developed by the deliberative bodies and working groups within the framework of the Organization which ensure the aims of the International Civil Aviation Organization.

Within ICAO technical specifications are developed in the form of:

- Standards and Recommended Practices
- Procedures for Air Navigation Services
- Regional Supplementary Procedures
- Guidance Material

A <u>Standard</u> is a specification recognized as necessary for the safety or regularity of international air navigation. Contracting States must conform to Standards or officially notify ICAO of deviations.

<u>Recommended Practices</u> are specifications recognized as desirable in the interest of safety, uniformity or efficiency of international air navigation. Contracting States endeavor to conform to Recommended Practices and are invited to notify ICAO of existing differences.

Standards and Recommended Practices are adopted by the Council and are incorporated in the Annexes. They are collectively referred to as <u>SARPS.</u>

<u>Procedures for Air Navigation Services (PANS)</u> primarily comprise operating practices and material too detailed for SARPS. They often amplify the basic principles and the

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1 Making A Standard is an International Civil Aviation Organization document obtained through the Interagency Group on International Aviation, Federal Aviation Administration, Department of Transportation, Washington, D.C., from Ms. Roberta Proffitt, and reproduced here in its entirety.

corresponding specification of the Annex. Procedures for Air Navigation Services are approved (rather than adopted) by the Council for world-wide application.

Regional Supplementary Procedures (SUPPS) are similar to PANS but are approved by the Council for regional rather than worldwide application.

ICAO issues Guidance Material in the form of Attachments to Annexes, Technical Manuals and ICAO Circulars in order to facilitate the implementation and promote the uniform application of SARPS and PANS. Attachment to Annexes are approved by the Council usually at the time of the adoption of the related SARPS. Technical Manuals and ICAO Circulars are published under the authority of the Secretary General in accordance with principles and policies approved by the Council.

A simple diagram shows some of the bodies involved in the development of the aforementioned specifications (see Figure A1). Note that the diagram shows these bodies surrounded by the Contracting States. All have some part in the evolution of ICAO Standards including aviation-related international organizations and the aviation experts available throughout the world.

The Assembly, in which all Contracting States are represented, is the sovereign body of ICAO responsible for establishing policies. It meets once every three years to review the work of the Organization in the technical, economic, legal and technical assistance fields.

The Council is the governing body of ICAO. It is a permanent body responsible to the Assembly and is composed of representatives of 30 Contracting States elected by the Assembly for a three-year term. The Council has the responsibility for final adoption of the Standards and Recommended Practices and the approval of procedures.

The principal body concerned with the development of these specifications is the Air Navigation Commission. It is composed of 15 persons with appropriate qualifications and experience in the technical field. Its members are nominated by Contracting States and are appointed by the Council. They are expected to function as independent experts and not as representatives of their States.

The Air Navigation Commission is assisted in its work by the internationally recruited technical personnel of the Air Navigation Bureau of the Secretariat and by panels of experts nominated by Contracting States and selected international organizations.

Meetings are the main vehicle for progress in the air navigation fields. It is through a variety of meetings within the Organization's structure that much of the work is done and the necessary consensus reached in decisions.

The process in the evolution of specifications can be divided into four phases:

1. Proposal
2. Development
3. Review
4. Approval/Adoption

In the first phase (Figure A1) a proposal for a specific study within the broad work programme of the Organization approved by the Assembly can originate from any of the following:

Contracting States

The Council

The Air Navigation Commission

The Secretariat

Air Navigation Meetings

International Organizations

Normally at the start of Phase II, the Development Phase, (Figure A2) the Secretariat analyses proposals and submits its findings to the Air Navigation Commission with a recommendation for future action. Depending upon the importance, maturity and characteristics of the problem, the Air Navigation Commission can submit it for resolution and development of draft technical specifications to any of the following:

Divisional-type Air Navigation Meeting

Technical Panel or Committee

Secretariat

States by Correspondence

Problems in any of the air navigation fields are normally assigned to Air Navigation Conferences or to Divisional Meetings; technical problems dealing with a specific subject and requiring detailed examination are submitted to Technical Panels or Committees; problems which are not mature enough for treatment by a panel or committee tend to be assigned to the Secretariat for study; where a problem is clearly defined, limited in scope and sufficiently mature, the opinions of States may be sought directly by State Letter.

The results of these actions are outlined in Figure A2. Some go directly to the Air Navigation Commission (ANC) for preliminary review in the form of Draft Technical Specifications with a Summary of Discussions and the rest are put into proper form by the Secretariat for ANC's preliminary review. The "Consolidation" is an integrated presentation showing the final effects of the recommendations on existing specifications.

The Preliminary review by the Air Navigation Commission starts the third or Review Phase. Preliminary Review is normally limited to consideration of controversial issues and recommendations which might indicate an oversight or error in previous action. Proposals are then submitted to States for review along with alternative proposals which might have been developed if necessary (See Figure A3). The comments of States and International Organizations are analyzed by the Secretariat and a working paper detailing the comments plus Secretariat proposals based on the analysis is prepared for a final review by the Air Navigation Commission. Following completion of this review, the Secretariat prepares a Draft Report to Council reflecting the Commission's decision. The draft report is reviewed by the Commission and when approved is issued as a Report to the Council by the President of the Air Navigation Commission. This report includes a draft amendment to the forward of the document being amended and also the

Resolution of Adoption which sets forth the Effective Date, the Notification Date and the Applicability Date.

In the final phase (outlined in Figure A4) the Council adopts or approves the specifications as appropriate. In the case of SARPS, States have an opportunity to register disapproval. Shortly after adoption of the amendment by Council, an interim edition of the amendment, called the "Green Edition", is sent to the States with a covering State Letter giving a brief background of the amendment and the changes resulting from it. The States are given the various dates peculiar to the amendment including the date by which they must notify the Council of their disapproval. Providing a majority of the States does not register disapproval, the amendment becomes effective on the date specified and a letter is sent announcing that it has become so. At the same time action is taken by the Secretariat to issue the "Blue Edition" which is the form of the amendment suitable for incorporation in the Annex or PANS.

The Notification Date is the date by which States must notify the Organization of the differences that will exist between their national regulations and the provisions of the Standard as amended.

To avoid confusing the Effective and Applicability dates, consider the Effective Date as the date the amendment is in its final agreed-upon form and the Applicability date as the date that States implement the amendment unless they have notified their differences.

The results of these procedures are that:

Standards and Recommended Practices become part of an appropriate Annex;

Attachment to Annexes and Procedures for Air Navigation Services (PANS), although they developed in the same manner as SARPS, are approved by the Council rather than adopted;

Regional Supplementary Procedures (SUPPS), because of their regional application, do not develop as we have outlined, but are also approved by the Council;

Guidance material - ICAO Circulars and Technical Manuals which amplify and facilitate tile implementation of SARPS and PANS, are published under the authority of the Secretary General in accordance with principles and policies approved by the Council.

From the foregoing it is noted that the process of developing an ICAO technical specification is a lengthy one. It can take several years from the initiation of an idea to the date the specification becomes applicable. The actual period will vary with each problem, but once a proposal has been submitted to the Organization in the form of a draft amendment to a regulatory document, it takes approximately 18 months to process through the stages we have described.

After the Applicability Date--then what? Although the International Civil Aviation Organization has no direct means of enforcing its Standards, they are observed throughout the world. The process may seem lengthy and cumbersome, but it has an outstanding advantage--the repeated consultations and extensive participation of States and International Organizations have produced a consensus based on logic and experience. When States incorporate the specifications in their national regulations, compliance is assured.

As the demand for air navigation services and facilities continues to grow with the expansion of international civil aviation--as new technology calls for new procedures and new standards--ICAO has a system capable of keeping pace with the changes. The International Civil

Aviation Organization will continue to be a vital factor in the safety, efficiency and uniformity so essential to modern-day aviation.

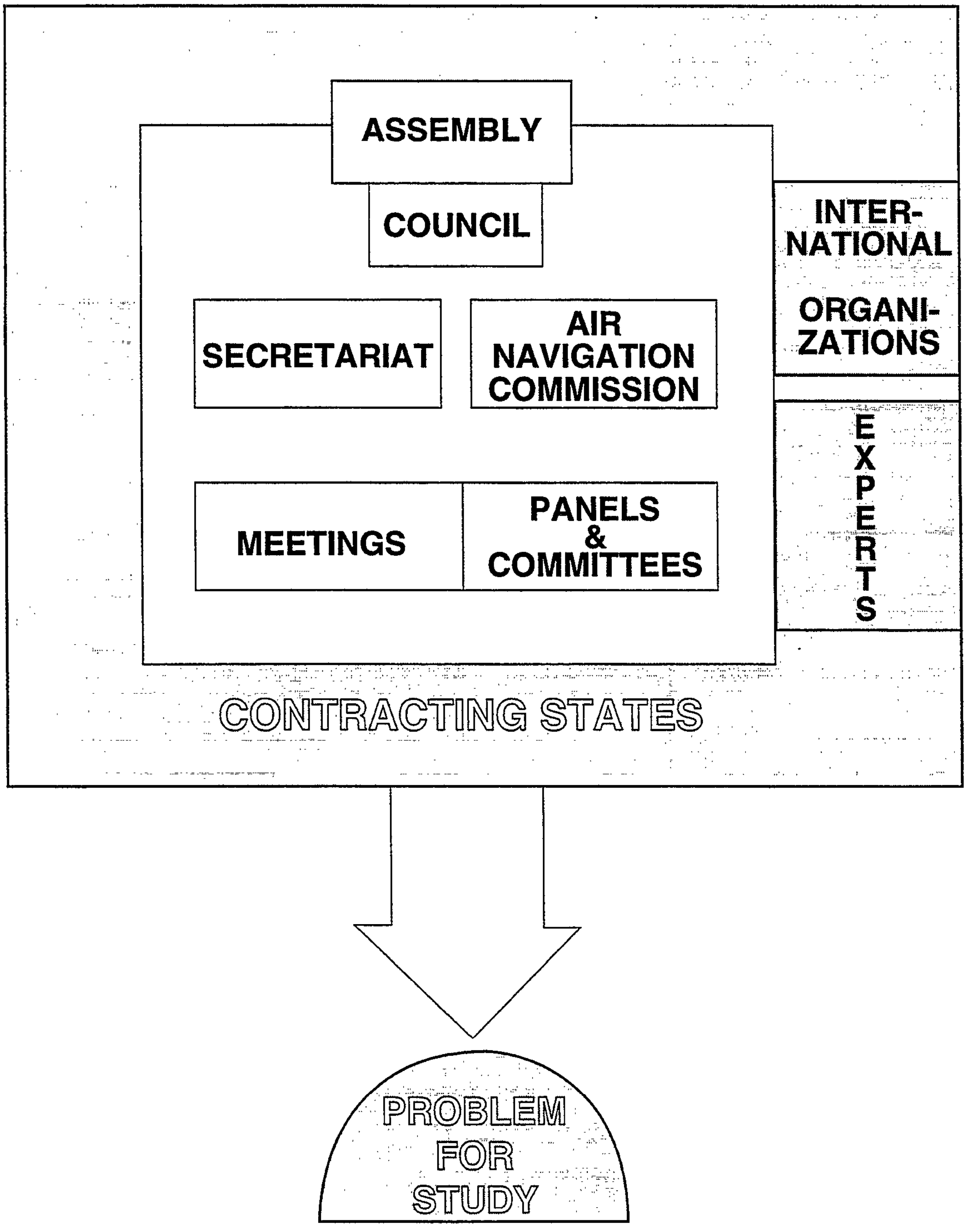

Figure A1. Proposal for a Specific Study for a Change in an ICAO Standard.

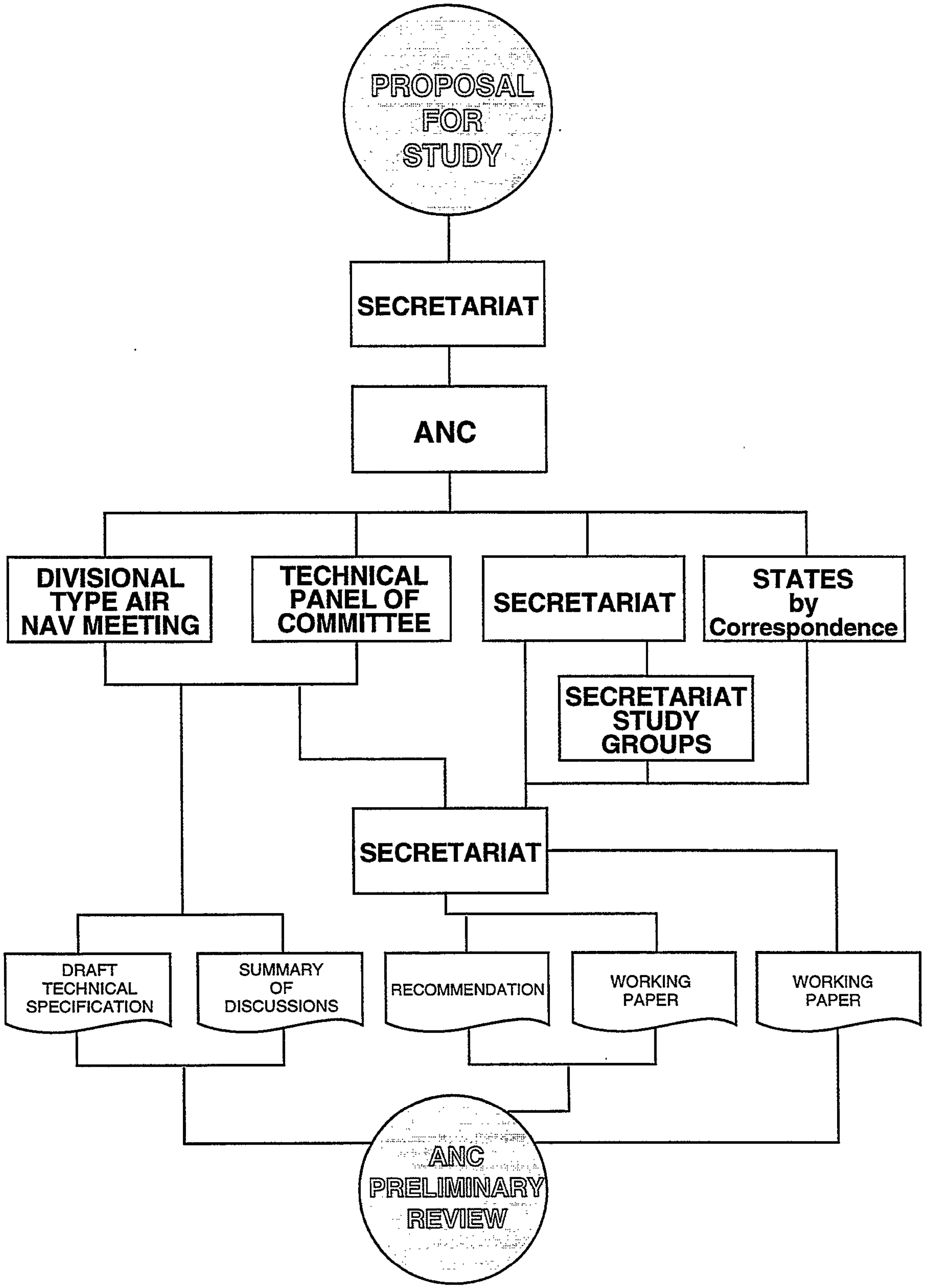

Figure A2. Development Phase for Proposed ICAO Standard Change.

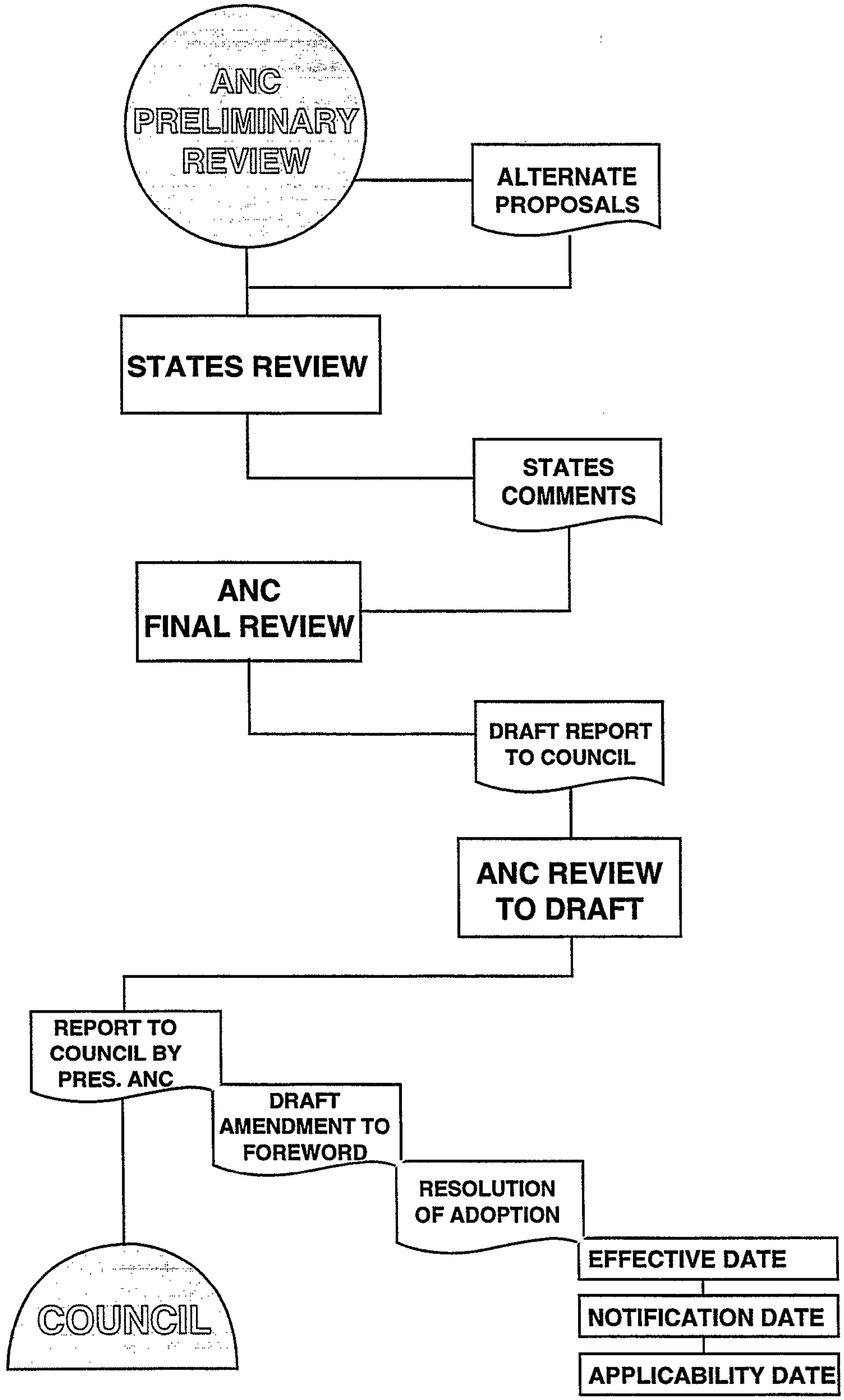

Figure A3. Review Steps for A Proposed Change in an ICAO Standard.

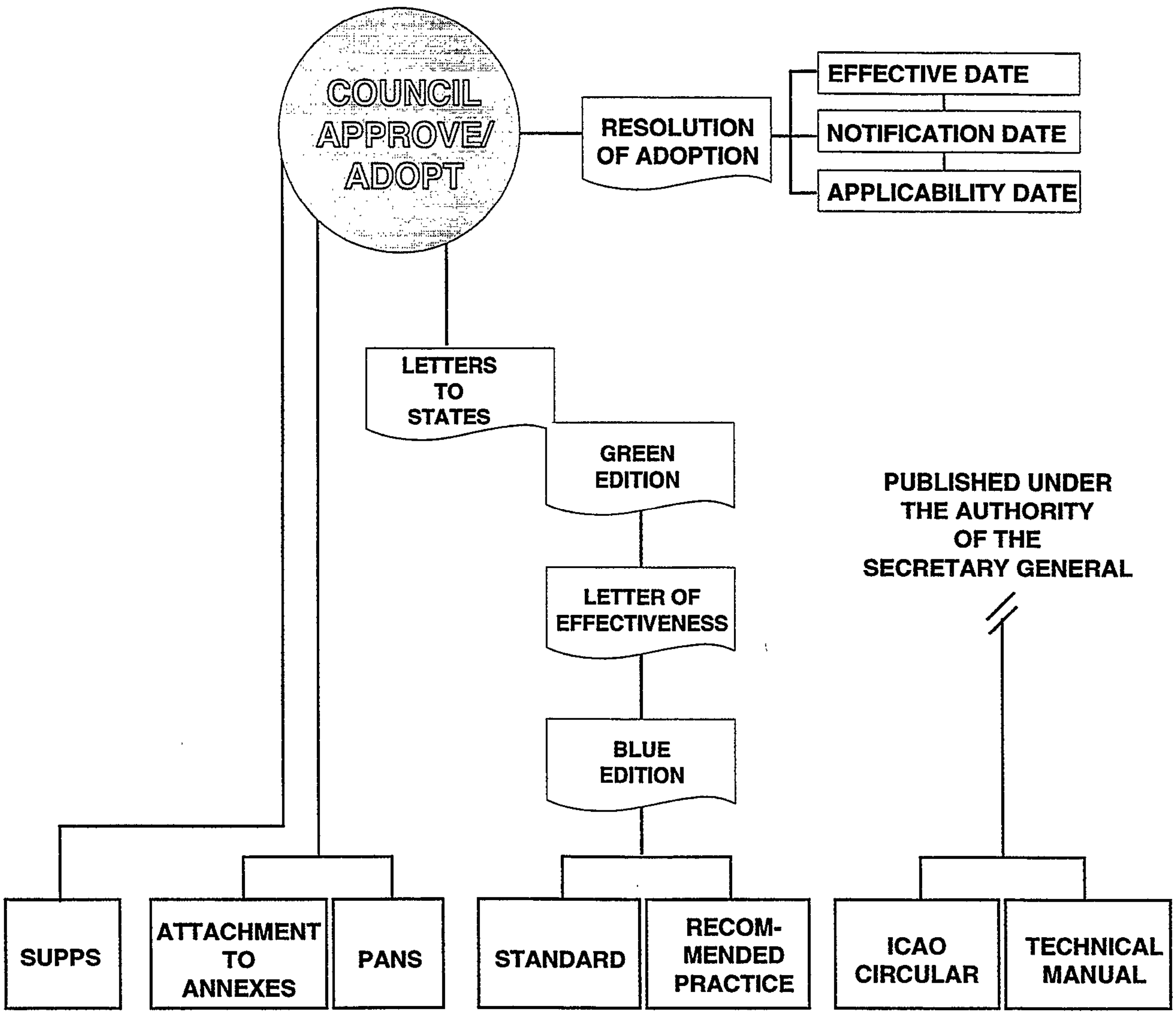

Figure A4. Adoption and Approval Steps for a Change in an ICAO Standard.

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