Manual on Required Navigation Performance (RNP)

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AMENDMENTS

The issue of amendments is announced regularly in the *ICAO Journal* and in the monthly *Supplement to the Catalogue of ICAO Publications and Audio-visual Training Aids*, which holders of this publication should consult. The space below is provided to keep a record of such amendments.

RECORD OF AMENDMENTS AND CORRIGENDA

AMENDMENTS			
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Chapter 1

INTRODUCTION

1.1 GENERAL

1.1.1 The Special Committee on Future Air Navigation Systems (FANS) identified that the method most commonly used over the years to indicate required navigation capability was to prescribe mandatory carriage of certain equipment. This constrained the optimum application of modern airborne equipment. Also, with satellites becoming available, this method would impose a laborious selection process by the International Civil Aviation Organization. To overcome these problems, the committee developed the concept of required navigation performance capability (RNPC). FANS defined RNPC as *a parameter describing lateral deviations from assigned or selected track as well as along track position fixing accuracy on the basis of an appropriate containment level*. Although this concept avoids the need for ICAO selection between competing systems from the beginning, it does not prevent ICAO from dealing with navigation techniques that are in use internationally. The RNPC concept was approved by the ICAO Council and was assigned to the Review of the General Concept of Separation Panel (RGCSP) for further elaboration. The RGCSP, in 1990, noting that capability and performance were distinctively different and that airspace planning is dependent on measured performance rather than designed-in capability, changed RNPC to required navigation performance (RNP).

1.1.2 The RGCSP then developed the concept of RNP further by expanding it to be a statement of the navigation performance accuracy necessary for operation within a defined airspace. A specified type of RNP is intended to define the navigation performance of the population of users within the airspace commensurate with the navigation capability within the airspace. RNP types are identified by a single accuracy value as envisaged by FANS.

1.1.3 System use accuracy is based on the combination of the navigation sensor error, airborne receiver error, display error and flight technical error. This combination is also known as *navigation performance accuracy.*

1.1.4 The RNP types specify the navigation performance accuracy of all the user and navigation system combinations within an airspace. RNP types can be used by airspace planners to determine airspace utilization potential and as an input in defining route widths and traffic separation requirements, although RNP by itself is not sufficient basis for setting a separation standard.

1.1.5 RNP types specify the minimum navigation performance accuracy required in an airspace. It is evident that an aircraft with a less accurate type of RNP would normally be excluded from airspace with more stringent requirements or, alternatively, may be allocated increased separation minima. If appropriately equipped, an aircraft with a level of navigation performance more accurate than that specified can fly in the airspace concerned (e.g. RNP 1 certified aircraft operating in RNP 4 airspace). There may be occasions, however, when for example an aircraft's level of navigation performance accuracy may meet the requirement of a more stringent RNP airspace, based on the navigation aid (navaid) infrastructure, but might not meet the requirements of a less stringent RNP airspace due to the lack of aids appropriate to its navigation equipment fit, e.g. RNP 1 certified aircraft based on dual distance measuring equipment (DME), may not be fitted with appropriate long-range aids to enable operation in RNP 12.6 airspace.

1.2 PURPOSE OF MANUAL

The basic purpose of this guidance material is to explain the concept and provisions of RNP, identify how RNP affects the system providers and system users, and provide regional planning groups with a basis for the development of documents, procedures and programmes to introduce RNP into the airspace. This manual supersedes the *Manual of Area Navigation (RNAV) Operations* (Doc 9573) and contains all relevant material from that document.

1.3 EXPLANATION OF TERMS

1.3.1 Development and explanation of RNP relies on the understanding of some particular terms. These terms have the following meanings:

Area navigation (RNAV). A method of navigation that permits aircraft operation on any desired flight path.

Navigation performance accuracy. The total system error (TSE) allowed in the individual lateral and longitudinal dimensions. TSE in each dimension must not exceed the specified RNP type for 95 per cent of the flight time on any portion of any single flight.

Required navigation performance (RNP). A statement of the navigation performance necessary for operation within a defined airspace. Navigation performance and requirements are defined for a particular RNP type and/or application.

Total system error. In the lateral dimension, a combination of navigation system error, RNAV computation error, display system error and FTE. In the longitudinal dimension, a combination of navigation system error, RNAV computation error, and display system error. (See section 3.2 and Appendix C (Estimating Navigation Performance Accuracy)).

1.3.2 Explanations of these and other terms associated with airborne navigation are included in Appendix A.

Chapter 2

CONCEPT AND APPLICATION OF REQUIRED NAVIGATION PERFORMANCE

2.1 GENERAL

2.1.1 The continuing growth of aviation places increasing demands on airspace capacity and emphasizes the need for the optimum utilization of the available airspace. These factors, allied with the requirement for operational efficiency in terms of direct routings and track-keeping accuracy, together with the enhanced accuracy of current navigation systems, have resulted in the concept of RNP.

2.1.2 RNP as a concept applies to navigation performance within an airspace and therefore affects both the airspace and the aircraft. RNP is intended to characterize an airspace through a statement of the navigation performance accuracy (RNP type) to be achieved within the airspace. The RNP type is based on a navigation performance accuracy value that is expected to be achieved at least 95 per cent of the time by the population of aircraft operating within the airspace.

2.1.3 The development of the RNP concept recognizes that current aircraft navigation systems are capable of achieving a predictable level of navigation performance accuracy and that a more efficient use of available airspace can be realized on the basis of this navigation capability.

2.1.4 Several factors may affect States' decisions as to which approval type (e.g. RNP 1, RNP 4) will be required along various air traffic services (ATS) routes for particular procedures, or in various areas. Area navigation (RNAV) equipment approval should address protected airspace where separation is predicated on ATS route widths.

2.1.5 Other types of navigation (which may or may not be based on RNAV) should, for an interim period, be permitted using conventional VOR/DME-defined ATS routes in accordance with international agreements reached for a particular region or State.

2.2 RNAV OPERATIONS WITHIN THE RNP CONCEPT

2.2.1 It is anticipated that most aircraft operating in the future RNP environment will carry some type of RNAV equipment. The carriage of RNAV equipment may even be required in some regions or States. This guidance material therefore makes frequent reference to the use of RNAV equipment. In order to receive approval to operate in an RNP environment, RNAV equipment should be required to provide at least the capabilities and features (or their equivalents) applicable to the appropriate RNP type as listed in section 5.2 of this manual.

2.2.2 Chapter 5 of this manual provides detailed guidance for defining operational and functional requirements applicable to the use of RNAV equipment in RNP environments. The guidance material is intended to ensure that RNP and related RNAV capabilities are implemented in a uniform and harmonized manner on a global basis. The operational and functional requirements should consequently be applicable to all RNAV-equipped aircraft intending to operate within airspace for which RNP has been prescribed by States or on the basis of regional air navigation agreement.

2.2.3 RNAV equipment operates by automatically determining the aircraft position from one or more of a variety of inputs. Distances along and across track are computed to provide the estimated time to a selected waypoint, together with a continuous indication of steering guidance that may be used, for example, in a horizontal situation indicator (HSI). In some States, accuracy requirements are such that RNAV equipment must either be coupled or capable of being coupled to the autopilot. A wide range of associated navigation data can also be obtained.

2.2.4 RNAV operations within the RNP concept permit flight in any airspace within prescribed accuracy tolerances without the need to fly directly over ground-based navigation facilities. This guidance material is primarily related to the use of RNAV equipment for en-route phases of flight.

2.2.5 The application of RNAV techniques in various parts of the world has already been shown to provide a number of advantages over more conventional forms of navigation and to provide a number of benefits, including:

a) establishment of more direct routes permitting a reduction in flight distances;

b) establishment of dual or parallel routes to accommodate a greater flow of en-route traffic;

c) establishment of bypass routes for aircraft over-flying high-density terminal areas;

d) establishment of alternatives or contingency routes on either a planned or an ad hoc basis;

e) establishment of optimum locations for holding patterns; and

f) reduction in the number of ground navigation facilities.

There is a need to ensure compatibility with requirements that may be specified for other phases of flight and the potential also exists to utilize RNP for the establishment of optimum arrival/departure routes and approaches; all of these benefits are advantageous to States, air traffic service (ATS) providers and users.

2.3 AIRSPACE USE

Defining RNP airspace

2.3.1 RNP may be specified for a route, a number of routes, an area, volume of airspace or any airspace of defined dimensions that an airspace planner or authority chooses. Potential applications of RNP include:*

a) a defined airspace, such as North Atlantic minimum navigation performance specifications (MNPS) airspace;

b) a fixed ATS route, such as between Sydney, Australia and Auckland, New Zealand;

c) random track operations, such as between Hawaii and Japan; and

d) a volume of airspace, such as a block altitude on a specified route.

2.3.2 An RNP type should be selected in order to meet requirements such as forecast traffic demand in a given airspace. This required navigation performance will determine the necessary level of aircraft equipage and airspace infrastructure.

Applying RNP in an airspace

2.3.3 Ideally, airspace should have a single RNP type; however, RNP types may be mixed within a given airspace. An example would be a more stringent RNP type (DME-DME) being applied to a specific route in a very high frequency (VHF) omnidirectional radio range (VOR)/DME airspace or a less stringent RNP type applied to a specific airspace.

2.3.4 RNP can apply from take-off to landing with the different phases of flight requiring different RNP types. As an example, an RNP type for take-off and landing may be very stringent whereas the RNP type for en-route may be less demanding.

2.3.5 Discussions of RNP types and application to airspace are provided in Chapters 3 and 4.

Relation of RNP to separation minima

2.3.6 RNP is a navigation requirement and is only one factor to be used in the determination of required separation minima. RNP alone cannot and should not imply or express any separation standard or minima. Before any State makes a decision to establish route spacing and aircraft separation minima, the State must also consider the airspace infra-structure which includes surveillance and communications. In addition, the State must take into account other parameters such as intervention capability, capacity, airspace structure and occupancy or passing frequency (exposure).** A general methodology for determining separation minima has been developed by the RGCSP.***

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* These examples are not exhaustive; they show but a few ways to apply RNP.

** See ICAO Circular 120 — *Methodology for the Derivation of Separation Minima Applied to the Spacing between Parallel Tracks in ATS Route Structures*.

*** *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (Doc 9689).

2.3.7 RNP is a fundamental parameter in the determination of safe separation standards. Figure 2-1 graphically represents broad categories of the fundamental parameters to be considered when envisaging a separation standard change. Figure 2-1, in basic terms, shows that the risk of collision is a function of navigation performance, aircraft exposure, and the airspace system's ability to intervene to prevent a collision or maintain an acceptable level of navigation performance. An increase in traffic in a particular airspace can result in airspace planners considering a change in airspace utilization (e.g. separation minima, route configuration) while maintaining an acceptable level of risk. In collision risk analysis, this acceptable level of risk is referred to as the target level of safety (TLS). Other metrics may be used for different types of analyses. Once the separation criteria and the TLS are determined, a minimum level of performance can be set for the airspace system parameters of navigation and intervention.

2.4 AIRCRAFT PERFORMANCE

2.4.1 The concept of RNP is based on the expected navigation performance accuracy of the population of aircraft using the airspace. This in turn places demands on individual aircraft, manufacturers of aircraft and aircraft operators to achieve the navigation performance required for a specific RNP type airspace on each flight. The RNP concept may also require different aircraft functional capabilities in different types of RNP airspaces. As an example, an RNP airspace with a high accuracy requirement may have functional requirements for parallel offset capability, whereas a less accurate RNP airspace may only require point-to-point navigation capability.

2.4.2 RNP aircraft requirements are presented in Chapter 5.

2.5 RNP SERVICE PROVISIONS

2.5.1 Since RNP is defined by a statement on navigation performance accuracy, there is an obligation on the part of the State and the aircraft operator to provide the necessary equipment to achieve the required navigation performance accuracy.

2.5.2 The State must ensure that services (i.e. communications, navigation and surveillance (CNS)) within a given airspace provide safe separation for a defined set of separation standards. The aircraft operator (and State of Registry) must in turn ensure that the aircraft intending to operate in a specified RNP airspace is equipped to achieve the required navigation performance. It should be noted that compliance with RNP requirements can be achieved in many different ways and neither the State nor the aircraft operator is restricted as to how RNP is achieved, as long as it can be demonstrated that the requirements can be met.

2.5.3 RNP operations are presented in Chapter 6.

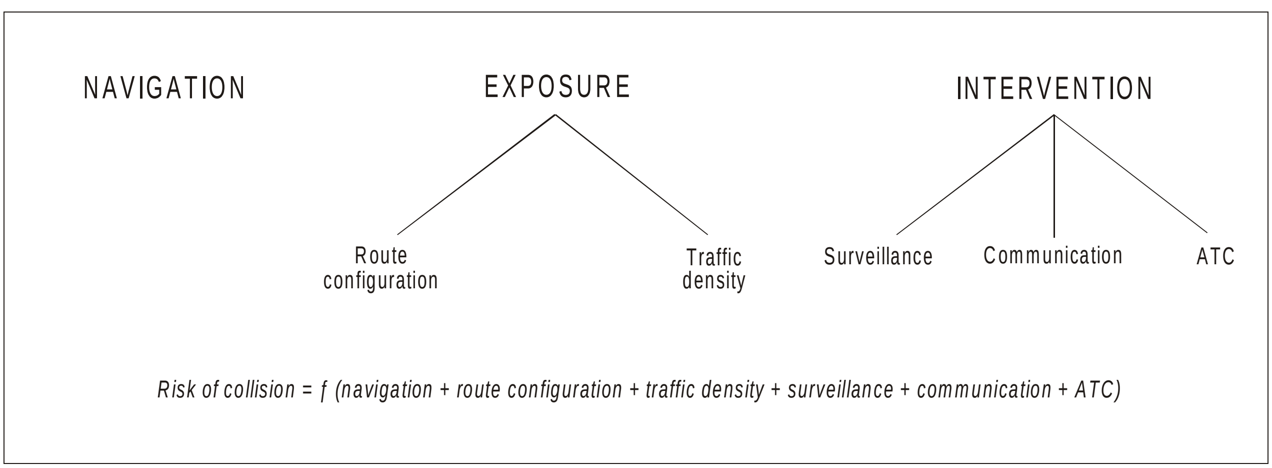

Figure 2-1. Airspace characteristics that affect separation standards

Chapter 3

GENERAL PROVISIONS OF REQUIRED NAVIGATION PERFORMANCE

3.1 GENERAL

The implementation of RNP allows enhancement of ATS system capacity and efficiency while at the same time retaining or improving established system safety. The types of RNP were developed to provide known levels of accuracy for navigation and to support planning for the development of airspace designs, air traffic control procedures and operational procedures. States should determine and make known the means by which the performance can be met within the designated airspace.

3.2 ELEMENTS OF RNP CONTAINMENT

3.2.1 RNP types are specified by airspace planners to establish the total navigation system error (TSE) allowed in the horizontal dimension (lateral and longitudinal) when operating within a defined airspace or on a designated route:

a) in the lateral dimension, the TSE is assumed to be the difference between the true position of the aircraft and the centre line of the route of flight programmed in the navigation system; and

b) in the longitudinal dimension, the TSE is assumed to be the difference between the displayed distance to a specified way-point and the true distance to that point.

3.2.2 In the lateral dimension, the TSE is a combination of the following factors:

a) navigation system error;

b) RNAV computation error;

c) display system error; and

d) flight technical error (FTE).

3.2.3 In the longitudinal dimension, the TSE is a combination of the following factors:

a) navigation system error;

b) RNAV computation error; and

c) display system error.

Note.— See Appendix C — Estimating Navigation Performance Accuracy.

3.2.4 In establishing that an aircraft can navigate to a specific RNP, the lateral and longitudinal (cross-track and along-track) dimensions must be evaluated independently and it must be shown that the TSE in each dimension must not exceed the specified RNP type for 95 per cent of the flight time on any portion of any single flight.

Note.— If the TSE is determined by analysing radial error, then this approach must be equivalent to the requirements in 3.2.4.

3.2.4.1 The following is provided as an example: if the specified RNP type is 1.85 km (1 NM), the approval process must show that the TSE in each dimension must not exceed the specified RNP type for 95 per cent of the flight time on any portion of any single flight:

a) the true position of the aircraft must be within 1.85 km (1 NM) of the programmed route centre line; and

b) the true distance to way-points must be within 1.85 km (1 NM) of the displayed distance to way-points.

3.2.5 No consideration is currently given to time or vertical navigation for the purpose of establishing RNP types for en-route operations. Vertical navigation en route will be based on barometric altimetry for the foreseeable future. If this changes, it may be necessary to consider vertical performance in the classification criteria.

3.3 RNP TYPES

General

3.3.1 In order to simplify RNP types and to make the required accuracy readily apparent to airspace planners, aircraft manufacturers and operators, the RNP type is specified by the accuracy value associated with the RNP airspace.

RNP types

3.3.2 Table 3-1 specifies five RNP types required for general application to en-route operations. These are RNP 1, 4, 10, 12.6 and 20, which represent accuracies of plus or minus 1.85 km (1.0 NM), 7.4 km (4.0 NM), 18.5 km (10 NM), 23.3 km (12.6 NM) and 37 km (20 NM), respectively. The rationale for the choice of RNP values is given in Appendix B.

3.3.3 RNP 1 is envisaged as supporting the most efficient ATS route operations by providing the most accurate position information, and through the use of RNAV allowing the greatest flexibility in routing, routing changes and real-time response to system needs. This classification also provides the most effective support of operations, procedures and airspace management for transition to and from the aerodrome to the required ATS route.

3.3.4 RNP 4 supports ATS routes and airspace design based on limited distance between navaids. This RNP type is normally associated with continental airspace.

3.3.5 RNP 10 supports reduced lateral and longitudinal separation minima and enhanced operational efficiency in oceanic and remote areas where the availability of navigation aids is limited.

3.3.6 RNP 12.6 supports limited optimized routing in areas with a reduced level of navigation facilities.

3.3.7 RNP 20 describes the minimum capability considered acceptable to support ATS route operations. This minimum level of performance is expected to be met by any aircraft in any controlled airspace at any time. Airspace operations or procedures based on capabilities less than those of RNP 20 would not be implemented except in special circumstances.

3.3.8 More demanding RNP types would be required for operations in the vicinity of most aerodromes, i.e. during the transition between aerodrome and ATS route. The possibility of extending the RNP concept to terminal operations is being assessed by ICAO.

3.3.9 Some States may need to implement RNP 5 for an interim period as a derivative of RNP 4, in order to permit the continued operation of present navigation equipment without modification of existing route structures.

3.3.10 Account should be taken of the fact that, in individual States where the navigation accuracy currently achieved for the main fleet of aircraft exceeds the RNP 4 requirements and independent radar monitoring systems are used to monitor the movement of aircraft, a corridor width of ±5 km (±2.7 NM) will continue to be used.

Time frame for RNP implementation

3.3.11 The primary means of achieving RNP is by the use of RNAV equipment which is already in widespread use. Many States and regions are developing considerable experience in such aspects of RNAV operations as airworthiness and operational approvals, airspace planning,

Table 3-1. RNP types — general application

	RNP type				
	1	*4*	*10*	*12.6*	*20*
Accuracy Navigation performance accuracy 95 per cent lateral and longitudinal position accuracy in the designated airspace	±1.85 km (±1.0 NM)	±7.4 km (±4.0 NM)	± 18.5 km (±10 NM)	±23.3 km (±12.6 NM)	±37 km (±20.0 NM)

aircraft separation and route spacing requirements, user techniques, training, publicity and information exchange. Furthermore, RNP 4, RNP 10, RNP 12.6 and RNP 20 have been selected in light of the navigation accuracy currently achievable in various regions, and they can therefore be readily implemented. Full exploitation of RNP 1 will, however, require that a high percentage of the aircraft population be equipped to meet that level of performance. Some operators, therefore, will need to invest in new equipment in order to fully realize the benefits of RNP 1 operations. For these reasons, it is considered that an evolutionary implementation of RNP is necessary and feasible.

Chapter 4

AIRSPACE REQUIREMENTS

4.1 AIRSPACE WHERE RNP APPLIES

RNP could apply to all phases of flight. The five RNP types specified in 3.3.2 to 3.3.10 were developed for general application. It is expected that more stringent RNP values will be needed for operations in the vicinity of most aerodromes. The possibility of defining RNP types applicable to terminal operations, including approach, landing and departure phases of flight, is being assessed by ICAO.

4.2 AIRSPACE CHARACTERISTICS

RNP route

4.2.1 RNP may be applied to ATS routes, including fixed and contingency routes.

Fixed RNP routes

4.2.2 Fixed RNP routes are permanent, published ATS routes which can be flight-planned for use by aircraft approved for a specific RNP type. Restrictions in the times of availability and flight levels are not precluded.

4.2.3 Fixed RNP routes should begin and end at promulgated reporting points, not necessarily defined by ground facilities. Way-points should be established along fixed RNP routes as required by States.

Contingency RNP routes

4.2.4 Contingency RNP routes are published ATS routes which can be flight-planned and which can be made available to aircraft approved for a specific RNP type during limited time periods (hours, days, seasons). They may also be established to meet unusual, temporary requirements arising at short notice.

4.2.5 The guidance on way-points given for fixed RNP routes in 4.2.3 is also appropriate for contingency RNP routes.

RNP area

4.2.6 RNP can apply to an area or a volume of airspace, or any airspace of defined dimensions. Within a defined RNP area, authorities may choose to require a specific RNP type approval for ATS routes.

4.2.7 Additionally, when approved by the State or the appropriate ATC authority, unpublished tracks (i.e. random tracks) may be flight-planned within designated and published RNP areas. They may be permitted:

a) in specified flight information regions or upper flight information regions or in areas laterally defined by geographic coordinates; and

b) during specified periods; and/or

c) within specified flight level bands.

RNP coordinate system

4.2.8 As navigation systems evolve from station-referenced to earth-referenced, an important consideration is the geodetic datum used for determination of actual position.

4.2.9 Geodetic datums are used to establish the precise geographic position and elevation of features on the surface of the earth. They are established at various levels of administration (international, national and local) and form the legal basis for all positioning and navigation. At present, there are many geodetic reference systems in use throughout the world which result in different latitude/longitude definitions of the same point on the ground, according to which system is used. Differences of several hundreds of metres are apparent in some areas of the world and the implications for aircraft flying under

RNP conditions are such that errors of this magnitude may not always be tolerated, especially in terminal areas. Moreover, specific problems may also arise in en-route operations, for example, when aircraft are transferred between area control centres of adjacent countries where different geodetic reference datums are in use. Similarly, aircraft flight management system (FMS) software could employ a different geodetic reference datum from that used to locate ground-based navigation aids (e.g. DME), or earth-referenced navigation aids such as the global navigation satellite system (GNSS). Flight test trials have attributed significant errors to the use of different geodetic reference datums in simulated high-precision RNP environments.

4.2.10 ICAO has chosen the World Geodetic System — 1984 (WGS-84) as the common world geodetic datum as there is a need to:

a) convert coordinates of airport key positions and ground-based navigation aids to a common geodetic reference datum;

b) ensure that all such locations are surveyed to a common standard that provides optimum accuracy, such as that obtained by GNSS surveying techniques; and

c) ensure that all FMS software is referenced to a common geodetic datum.

4.2.11 The ultimate responsibility for the accuracy of position data for aviation use rests with States; however, a collective effort will be required to implement WGS-84 on a global basis before earth-referenced systems can be adopted for all classes of air navigation.

4.3 AIRSPACE REQUIREMENTS

Navigation performance accuracy

Normal performance

4.3.1 RNP is intended to characterize an airspace through a statement of the navigation performance accuracy (RNP type) to be achieved within the airspace during normal flight operations.

4.3.2 If it is necessary for ATC to intervene, to prevent an aircraft from straying from its cleared route, e.g. due to aircraft system failure, navaid out-of-tolerance conditions or blunder errors, sufficient assistance should be provided to enable the aircraft to regain the route centre line and/or proceed to the next way-point.

ATS procedures in RNP airspace

Normal procedures

4.3.3 ATS procedures in RNP airspace will generally be the same as existing ATS procedures and those planned to better utilize RNAV capability.

Special procedures

4.3.4 RNP airspace may have different functional requirements for different RNP types. Such functional requirements are presented in 5.2. As an example, one functional requirement of an RNP type airspace may be the capability to fly offset from the planned route centre line by a specified distance; this is known as the parallel offset. This function can be a very useful tool for ATC in both strategic and tactical situations. In a tactical situation, an offset may be employed instead of radar vectoring in certain circumstances, such as to facilitate an uninterrupted climb or descent. In a strategic situation, a systematic offset may be employed as a means of increasing capacity without impairing safety in the airspace. Details, such as offset distance, turn performance, etc., may need to be covered in regional or ATS inter-facility agreements. Further details on parallel offset functions may be found in 6.1.7 to 6.1.9.

Procedures for transit between different types of RNP airspace

4.3.5 Since there are a number of RNP types and potential applications, careful consideration should be given to the development of transit procedures between different types of RNP airspace. Consideration should be given, but not confined, to the method of accomplishing this transit. This requires detailed planning, including, inter alia:

a) determining the specific points where the traffic will be directed as it transits from an RNP type airspace with a more stringent accuracy to an RNP type airspace with a less stringent accuracy;

b) testing the plan through simulation, once plans for the transit have been formulated;

c) clearing only aircraft approved for operations in specific RNP type airspace; and

d) coordinating with all concerned in order to obtain a regional agreement detailing the required responsibilities.

Flight crew contingency procedures within RNP airspace

4.3.6 The flight crew should notify ATC of contingencies (equipment failures, weather conditions) that affect its ability to maintain navigation accuracy, state its intentions, coordinate a plan of action and obtain a revised ATC clearance.

4.3.7 If unable to notify ATC and obtain an ATC clearance prior to deviating from the assigned flight path, the flight crew should follow established contingency procedures as defined by the region of operation and obtain ATC clearance as soon as possible.

ATC contingency procedures

4.3.8 ATC should be made aware whenever it is impossible for an aircraft to maintain its navigation performance accuracy appropriate to the RNP airspace being used.

4.3.9 Air traffic controllers should take appropriate action to provide increased separation, as well as to coordinate with other ATC units as appropriate, when informed that the flight is not able to maintain the required navigation performance accuracy.

Chapter 5

AIRCRAFT REQUIREMENTS

5.1 GENERAL

5.1.1 There are many different types of navigation equipment currently available that will meet the requirements of one or more RNP types. This equipment covers a wide range of capability and sophistication. The VOR/DME navigation systems and simple RNAV computer systems which can only accept VOR/DME inputs are the least sophisticated of the equipment. The somewhat more complex types of RNAV equipment using inputs such as inertial navigation system (INS) or LORAN-C must also be considered for approval for use, provided that special operating procedures are applied or additional navigation fixes used to ensure that the required navigational accuracy may be maintained. The most sophisticated equipment is seen in the advanced RNAV and FMS with which an increasing number of aircraft are fitted.

5.1.2 The FMS is an integrated system consisting of airborne sensor, receiver and computer with both navigation and aircraft performance databases that provides optimum performance guidance to a display and automatic flight control system, but the term is often used to describe any system which provides some kind of advisory or direct control capability for navigation (lateral and/or vertical), fuel management, route planning, etc. These systems are also described as performance management systems, flight management control systems and navigation management systems. In this guidance material, FMS is used in a generic sense and is not intended to imply any one specific type of system. It is essential to note that, while it is the responsibility of operators to determine the scope of the database used in an FMS, the level of accuracy and thoroughness of the source material on which databases rely are the responsibility of States. Database providers have a responsibility to ensure that they accurately reproduce the source material as provided by States.

5.1.3 Navigation computers are also available for retrofit to existing aircraft. These can be operated in conjunction with INS, LORAN-C or simply with VOR/DME plus air data (heading, true airspeed, etc.). Even with the latter input only, the system can operate accurately as long as the aircraft remains within adequate DME cover; gaps in DME coverage and/or accuracy are acceptable within predefined limits as the system is capable of operating in "memory mode" for limited periods.

5.1.4 Airborne navigation equipment encompasses:

a) systems which use external navigation aids such as VOR/DME, DME/DME, GNSS, LORAN-C; and

b) systems which are self-contained, e.g. INS, or inertial reference systems.

5.1.5 *General operational limitations.* Due to the availability and integrity of the various sensor systems, effects of propagation and bias errors, and potential interference with certain sensors from outside sources, certain operational limitations must be imposed on the use of some types of area navigation equipment installations. These general limitations are as follows:

a) *Operational areas.* The operator should define the area(s) in which operations are intended and ensure that equipment installations are capable of meeting the RNP for those areas; and

b) *Operational equipment*. LORAN-C, VOR/DME and INS without acceptable automatic position updating may not be capable of serving as stand-alone RNAV equipment installations, except when shown to meet the appropriate RNP requirements.

5.1.6 *System availability and continuity.* Navigation systems should be required to demonstrate an acceptable availability and continuity of function prior to approval. National authorities may choose to rely on a redundancy of systems in order to obtain the system availability required. Navigation function availability may be assured by the use of multisensor area navigation systems which incorporate various position-fixing sensors, each of which is individually usable for airborne area navigation. Some RNAV systems permit the use of combinations of systems or pilot selection of one system in preference to another, depending on factors such as reception and weather conditions.

Note.— The term "continuity of function" as used in this paragraph refers to an assurance that, through a combination of sensors or equipage, guidance information permitting navigation to the appropriate level of RNP will continue to be provided for an acceptable period of time after the loss of a sensor.

5.1.7 Operators have the responsibility to ensure the required level of performance within the notified RNP environment by means of appropriate RNAV equipment installations and prescribed procedures and training for the flight crew. Where appropriate, national authorities should provide a means for operators to identify relevant levels of accuracy, integrity and availability for RNP for RNAV routes or procedures.

5.1.8 Procedures and/or capabilities should enable erroneous flight crew inputs to be detected before the aircraft position accuracy can be degraded.

5.1.9 For RNP operations the following equipment provisions need to be considered:

a) RNP 1 and better:

— the equipment should provide a means to confirm reasonableness of sensor input data before the equipment uses the data; and

— the equipment should be able to compute an estimate of its position error, depending on the sensors being used and time elapsed.

b) RNP 4, 10, 12.6 or 20:

— the provisions in a) are desirable.

5.1.10 The airworthiness and operational approval of this equipment will rest with the national aviation administration concerned. States may also need to amend legislation to reflect the use of approved RNAV and FMS equipment for operations in RNP airspace.

5.2 FUNCTIONAL REQUIREMENTS

General

5.2.1 This section is an overview of the essential functions which RNAV equipment should be required to perform. The functions listed below should be viewed as the minimum acceptable level of performance. Commentaries describing the function and the requirements for the applicable RNP types are defined, and detailed information can be found in the RNP Minimum Aviation System Performance Standards (MASPS), contained in RTCA document DO-236A and EUROCAE document ED-75 .

5.2.2 Navigation equipment should be capable of enabling aircraft to be navigated within the constraints of the air traffic service to the accuracy required in a promulgated RNP type of airspace. It is anticipated that most aircraft operating in the future RNP environment will carry some type of RNAV equipment. The carriage of RNAV equipment may be required in some regions or States. This guidance material therefore makes frequent reference to the use of RNAV equipment.

System functions

5.2.3 In order to give the flight crew control over the required lateral guidance functions, RNAV equipment should at least be able to perform the following functions:

a) display present position in:

1) latitude/longitude; or

2) distance/bearing to selected way-point;

b) select or enter the required flight plan through the control display unit (CDU);

c) review and modify navigation data for any part of a flight plan at any stage of flight and store sufficient data to carry out the active flight plan;

d) review, assemble, modify or verify a flight plan in flight, without affecting the guidance outputs;

e) execute a modified flight plan only after positive action by the flight crew;

f) where provided, assemble and verify an alternative flight plan without affecting the active flight plan;

g) assemble a flight plan, either by identifier or by selection of individual way-points from the database, or by creation of way-points from the database, or by creation of way-points defined by latitude/longitude, bearing/distance parameters or other parameters;

h) assemble flight plans by joining routes or route segments;

i) allow verification or adjustment of displayed position;

j) provide automatic sequencing through way-points with turn anticipation. Manual sequencing should also be provided to allow flight over, and return to, way-points;

k) display cross-track error on the CDU;

l) provide time to way-points on the CDU;

m) execute a direct clearance to any way-point;

n) fly parallel tracks at the selected offset distance; offset mode should be clearly indicated;

o) purge previous radio updates;

p) carry out RNAV holding procedures (when defined);

q) make available to the flight crew estimates of positional uncertainty, either as a quality factor or by reference to sensor differences from the computed position;

r) conform to WGS-84 geodetic reference system (as from 1998); and

s) indicate navigation equipment failure.

Desired functions

5.2.4 High-density airspace may require development of specific RNAV functions in order to provide the operational capability to meet increasing demand. Whilst responding to necessary regional needs, the development of these functions should be conducted with close coordination between manufacturers, users and ATC service providers, taking into account actual and expected state-of-the-art-technology. Such cooperation should allow progressive global harmonization of the operational use of RNAV equipment. Some of the RNAV functions which are expected to be applicable to RNP include the following:

a) generate command signal outputs for autopilot/flight director;

b) display and report of 3D and 4D position data;

c) indicate track angle;

d) display way-point reference data in 3D and 4D;

e) provide a minimum of 10 active en-route way-points;

f) provide a minimum of 20 active terminal/approach way-points;

g) indicate way-point approach by alert lights/visual display;

h) provide automatic navigation aids (navaids) selection, integrity check, reasonableness check, manual override or deselect;

i) comply with turn performance requirements; and

j) indicate loss of required navigation accuracy or integrity, and appropriate failure annunciation for the system, including relevant sensors.

5.3 SYSTEM PERFORMANCE

Navigation accuracy requirements

5.3.1 RNAV and FMS equipment with the appropriate sensors may be approved by States for navigation in designated RNP airspace. Steps are being taken in a number of States to amend national legislation to permit the use of properly installed, approved and maintained RNAV and FMS equipment for this purpose.

Way-points

5.3.2 A way-point is geographically defined in terms of two or three dimensions. Way-point location is necessary in the computation of navigation information. For operations in RNP 1 or RNP 4 environments the following criteria should apply:

a) RNP 1:

— a way-point should be identified by name (if available in the database) or location (latitude/longitude); and

— equipment should be able to construct a route of at least ten way-points. The way-point input storage and retrieval resolution capability should be consistent with the required system use accuracy.

b) RNP 4, 10, 12.6 and 20:

— bearing and distance from another defined point or by other means will suffice, provided the required level of navigation performance accuracy can be demonstrated; and

— equipment should provide at least the capability to manually enter the coordinates of four (4) way-points to a resolution consistent with the required system use accuracy.

Route execution

5.3.3 RNAV systems should provide the required navigation and position fixing accuracy for all ground speeds up to the maximums achievable for the aircraft in which it is installed. They should provide usable navigation information necessary during the execution of turns, including holding patterns.

5.3.4 For RNP operations the following accuracy should be achieved:

a) RNP 1:

— a system use accuracy equal to or better than 0.93 km (0.5 NM), one standard deviation; and

— a 95 per cent containment of plus or minus 1.85 km (1 NM).

b) RNP 4:

— a system use accuracy equal to or better than 3.7 km (2.0 NM), one standard deviation; and

— a 95 per cent containment of plus or minus 9.26 km (4 NM).

5.3.5 Cross-track deviation:

a) a continuous display of displacement from the intended track or position should be provided by RNAV systems in all RNP environments; and

b) the display resolution should be consistent with the requirements of the RNP operation being flown.

5.3.6 Automatic way-point sequencing: in all RNP environments, where appropriate, and at a point determined by the RNAV system, the system should automatically transfer to, or communicate the need for the flight crew to transition to, the next leg.

5.3.7 Automatic flight control system outputs:

a) the requirements for RNAV guidance should be provided by displaying cross-track deviation as specified in 5.3.5; and

b) way-point distance and desired track should be provided.

5.3.8 Turn anticipation:

a) the system should be provided with turn anticipation capabilities to enable a smooth transition between tracks within the limits of accuracy detailed in 5.3.4; and

b) the system should provide means to alert the flight crew prior to arrival at a way-point to permit turn anticipation in accordance with the requirements of 5.3.24.

Route planning and construction of flight plan

5.3.9 The system should allow the construction and/or modification of a flight plan. The methods for doing this may consist of the following:

a) insertion of individual way-points and related data;

b) the selection of individual way-point data from the database;

c) the extraction of routes or portions of routes from a database; and

d) a means should be available by which the flight crew can determine the correctness of the flight plan.

5.3.10 For RNP operations the equipment should provide the following:

a) RNP 1:

— a means for the insertion or modification of data in the flight plan;

— a navigation database and a means to verify selected way-points should be available; and

— maintain system use accuracy during and after modification of the flight plan.

b) RNP 4, 10, 12.6 and 20:

— a means for the insertion or modification of data in the flight plan; and

— if the system has a navigation database, a means to verify selected way-points should be available.

5.3.11 For routes requiring specific functional capabilities (5.6.3 e) refers), including ATS routes requiring controlled turns, the applicable route or procedure to be flown must be automatically loaded into the FMS flight plan from the FMS database and verified by the flight crew.

In-flight updating of flight plans

5.3.12 The flight crew should be able to verify the suitability of the data in respect of the flight plan being flown and the stored database at any time without the guidance and navigation display being affected. Route data, if used, should include the names or coordinates of the way-points and should include the related distances and tracks. The present track and distance to go to the next way-point should be provided.

5.3.13 The flight crew should be able to modify the flight plan at any time. When a ground-air data link is used, positive input action should still be required on the part of the flight crew.

Note.— The above should be provided for both RNP 1 and RNP 4 operations.

Navigation confidence

5.3.14 The system should be designed to reject incorrect inputs before the accuracy of the computed position can be impaired; this should be achieved by using redundancy of information to increase the reliability of the guidance output with a minimum of flight crew intervention. Moreover, the rejection level of the installation must be appropriate to the demands of the airspace, and manufacturers should incorporate as many consistency checks as possible in order to protect filters and guidance output.

Navigation database

5.3.15 A navigation database should consist of current navigation reference data officially promulgated for civil aviation use, and contain at least navigation aid and way-point information covering the region of intended operation, and ATS routes. The ability to store a number of flight plans should be provided. For RNP operations the following criteria should apply:

a) RNP 1:

— an internal database or other operationally suitable method of navigation data entry and storage should be provided. This should be sufficient for storage of standard navigation aid information (e.g. VORTAC and DME) and way-point information required for the flight plan and alternates. This data should include ATS routes when applicable;

— data integrity should be assured by provisions for clear identification of all changes to navigation information used in each navigation database version and for the determination of the correctness of the changes incorporated into the navigation database;

— the flight crew should be able to verify that a valid database has been correctly loaded;

— the database validity period should be available for display to the flight crew; and

— the data resolution should support the required system use accuracy.

b) RNP 4, 10, 12.6 and 20:

— a navigation database is optional. If provided, it should conform to the requirements for RNP 1.

Navigation data coordinate system

5.3.16 In order to assure that airborne and ground systems are based on the same reference system, navigation should be based upon the application of the WGS-84 geodetic reference system for all RNP types. All coordinates provided in a navigation database should be in the WGS-84 reference system or equivalent.

Tuning and selection of navigation aids

5.3.17 Those systems employing inputs from VORs and/or DME should provide the capability of automatic selection and tuning of DME and/or VOR channels in accordance with acceptable procedures and related aircraft position and database requirements.

5.3.18 The system should be capable of selecting aids which will provide acceptable navigation accuracy and of selecting alternative aids if appropriate. The selected frequencies and/or aid to air navigation (navaid) ICAO identifiers used should be available for display to the flight crew.

5.3.19 The flight crew should be able to inhibit individual navaids from the automatic selection process. It should be possible to manually tune a navaid facility for display of the navaid data, if such a capability is needed to support the specified RNP. For RNP operations the following criteria should apply:

a) RNP 1:

— aids should only be selected for application in those areas where it can be ensured that data cannot be corrupted by another aid operating on the same frequency or in an area where topographical features normally would not cause multi-path errors;

— for multi-sensor navigation, the system should ensure geometry consistent with the required system use accuracy; and

— the system should provide the capability to automatically select navaids (if applicable).

b) RNP 4, 10, 12.6 and 20:

— it should be possible to manually inhibit a navaid facility; and

— the features described in 5.3.16, 5.3.17 and 5.3.18 are optional.

Navigation mode(s) and annunciation

5.3.20 The RNAV system should present sufficient information to allow determination that the equipment is functioning properly. This should include an indication of sensors being used or the method of position fixing. It is also necessary that degraded navigation be brought to the attention of the flight crew.

5.3.21 Navigation information should initially be provided or be re-established within the time period defined by the appropriate authority as acceptable for the relevant RNP.

5.3.22 For RNP operations the following criteria should apply:

a) For RNP 1 operations:

— the flight crew should be able to determine the navigation mode and/or the expected system use accuracy. The system should provide a warning of a degradation of system use accuracy below that required; and

— following degradation, the flight crew should be able to determine the remaining capability necessary to satisfy non-normal navigation requirements consistent with the RNP used.

b) RNP 4, 10, 12.6 and 20:

— a means should be provided to enable the flight crew to monitor navigation mode and position.

Position display

5.3.23 The computed aircraft position should be available for display in terms of present latitude and longitude and/or range and bearing of the aircraft to or from the active or other way-points selected by the flight crew. The equipment should enable the flight crew to provide ATC present track and distance to and from any way-point in the flight plan.

Turn performance

5.3.24 Where traffic demand necessitates the provision of a dense network of RNP 1 routes, (e.g. closely spaced parallel routes), ATS providers may require a controlled turn performance in order to ensure that aircraft remain within the allowable tolerances of RNP 1 routes during turn manoeuvre(s) of 30 to 90 degrees.

5.3.25 RNAV systems operating in an RNP 1 environment should execute turns such that the aircraft should remain within the following limits:

a) RNP 1:

— during operations on ATS routes or in areas notified exclusively for RNP 1-approved aircraft, the equipment should enable an aircraft to maintain a position within 1.85 km (1 NM) of its ATC-cleared position for 95 per cent of the total flying time;

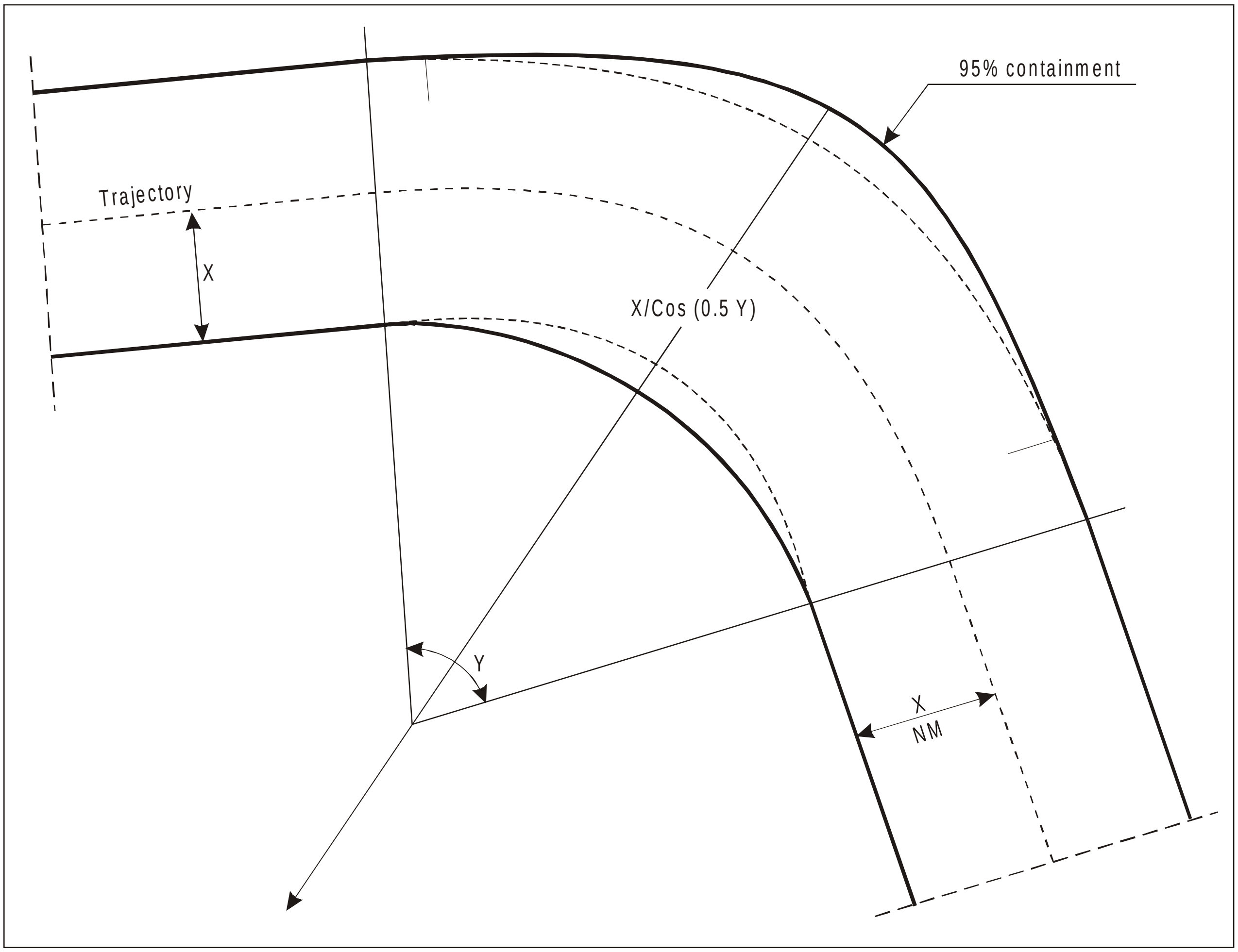

Figure 5-1. Controlled turn — RNP 1 route

— where the ATS route(s) notified for RNP 1 operations require controlled turns of 30 to 90 degrees, a fixed radius, as depicted in Figure 5-1, will be specified by the ATS route designator and included for all turns on the RNP 1 ATS route in accordance with Annex 11, Appendix 1. The aircraft should remain within the allowable RNP 1 tolerance of the tangential arc specified by the radius between the straight leg segments; and

— where the turn parameters are not specified, the equipment should determine the turn performance.

b) RNP 4, 10, 12.6 or 20:

— provide a capture to the next track in such a manner as to minimize overshoot; and

— provide the ability to accomplish turns of up to 90 degrees of course change, with or without offset, without exceeding the turning area envelope shown in Figure 5-2. Procedural techniques may be an acceptable means of meeting this requirement.

Parallel offsets

5.3.26 RNAV systems may provide the ability to fly parallel tracks offset by up to 37 km (20 NM) from the primary track defined by the way-points. The selection of an offset and the offset distance should be continuously indicated:

a) tracks offset from the parent track should be continued for all ATS route segments and turns until either removed by the flight crew or removed

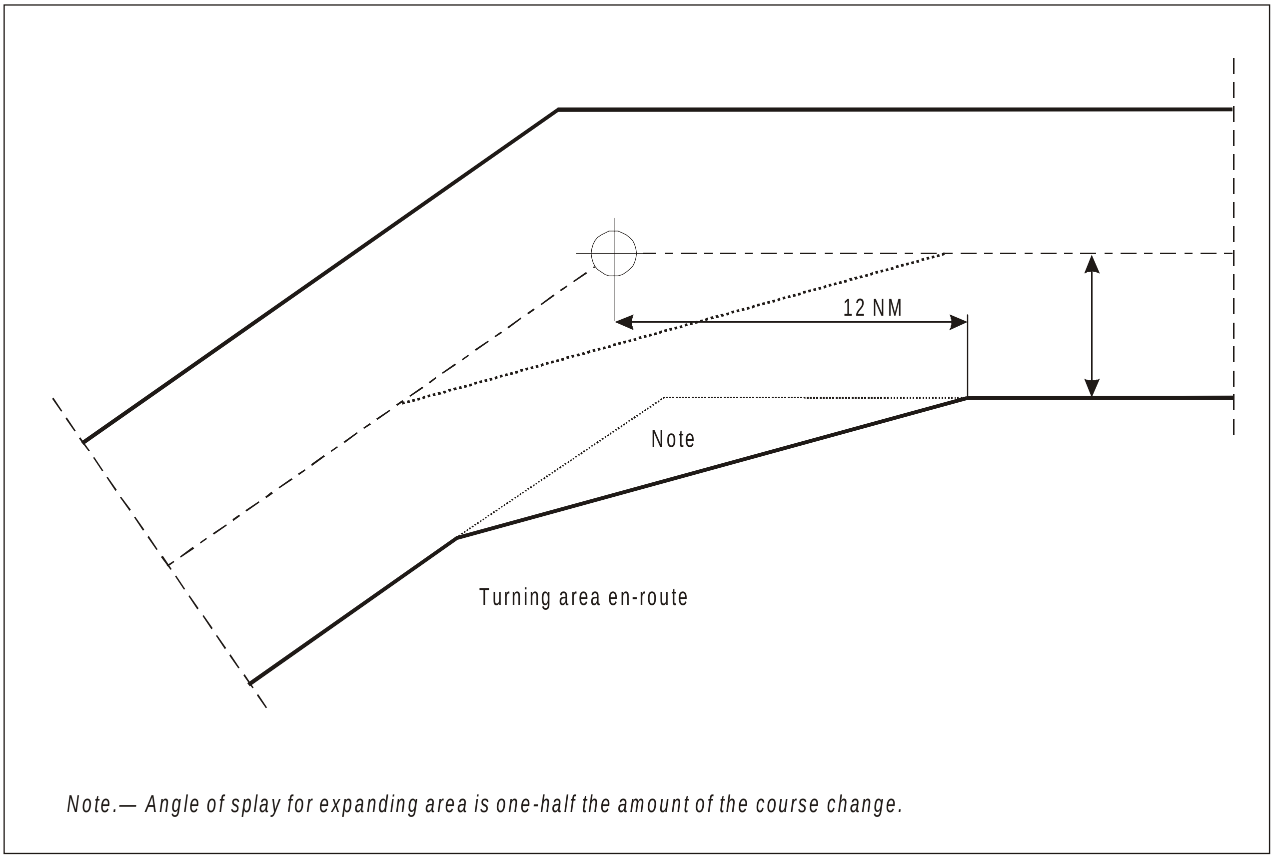

Figure 5-2. Turning area envelope

automatically by, e.g. amending the active flight plan, joining an RNAV hold, or when there is a course change of 90 degrees or greater.

b) the cross-track offset distance should be inserted via the RNAV control and display unit (CDU) in steps not greater than 1.85 km (1 NM).

c) the offset facility is desirable for RNP 4, 10, 12.6 and 20 operations.

d) parallel offset capability should be provided for RNP 1 operations. Where parallel offset capabilities are used, the performance specified in 5.3.4 a) should be maintained referenced to the offset track. Turns between the inbound and outbound offset tracks should be executed such that the aircraft remains within the limits defined in 5.6.3 e) for 95 per cent of its flight time.

5.3.27 *Entry and recovery from offsets.* The intercept angle between a parent track and an offset track should be 45 degrees or less to minimize the risk for track overshoot.

5.3.28 Direct-to function:

a) RNAV systems should have the capability of establishing a direct track to any selected way-point position; and

b) for all RNP operations, the execution of the aircraft track change should enable the interception of the direct leg without excessive overshoot of the new track.

5.3.29 Holding:

a) where provided, the system should, with the minimum of flight crew intervention, be capable of initiating, maintaining and discontinuing standard holding procedures at all altitudes;

b) for RNP 1 operations, the facility for maintaining and discontinuing an RNAV hold should be provided. The system navigation performance during both straight legs and turns should be in accordance with 5.3.3 to 5.3.8; and

c) for RNP 4, 10, 12.6 and 20 operations, the provision of RNAV holding capability is desirable.

5.3.30 Bearing/distance to way-point(s):

a) RNAV equipment should be capable of determining and presenting for display on request the present position of the aircraft in relation to selected way-point(s) in terms of distance, track and flying time along the active flight plan; and

b) RNAV equipment for any RNP operation should provide the capability to display distances and bearings to way-points. The equipment should enable the flight crew to provide ATC with the distance to (or from) any way-point up to a distance of at least 1 848 km (999 NM), and to provide ATC with the course to or bearing from any way-point in 1 degree increments.

5.3.31 When an ATS route notified exclusively for RNP 1 operation includes a requirement for controlled turns, this should be indicated through an alphabetic suffix to the ATS route designator in accordance with Annex 11, Appendix 1, 2.4. It should be noted that the controlled turn radii specified in Annex 11 are based on aircraft manufacturers' recommendations derived from studies considering the capabilities, including maximum ground speed and maximum bank angle at different levels, of various aircraft types.

5.4 SYSTEM DESIGN, CONSTRUCTION AND INSTALLATION

5.4.1 Each aircraft should have navigation equipment that enables it to proceed in accordance with its operational flight plan and the requirements of air traffic services.

5.4.2 The design and construction of navigation equipment should conform to the appropriate design standards, including national variants.

5.4.3 Navigation equipment should be installed in accordance with instructions and limitations provided by the manufacturer of the equipment.

5.4.4 These instructions and limitations should include, but not be limited to, location of controls and system displays, warning and advisory indications, power supplies, failure protection, environmental conditions, electromagnetic interference, P-static protection, P-static charging/discharging and anti-ice protection.

Monitoring

5.4.5 *System self-monitoring.* For all RNP operations, RNAV systems should be designed to perform a continuous automatic self-test of position computation performance. Should performance fall below the required system use accuracy, the flight crew should be made aware in order that ATC may be informed.

5.4.6 *Sensor monitoring.* If a significant sensor error is detected and automatic reconfiguration possibilities have been exhausted, a warning should be displayed to the flight crew and the equipment should ignore the position derived from an out-of-tolerance sensor. Provision should be made to identify and deselect the discrepant sensor.

5.4.7 *Alert outputs.* For all RNP operations, alert outputs should be provided for the following:

a) equipment failures;

b) reversion to supplementary or non-standard modes of navigation; or

c) loss of the capability to support a specified RNP.

Measure of navigation system performance

5.4.8 A navigation system performance indicator should be determined by systems meeting RNP requirements, giving information on the quality and accuracy of navigation performance. This should be available to the flight crew.

Data link interface

5.4.9 While there are no current ATS requirements for RNAV equipment to provide a data link interface, the Note below is provided for information purposes.

Note.— It is expected that ATC data link services will be progressively implemented in RNAV systems. In the future, there may be a requirement to provide information for transmission via data link.

5.5 AIRWORTHINESS APPROVAL OF RNAV/FMS EQUIPMENT

5.5.1 Since RNAV and FMS aircraft installations are subject to airworthiness approval by the national aviation administration concerned, it is not practicable to detail the procedures adopted by individual States. In general terms, the information submitted to support an application for approval will need to be sufficient to permit an assessment to be made of the acceptability of the equipment/system for its intended use. Furthermore, evidence of the testing carried out to demonstrate the navigation performance accuracy appropriate to the RNP type will be required. Moreover, where the system is intended for use in designated areas for which airworthiness approval would be required, the information must adequately reflect the relevant airworthiness considerations that would affect the aircraft's ability to comply with the operational requirements for flight within such designated airspace.

5.5.2 Appropriate RNAV equipment will have to be certified for use in all phases of flight. Specific information relating to the various sensors providing input to the RNAV equipment is found in the respective national or regional material. The initial certification of RNAV equipment requires a technical evaluation to verify such criteria as accuracy, failure indications and environmental qualifications appropriate to the relevant RNP type. Subsequent installations of the same RNAV equipment system in other aircraft may require additional technical evaluation, depending on the degree of integration of the system with other aircraft systems. A technical evaluation will be necessary to change RNP type approval.

5.5.3 While the navigation performance accuracy is the basis for defining an RNP type, the other navigation performance parameters of availability, coverage, reliability, fix rate, fix dimension, capacity, time to recover and integrity determine the utilization and limitations of the individual navigation systems, both ground and airborne, and characterize the means by which a user derives navigation information within an RNP type airspace, as described in Appendix C. Numerical values for these parameters will be quantified by the appropriate technical bodies.

5.6 OPERATIONAL APPROVAL OF RNAV/FMS EQUIPMENT

5.6.1 The State of the Operator will be the authority responsible for approval of flight operations in the various RNP type airspaces. The approving authority will ensure that the aircraft has equipment installed and operating in a manner appropriate to the RNP type approval being sought. The equipment users' manual should also include any airworthiness limitations associated with use of the equipment. At least the following items should be considered:

a) accuracy limitations associated with geographical location, availability of radio navigation facilities or reversionary modes (e.g. manual tuning or dead reckoning (DR) operation);

b) system status required for compliance with published operational requirements (RNP type);

c) limitations associated with use of VOR/DME-defined ATS routes, where RNAV equipment or FMS is not approved as the primary means of navigation;

d) limitations, including those associated with take-off, terminal and approach phases of flight;

e) essential monitoring procedures; and

f) limitations and procedures associated with abnormal operations (e.g. electrical power interruption and recovery, system warnings, engine inoperative performance data) and the minimum equipment list (MEL).

5.6.2 The approving authority must be satisfied that operational programmes are adequate. Training programmes and operations manuals should be evaluated.

5.6.3 The approving authority should have a high degree of confidence that each operator can maintain the appropriate levels of RNP. The following minimum requirements apply:

a) approval should be granted for each individual operator, as well as for each individual aircraft type group/equipment (manufacturer/model) utilized by an operator;

b) each aircraft type group utilized by an operator should be shown to be capable of maintaining navigation performance accuracy relevant to the RNP type approval being sought;

c) each aircraft carrying RNAV/flight management systems should receive airworthiness approval in accordance with 5.5 prior to being reviewed for operational approval. The authorities granting operational approval should evaluate the airworthiness documents for each aircraft type group/equipment (manufacturer/model). In most cases the airworthiness documents are expected to give the authority confidence that navigation performance will meet the required levels. In certain cases, it may be necessary for the operator to prove RNP for the aircraft type by flight test. It will be necessary for approving authorities to develop procedures to grant operational approval;

d) if in-service experience shows that the navigation performance of a particular aircraft type utilized by an operator does not meet the requirements, the operator should be required to take steps to improve navigation performance to required levels. If performance is not improved, operational approval for the aircraft type should be withdrawn from that operator. In cases where navigation performance is observed to be grossly in error, approval should be withdrawn immediately; and

e) during operations on ATS routes or in areas notified exclusively for RNP 1-approved aircraft, the equipment should enable an aircraft to maintain a position within 1.85 km (1 NM) of its ATC-cleared position for 95 per cent of the total flying time and, where the ATS route(s) notified for RNP 1 operations require controlled turns of 30 to 90 degrees, a fixed radius, as depicted in Figure 5-1, will be specified by the ATS route designator and included for all turns on the RNP 1 ATS route in accordance with Annex 11, Appendix 1. The aircraft should be required to remain within the allowable RNP 1 tolerance of the tangential arc specified by the radius between the straight leg segments. If unspecified, the equipment should determine the turn performance.

5.7 REFERENCE DOCUMENTS

Appendix D contains a list of references to examples of specific rules pertaining to RNAV operations, including equipment approval requirements and procedures.

Chapter 6

REQUIRED NAVIGATION PERFORMANCE OPERATIONS

6.1 PROVISION OF NAVIGATION SERVICES

State of service obligation

General

6.1.1 The concept of RNP involves the navigation performance accuracy that must be maintained by an aircraft operating within a particular area or on a particular route. Since required levels of navigation performance vary from area to area depending on traffic density and complexity of the tracks flown, States have an obligation to define an RNP type of their airspace(s) to ensure that aircraft are navigated to the degree of accuracy required for air traffic control. States of service should ensure that sufficient navaids are provided and available to achieve the chosen RNP type(s) and should provide the relevant information to operators. Providers of air traffic services therefore should also consider the parameters in Appendix C (i.e. availability, coverage, reliability, fix rate, fix dimension, capacity, ambiguity, time to recover and integrity) in the navigation aids they provide. Appendix C also provides navigation system descriptions for a variety of navigation systems.

6.1.2 The levels of sophistication in CNS vary widely throughout the world. In turn, ATC separation minima which are used to safely separate aircraft operating within a specified area are dependent on the CNS capability within the airspace. In establishing an RNP airspace or route, it will be necessary to define the separation minima or minimum protected airspace that applies. The RGCSP is developing a methodology to interrelate CNS, traffic density and other parameters in order to develop airspace separation minima.

6.1.3 The lateral and vertical dimensions of the airspace in which the RNP types are implemented must be defined and promulgated in appropriate national and regional documentation. When an RNP type is defined for a route, the lateral dimensions with respect to the route centre line must be defined.

ATC for RNP airspace

6.1.4 *General.* For the definition of ATC for RNP airspace, it is necessary to distinguish between the following:

a) RNP fixed and contingency routes; and

b) RNP areas, including random tracks.

6.1.5 *ATC for RNP fixed and contingency routes.* From an ATC point of view, it is considered that existing ATC techniques and equipment can continue to be used for RNP fixed or contingency ATS routes. It is possible that closely spaced parallel tracks will be introduced, or routes will be established close to airspace currently reserved for other purposes. In such cases, some form of alert in case of track deviation or conflict may be necessary.

6.1.6 *ATC for RNP areas, including random tracks.* In the case of applying random tracks in RNP areas, an increasing need for changes to the ATC system will arise, as:

a) in areas of low traffic density the amount of change may be small, but account will have to be taken of flight plan processing, conflict detection and resolution;

b) in areas of higher traffic density, ATC computer systems will have to accept and process flight plan data concerning random navigation (4.2.7 refers). Air traffic controllers must be able to easily amend and update the relevant flight plan information in the computer system. Prediction and display of potential conflicts at the planning stage may be required; and

c) radar control may also require conflict alert and resolution, including selectable presentation of track prediction. ATC will require a method of showing the latitude and longitude of key crossing points on the predicted track. This might simply be displayed in terms of position in relation to a grid or by automatic readout of the latitude and longitude or name code.

ATC use of parallel offset

6.1.7 As a tactical tool to solve separation problems, ATC may require aircraft to fly offset from the planned route centre line by a specified distance (parallel offset). It would be employed instead of radar vectoring.

6.1.8 When wishing to exploit the tactical parallel offset capability of RNAV-equipped aircraft, controllers must ensure that the aircraft has the offset capability as part of its RNAV system. They must also apply the same level of prudence in its application as they would for radar vectoring. Although the execution of the manoeuvre and the subsequent navigation of the aircraft remains the responsibility of the pilot, continuous ATC surveillance will also be required for such operations.

6.1.9 When choosing offset values it is important that these are compatible with approved separation minima. The chosen value should allow sufficient latitude for controller intervention in the event of deviations from cleared tracks and will also be dependent upon availability of system functions such as short-term conflict alert or automatic check of track adherence.

Flight plan requirements

Route designator

6.1.10 RNP routes should be assigned a suitable route designator in accordance with the provisions of Annex 11. Additionally, the specific RNP type(s) applicable to a particular route segment(s), route(s) or area should be included after the route number, e.g. ATS route A576 between Auckland, Sydney, Curtin Bali and Singapore, could involve the nomination of a variety of RNP types, such as A576 (1), A576 (4), A576 (12.6) or A576 (20).

6.1.11 In airspace such as the North Atlantic, or an area designated for random track operations, where the same RNP type would probably apply on all routes, it may be preferable to indicate the applicable RNP type by means of an appropriate note on a chart.

6.1.12 This approach would enable pilots and ATS staff to readily identify the RNP type applicable to a particular route segment(s), route(s) or area, and would provide a sufficient degree of flexibility to easily amend RNP types or to introduce any new RNP types that might be specified in the future.

Indicated navigation capability

6.1.13 It is essential that ATS receive information that a flight, planned for operation along routes or through RNP areas, has the required navigation capability. The appropriate procedures and formats are contained in Procedures for Air Navigation Services — *Rules of the Air and Air Traffic Services* (PANS-RAC, Doc 4444), Appendix 2, Item 10.

Introducing RNP into an airspace

6.1.14 It will be necessary for national administrations to evolve to the WGS-84 geodetic reference system and develop a process for identifying national reference data for use in flight management system (FMS) databases. National administrations should be required to have this geodetic reference system in place prior to the effective date of RNP operations. Manufacturers, operators and database suppliers, in the meantime, should be responsible to ensure that RNAV systems are able to transition to the WGS-84 system or equivalent.

6.1.15 National administrations should be aware that conversion of coordinates from their current reference system to WGS-84 will require application of quality control in respect of the surveys which might be necessary and the conversion process itself.

6.1.16 The following aspects should be considered in order that RNP might be introduced by States and regions on an evolutionary basis:

a) availability of technical means of compliance, e.g. aircraft equipage and ground infrastructure;

b) lead time for installation of elements of the airborne systems;

c) availability of appropriate levels of communication and surveillance;

d) lead time for the development and implementation of regional transition plans;

e) current situation regarding studies, research and development for the more demanding levels of RNP;

f) existence of standards and procedures;

g) airspace demand requirements;

h) availability of airworthiness and operational approval procedures;

i) technical means to permit continued reduced separation at national and regional boundaries;

j) desirability of real-/fast-time simulation facilities in support of reduced separation standards;

k) airspace/sectorization design requirements;

l) lead time for education/training;

m) lead time for publication requirements;

n) cost/benefit considerations; and

o) amendment of State legislation.

State of the Operator obligation

6.1.17 The following is intended as an example for use by States and operators to ensure that properly fitted, maintained and operated aircraft will have an operational navigation performance equal to or better than the required accuracy.

6.1.18 Navigation equipment utilized is the choice of the operator. The essential provision is that the equipment meets the level of navigation performance accuracy established for each specific RNP type. The following points need to be borne in mind:

a) operators must seek approval from their State (i.e. the State of the Operator). The operator must show (considering factors unique to the proposed area of operation) that safe operation can be conducted within the area of operation, and that the facilities and services necessary to conduct the operation are available and serviceable during the period when their use is required;

b) before approval is granted, the operator should provide assurance that the type of equipment is of proven reliability and performance. Information on the airworthiness aspect is as in 5.4;

c) although it may be assumed that all approved equipment should be capable of operating to specified RNP accuracy requirements, the operational procedures play an important part in achieving the desired performance. It is also important that the operating environment be taken into account. The approval process could include the examination of:

   1) procedures (normal and abnormal) taking into account the characteristics of the equipment and its specific requirements for verification, updating and cross-checking of computed position information and steering commands;

   2) the adequacy of the coverage of ground navaids (if applicable) and the dead-reckoning capability to cover gaps;

   3) navigation database update arrangements (if applicable);

   4) flight crew training arrangements;

   5) maintenance procedures after navigation discrepancy reports; and

   6) flight, operations and training manuals; and

d) States should define an appropriate administrative procedure in order to:

   1) avoid an overload of their approval services; and

   2) minimize expenditures for operators.

6.1.19 Advantage could be taken of the experience in other States by use of cross-approval procedures and of a standardized manual of operations.

6.2 TRAINING REQUIREMENTS

General

6.2.1 It will be the responsibility of the relevant State authorities to ensure that adequate provision is made for the training of flight crew and air traffic controllers in RNP operations.

6.2.2 Experience has shown that activities such as RNAV implementation seminars have helped facilitate the efficient introduction of RNAV separation minima in particular regions by informing pilots, operators and air traffic control personnel of the various requirements. Consideration should therefore be given to conducting RNP seminars to facilitate the introduction of RNP operations within a State or region.

Flight crew training

6.2.3 The training requirements of operators in respect of equipment and operating procedures should be adequately covered in the relevant operations and training manuals, where available.

6.2.4 As a minimum, States should include training in equipment and operating procedures in pilots' training syllabi, such as instrument ratings, aircraft type ratings and refresher training. The training should ensure that flight crews:

a) have a general knowledge of the application of RNP;

b) have a thorough understanding of the equipment;

c) are aware of its limitations;

d) have been trained in the operating procedures and safeguards necessary to obtain optimum efficiency and maintenance of required navigational accuracy;

e) are in current practice and have received recent training on the equipment;

f) appreciate the need to advise ATC should the accuracy of their navigation be in doubt; and

g) are conversant with contingency procedures.

ATC training

6.2.5 From the ATC point of view, the handling of traffic along RNP fixed and contingency routes will not be changed significantly.

6.2.6 The introduction of RNP areas including random tracks may bring about changes to the operation of ATC which would make it essential for additional training to be provided, taking into account matters such as:

a) potentially different RNP type routes in the same sector;

b) transition between different RNP type areas;

c) radiotelephony (RTF) procedures (see 6.3);

d) revised military/civil and civil/civil co-ordination procedures;

e) conflict prediction and resolution along unpublished tracks; and

f) revised contingency procedures.

6.2.7 As more sophisticated navigation applications become more widely used (e.g. parallel offset capability, RNAV standard instrument departures (SID), and standard instrument arrivals (STAR), holding and approaches), their integration into ATC procedures will require that controllers are trained to accept and exploit the use of these advanced capabilities.

6.3 SPECIAL RADIOTELEPHONY PROCEDURES FOR RNP OPERATIONS

The en-route application of RNP should not necessitate a complete set of new RTF phraseologies. Many circumstances can be adequately dealt with by using existing phraseology as promulgated in the PANS-RAC (ICAO Doc 4444), if properly adapted.

Appendix A
EXPLANATION OF TERMS

Accuracy. The degree of conformance between the estimated or measured position and/or the velocity of a platform at a given time and its true position or velocity. Radio navigation performance accuracy is usually presented as a statistical measure of system error and is specified as:

a) *Predictable*. The accuracy of a position in relation to the geographic or geodetic coordinates of the earth.

b) *Repeatable*. The accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.

c) *Relative*. The accuracy with which a user can determine one position relative to another position regardless of any error in their true positions. (RTCA/DO-208, *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using GPS*)

Along-track error (ATRK). A fix error along the flight track resulting from the total error contributions. (Derived from RTCA/DO-208)

Ambiguity. System ambiguity exists when the navigation system identifies two or more possible positions of the vehicle, with the same set of measurements, with no indication of which is the most nearly correct position. The potential for system ambiguities should be identified together with a provision for users to identify and resolve them. (FRP)

Area navigation (RNAV). A method of navigation that permits aircraft operation on any desired flight path.

Area navigation equipment. Any combination of equipment used to provide RNAV guidance. (RNP GM)

Availability. Availability is an indication of the ability of the system to provide usable service within the specified coverage area and is defined as the portion of the time during which the system is to be used for navigation during which reliable navigation information is presented to the flight crew, autopilot, or other system managing the flight of the aircraft. (Derived from RTCA/DO-208)

Capacity. The number of system users that can be accommodated simultaneously. (FRP)

Circular protected area (CPA). A circular area of protected airspace, centred on the desired position of an aircraft.

Note.— This area is based on the specified navigation performance requirements, e.g. RNP, and ATC intervention (communication and surveillance) capabilities.

Containment limit (cross-track/along-track). A region about an aircraft's desired position, as determined by the airborne navigation system, which contains the true position of the aircraft to a probability of 99.999 per cent.

Note.— The cross-track and along-track containment limit encompasses the specified RNP, containment integrity and containment continuity, but excludes allowance for ATC intervention (communication and surveillance) capabilities.

Containment value (containment distance). The distance from the intended position within which flights would be found for at least ninety-five per cent of the total flying time.

Coverage. The coverage provided by a radio navigation system is that surface area or space volume in which the signals are adequate to permit the user to determine position to a specified level of accuracy. Coverage is influenced by system geometry, signal power levels, receiver sensitivity, atmospheric noise conditions and other factors that affect signal availability. (RTCA/DO-208)

Cross-track error. The perpendicular deviation that the aircraft is to the left or right of the desired track. (Derived from RTCA/DO-208)

Earth-referenced navigation (ERN). Navigation which is dependent on an external navigation source or inertial reference system (IRS) but is not dependent on a single fixed site. ERN may use either time or phase differences from hyperbolic radio navigation systems or satellite sources with geodetic datums to determine position (normally converted latitude and longitude) on the surface of the earth. LORAN-C and GPS are different forms of ERN. (RTCA/DO-208)

En-route operations. Operations conducted on published ATS routes, direct point-to-point operations between defined way-points or along great circle routes which are other than take-off, landing, departure, arrival or terminal operations.

Fix dimension. A characteristic which defines whether the navigation system provides a linear, one-dimensional line of position, or a two- or three-dimensional position fix. The ability of the system to derive a fourth dimension (i.e. time) from the navigational signals is also included. (FRP)

Fix rate. The number of independent position fixes available from the system per unit of time. (FRP)

Flight management system (FMS). An integrated system, consisting of airborne sensor, receiver and computer with both navigation and aircraft performance databases, which provides performance and RNAV guidance to a display and automatic flight control system. (RTCA/DO-208)

Flight technical error (FTE). The accuracy with which the aircraft is controlled as measured by the indicated aircraft position with respect to the indicated command or desired position. It does not include blunder errors. (RTCA/DO-208)

FRP. (United States) Federal Radionavigation Plan.

GNSS. Global navigation satellite system.

GPS. Global positioning system.

Integrity. The ability of a system to provide timely warnings to users when the system should not be used for navigation. (RTCA/DO-208)

Manoeuvre anticipation. Time and distance from a way-point at which path changes are initiated in order to transition to a new course. (RTCA/DO-208)

Navigation. The means by which an aircraft is given guidance to travel from one known position to another known position. (RTCA/DO-208)

Navigation guidance. The calculation of steering commands to maintain the desired track from the present aircraft position to a new position. (RTCA/DO-208)

Navigation information. Aircraft parameters such as position, velocity vector and related data such as track angle, ground speed and drift angle used for navigation guidance. (Derived from RTCA/DO-208)

Navigation performance accuracy. The total system error (TSE) allowed in the individual lateral and longitudinal dimensions. TSE in each dimension must not exceed the specified RNP type for 95 per cent of the flight time on any single flight. (See 3.2).

Parallel offset path. A desired track parallel to and left or right of the "parent" track specified in nautical miles of offset distance. (RTCA/DO-208)

Reliability. A function of the frequency with which failures occur within the system. The probability that a system will perform its function within defined performance limits for a specified period under given operating conditions. Formally, reliability is one minus the probability of system failure. (FRP)

Required navigation performance (RNP). A statement of the navigation performance accuracy necessary for operation within a defined airspace.

Route spacing. The distance between air traffic services (ATS) route centre lines.

Note.— This distance is based on the specified navigation performance requirements, e.g. required navigation performance (RNP), and air traffic control (ATC) intervention (communication and surveillance) capabilities.

Sensor. A unit capable of providing information for use by the RNAV or FMS.

Station-referenced navigation. Position determination which is referenced to a particular source. (RTCA/DO-208)

Supplemental air navigation system. An approved navigation system that can be used in conjunction with a sole-means navigation system. (RTCA/DO-208)

System use accuracy. The combination of the navigation sensor error, airborne receiver error, display error and flight technical error. Also called navigation performance accuracy. (Derived from RTCA/DO-208)

Terminal area operations. Operations conducted on published standard instrument departures (SIDs), or published standard instrument arrivals (STARs), or other flight operations whilst under terminal control.

Time to alarm. The maximum allowable elapsed time from the start of system failure (i.e. alarm limit) until the time that the integrity alarm is annunciated.

Time to recover navigation. The time required for restoration of navigation service after signal interruption.

Total system error. In the lateral dimension, a combination of navigation system error, RNAV computation error, display system error and FTE. In the longitudinal dimension, a combination of navigation system error, RNAV computation error, and display system error. (See section 3.2 and Appendix C (Estimating Navigation Performance Accuracy)).

Appendix B

RATIONALE FOR THE CHOICE OF RNP VALUES

1. The RGCSP recognized that the RNP requirement for precise navigation (i.e. RNP 1) reflected the capabilities of aircraft flying with advanced navigation systems, such as those which utilize updates from multiple DME transponders, and dynamically select the transponders whose geometric positions, in relation to the aircraft, yield the most accurate solution.

2. The RGCSP also accepted the characterization of basic RNP (i.e. RNP 4) as reflecting the lateral track-keeping accuracies expected from aircraft navigating by VOR. While it expected the 95 per cent containment value of 7.4 km (4 NM) to be applied in most cases in which basic continental performance is appropriate, the panel also recognized that some regions may prefer to liberalize the requirement to allow 95 per cent containment of 9 km (5 NM) in certain airspaces.

3. In choosing other RNP values, the RGCSP relied on an approach that analyses the probability that aircraft flying along adjacent parallel routes would have laterally overlapping positions. This probability was expressed as a function of four variables:

a) S, the spacing between the routes;

b) λ_1, which was $\times \frac{\sqrt{2}}{2}$ (the standard deviation of typical lateral errors) or, equivalently, about 1/3 of the 95 per cent containment distance;

c) α, which approximated the rate at which large errors occur; and

d) λ_2, which was approximately $\times \frac{\sqrt{2}}{2}$ (the standard deviation of the distribution of large lateral errors).

4. Overlap probabilities computed in the analysis used fixed values of α and λ_2 found to prevail in North Atlantic airspace (the only oceanic airspace for which reliable data were available); but the computed probabilities were not, in themselves, central to the RGCSP's conclusion.

5. The analysis also fixed several values of route separation S and, for each of them, plotted the lateral overlap probability as a function of the 95 per cent containment distance (see Figures B-1 and B-2; a summary of these figures is given in Table B-1). Each of the plotted

Table B-1. Candidate RNP values

Route spacing		*Conservative RNPs*		*Liberal RNPs*	
km	*NM*	α = *0.0003*	α = *0.0008*	α = *0.0003*	α = *0.0008*
37	20	3	3	3	4
74	40	6	7	7	8
110	60	9	10	11	12
148	80	13	14	15	17
185	100	16	17	19	21
222	120	19	20	23	25

Note.— It is immediately clear from this table that the conservative candidates are approximately 1/6 of the corresponding route separations, while liberal candidates are approximately 1/5 of the corresponding separations.

curves was nearly flat — i.e. increased very slowly — for small values of 95 per cent containment distance. However, when the 95 per cent containment distance reached values roughly between S/6 and S/5, each curve exhibited a sharp "knee" (i.e. change in gradient) at which the overlap probability began to rapidly increase. This suggested that the RGCSP base its choice of RNP on the rate at which the overlap probability increased with respect to 95 per cent containment distance. In particular, the RNP for a given route separation S should be the greatest integer number of nautical miles for which that rate remained less than some small percentage, such as 1 per cent or 10 per cent. A rough rule of thumb was that the greatest 95 per cent containment values producing increases of less than 1 per cent were approximately S/6, while those producing increases of less than 10 per cent were approximately S/5. Though the probabilities at which the curves were nearly flat varied almost linearly with α, the "knee" showed very little sensitivity to either α or λ_2.

6. In choosing an RNP value just below the "knee" of the curve corresponding to the chosen route separation, an airspace planner would ensure that nearly the lowest lateral overlap probability possible for that airspace had been achieved. On the other hand, operators complying with that RNP could have confidence that as long as the route structure did not change, they would not be asked to improve their normal navigational performance, as further reductions in 95 per cent containment distance would do little to reduce the probability of lateral overlap. The

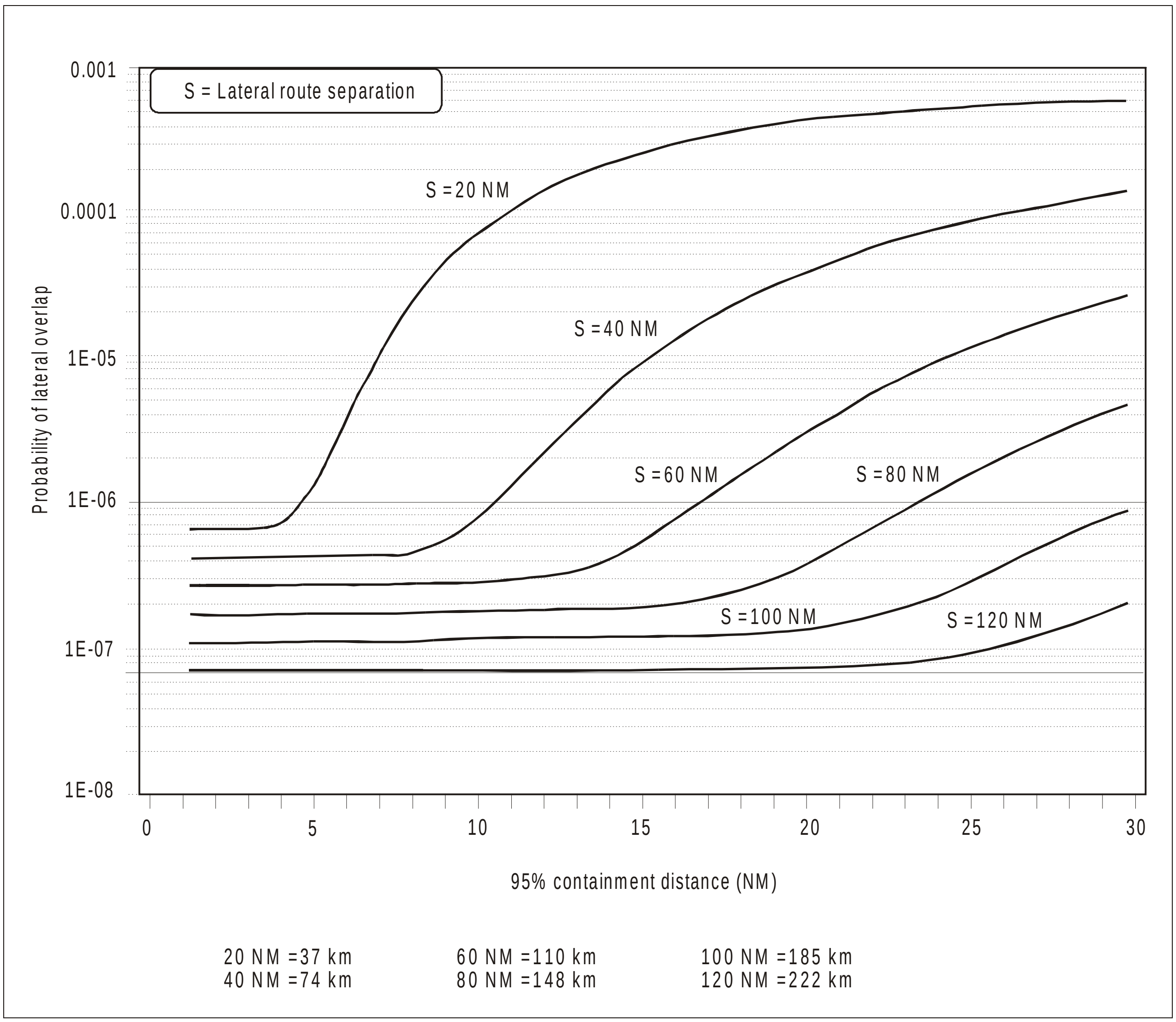

Figure B-1. Lateral overlap probability for alpha = .0008, lambda2 = 45

RGCSP accepted this application of the law of diminishing marginal returns in choosing RNP values for oceanic airspace.

7. While recognizing that the principle described above could be applied to yield several RNP values, and that additional values might eventually be needed in some regions, the RGCSP preferred, for the sake of simplicity, to follow the example of the FANS Committee and define only two oceanic RNP values. Since the existing NAT MNPS value of 23.3 km (12.6 NM) agreed fairly closely with the value that would result from applying the analysis described above to route systems utilizing 110 km (60 NM) lateral separation, and since the panel did not wish to impose re-certification costs on operators for the sake of a marginal reduction in lateral overlap probability, it adopted the existing value of 23.3 km (12.6 NM) as the RNP applicable to heavily used oceanic airspace. Furthermore, the analysis indicated that RNP values in the range 35-46 km (19-25 NM) were appropriate for route systems utilizing 222 km (120 NM) lateral separation, which was the largest separation applied to any route system. The RGCSP, acting conservatively, selected 37 km (20 NM) as the RNP value appropriate to oceanic areas with low traffic volume. In making this choice, the panel also noted the results of data collections on the navigational accuracy of inertial navigation systems, which showed that 95 per cent of the time, INS drift was slightly less than 3.7 km (2 NM) per hour. Recognizing that relatively few oceanic legs required more than ten hours of flying (and on some of

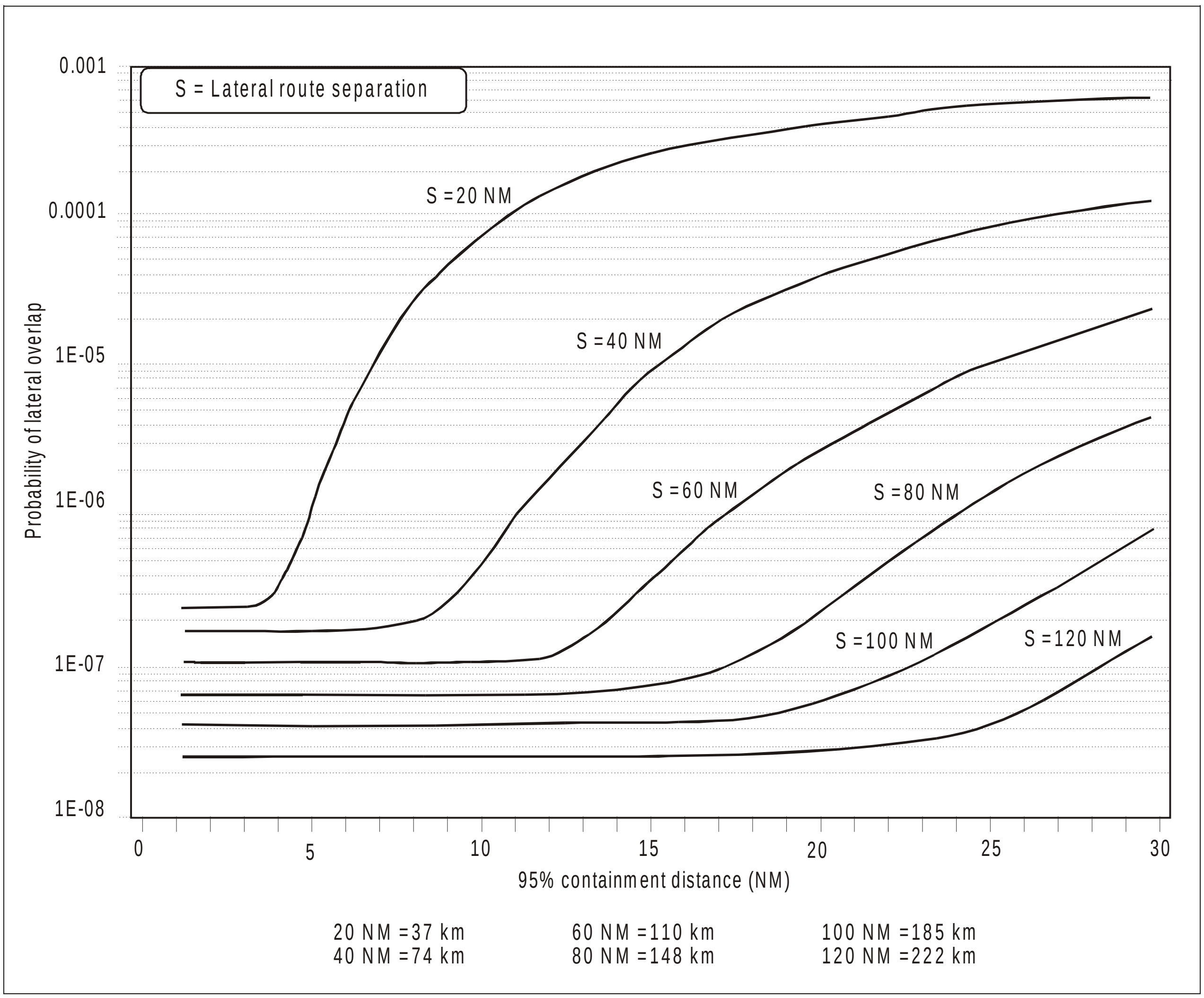

Figure B-2. Lateral overlap probability for alpha = .0003, lambda2 = 45

those that did, navigation systems more accurate than INS were typically used), the panel expected that RNP 20 would be achievable by most of the aircraft that, at that time, flew on oceanic routes.

8. Subsequent to the initial publication of Doc 9613, the Asia/Pacific Air Navigation Planning and Implementation Regional Group (APANPIRG) developed RNP 10 for application in oceanic and remote areas of the Pacific where the availability of navigation aids is limited. The rationale for the introduction of RNP 10 to support 50 NM longitudinal separation was developed by the Civil Aviation Authority of Australia. The rationale for the introduction of RNP 10 to support 50 NM lateral separation was developed by the Federal Aviation Administration of the U.S. Department of Transportation.

Appendix C

ESTIMATING NAVIGATION PERFORMANCE ACCURACY

1. INTRODUCTION

This appendix:

a) reviews the RNP error budget assumptions;

b) presents information on individual navigation systems;

c) presents an overview of navigation error characteristics; and

d) provides example error budgets for flight technical error (FTE).

2. RNP ERROR BUDGET ASSUMPTIONS

2.1 An error budget should:

a) allow for equipment manufacture and installation;

b) allow users to determine whether the expected aircraft tracking performance is consistent with their operational requirements; and

c) assist in the design of airspace procedures.

2.2 Error budgets must be simple because the available database usually does not substantiate more than elementary statistical procedures.

2.3 This same lack of a database is the reason that the root-sum-square (RSS) calculation procedure is almost universally accepted throughout the navaid industry to estimate system performance.

2.4 The RNAV errors are usually defined in terms of the lateral cross-track and along-track errors for two-dimensional (2-D) desired flight paths (see Figure C-1). The RNAV output position measurements, as well as the guidance inputs to the lateral and vertical channels of the aircraft flight control systems (AFCS), are specified as particular errors.

2.5 *Navigation performance accuracy in the lateral dimension.* The total system error (TSE) in the lateral dimension is a combination of:

a) navigation system error;

b) RNAV computation error;

c) display system error; and

d) flight technical error (FTE).

2.6 *Navigation performance accuracy in the longitudinal dimension.* The TSE in the longitudinal dimension is a combination of:

a) navigation system error;

b) RNAV computation error; and

c) display system error.

2.7 The combination of the navigation system errors and RNAV computation error is known as the system accuracy error, or position determination error.

3. NAVIGATION SYSTEM DESCRIPTIONS

3.1 The following paragraphs briefly describe currently available navigation systems that may be used to meet RNP requirements. The systems are described in more detail in the pertinent advisory material and manufacturer publications. All of the navigation systems presented are characterized in terms of equipment performance parameters, which determine the utilization and limitations of the individual navigation systems, and characterize the means by which a user derives navigation information. The equipment performance parameters are accuracy, availability, coverage, reliability, fix rate, fix dimension, capacity, ambiguity, time to recover navigation and integrity.

Navigation systems

3.2 Many public transport and business/executive jet aircraft have an FMS installation as an integral part of the avionics system. The core of the FMS is a computer that, as far as lateral navigation is concerned, operates with a large database which enables many routes to be pre-programmed and fed into the system by means of a data loader. In operation, the system is constantly updated with respect to positional accuracy by reference to conventional navigation aids, and the sophisticated database will ensure that the most appropriate aids are selected automatically.

3.3 RNAV equipment can accept a variety of navigation inputs; it is therefore convenient to consider the general characteristics of RNAV airborne equipment under the following headings:

a) VOR/DME;

b) LORAN-C;

c) INS;

d) DME/DME; and

e) GNSS.

3.4 In this manual, it is assumed that all of the above systems are either coupled, or capable of being coupled, directly to the autopilot. This facility may become a prerequisite of future RNAV equipment.

VOR/DME

3.5 Within the category of RNAV systems based on VOR/DME, there is a considerable variation in capability. Possibly the least complex of this type of equipment are systems using VOR/DME station moving. In effect, this type of RNAV electronically offsets a selected VOR/DME facility (by a range and bearing calculated and set by the operator) to the position of the next way-point and the aircraft is then provided with apparent VOR steering guidance to that way-point. The equipment is still subject to the designated operational coverage and reception limitations of the selected facility and any other errors inherent in the system. For such RNAV equipment to be approved, it must have the capability to accept a minimum of three present way-points, and its use would necessarily be limited to those routes within adequate VOR/DME coverage.

LORAN-C

3.6 LORAN-C is a radio navigation system that uses time-synchronized time signals from ground transmitting stations spaced several hundred miles apart. The stations are configured in chains of three to five stations which

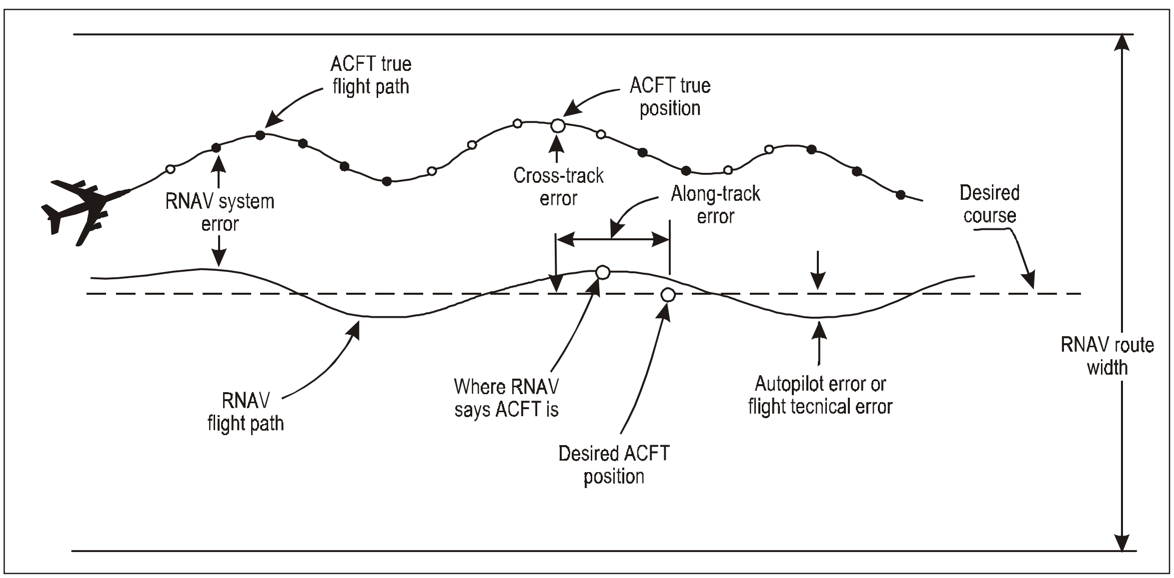

Figure C-1. RNAV system error

transmit with the same group repetition interval. Within each chain, one station is designated as master and the remainder as secondaries; the master has unique pulse and phase transmission characteristics to distinguish it from the secondaries.

3.7 Aircraft position is derived by measuring the difference in arrival time of LORAN-C pulses from three or more ground stations. LORAN-C equipment may be a stand-alone system, but modern systems are more usually integrated with a navigation computer in order to provide positional and associated information.

3.8 The LORAN-C ground wave is used for navigation and adequate signal coverage is normally in the region of about 1 700 km (900 NM). The usable coverage area may, however, be affected by ground conductivity, atmospheric or other interference with the signal reception.

3.9 There are a number of disadvantages to the LORAN-C system:

a) the signals are subject to local interference from such sources as low frequency transmitters and power line emissions;

b) a failure of one transmitter can leave a major area without coverage; and

c) approval of LORAN-C for RNAV operations will be limited to the geographical area of good ground wave signal reception.

INS

3.10 The INS is totally self-contained equipment that operates by sensing aircraft accelerations with a gyro-stabilized platform. Output functions of the system include accurate present position information, navigation data, steering commands and angular pitch, roll and heading information. Most aircraft fitted with INS have a duplicated or triplicated system. The normal operating practice is to input the systems with the aircraft's known position to a high degree of accuracy prior to departure from the aircraft stand. By pre-setting a series of way-points, the system will navigate the aircraft along a predetermined track. Way-points are usually fed into the system prior to departure, but new way-points can be inserted at any time.

3.11 The major disadvantage of INS is that its accuracy becomes degraded with elapsed time since the last update, for which a linear decay of 2.8 to 3.7 km (1.5 to 2 NM) per hour must be allowed, although significantly better accuracies are often achieved in practice. Whereas INS can be expected to guide an aircraft to within the normal tolerances of a VOR-defined route system for something in excess of 1 850 km (1 000 NM) following correct alignment before departure, it is apparent that a basic dual INS without automatic updating would not be sufficiently accurate for use in such airspace following several hours of flight, unless special measures were adopted which would enable the pilot to verify system accuracy by various updating or cross-checking methods.

3.12 A substantial number of aircraft have three INSs and it is usual for these to be operated in so-called triple-mix mode which provides an average of the positional data provided by the three independent systems. Normally this process provides a better position estimate, because if one of the three systems differs significantly from the other two, its data can be excluded from the averaging process.

3.13 Many INSs have sophisticated automatic updating facilities employing dual DME and/or VOR inputs. The most complex of these employ auto-tune devices which will check and provide constant updates from multiple DMEs within range of the aircraft (see also 3.14).

DME/DME

3.14 The most accurate means currently available for updating RNAV and flight management system equipment within continental airspace is by reference to multiple DMEs, with a minimum of two suitably positioned facilities being needed to provide a position fix. The quality of the positional information will be dependent on the relative geometry of the DMEs and their range from the aircraft, and therefore the system will have a fall-back routine whereby other combinations of aids may be utilized.

GNSS

3.15 GNSS are evolving. GNSS providing independent navigation, where the user performs on-board position determination from information received from broadcast transmissions by a number of satellites, will provide highly reliable, highly accurate and high integrity global coverage. Although the RNP concept allows for more than one satellite navigation system to be in use simultaneously, from an aircraft equipment point of view, maximum interoperability is essential as it would significantly simplify avionics and thereby reduce cost. It would also be beneficial if one system could serve as a complement to and/or in a backup role for the other.

3.16 Criteria to enable adequate integrity monitoring and health warning services for satellite navigation systems must be developed. Two distinct approaches to the problem of integrity, namely receiver autonomous integrity monitoring (RAIM) and the provision of a GNSS integrity channel (GIC) have been identified. Both are under investigation in several States and international organizations. Subject to the satisfactory development of integrity monitoring, it is confidently expected that GNSS will meet the civil aviation requirements for navigation.

4. NAVIGATION ERROR CHARACTERISTICS

Navigation system error

4.1 Navigation system error is defined at the output of the navigation receiver and therefore includes both the signal-in-space and airborne equipment error. The unique signal characteristics of a navigation system can have many error components, including propagation error, errors in the transmitted signal arising from geographical siting, magnetic alignment of the ground station and receiver errors such as receiver noise. The distribution and rate of change, as well as the magnitude of the errors, must be considered. Error distributions may contain both bias and random components. The bias component is generally easily compensated for when its characteristics are constant and known. For example, VOR radials can be flight-checked and the bias error reduced or eliminated through correction of the radial used on aeronautical charts. The LORAN-C seasonal and diurnal variations can also be compensated for by implementing correction algorithms in aircraft equipment logic and by publishing corrections periodically for use in air equipment. Ionospheric corrections may be incorporated into GNSS solutions.

4.2 The distribution of the random or nonpredictable varying error component becomes the critical element to be considered in the design of navigation systems. The rate of change of the error within the distribution is also an important factor, especially when the system is used for approach and landing. Errors varying at a very high frequency can be readily integrated or filtered out in the aircraft equipment. Errors occurring at a slower rate can, however, be troublesome and result in disconcerting indications to the pilot. An example of one of these types of errors would be a “scalloped” VOR signal that causes the course display indicator (CDI) to vary. If the pilot attempts to follow the CDI closely, the aircraft will start to “S-turn” frequently. The manoeuvring will cause unnecessary pilot workload and degrade pilot confidence in the navigation system. This indication can be further aggravated if navigation systems exhibit different error characteristics during different phases of flight or when the aircraft is manoeuvring.

4.3 In summary, the magnitude, nature and distribution of errors as a function of time, terrain, avionics, aircraft type, aircraft manoeuvres and other factors must be considered. The evaluation of errors is a complex process, and the comparison of systems based on a single error number will be misleading.

RNAV computation error

4.4 Navigation system error/airborne equipment error components, in accordance with common practice, may include errors in the receiver outputs and errors contributed by the converter. In those cases in which an RNAV equipment accepts inputs directly from the navigation receiver, the error components normally included for the converter are not incurred; therefore, the appropriate value for airborne equipment error can be correspondingly reduced. The RNAV computation error can be estimated to be the output resolution of the RNAV equipment.

Display system error

4.5 Display system error may include error components contributed by any input, output or signal conversion equipment used by the display as it presents either aircraft position or guidance commands (e.g. course deviation or command heading) and by any course definition entry devices employed. For systems in which charts are incorporated as integral parts of the display, the display system error necessarily includes charting errors to the extent that they actually result in errors in controlling the position of the aircraft relative to a desired path over the ground. To be consistent, in the case of symbolic displays not employing integral charts, any errors in way-point definition directly attributable to errors in the reference chart used in determining way-point positions should be included as a component of this error. This type of error is virtually impossible to handle and, in general practice, highly accurate, published way-point locations are used to the greatest extent possible in setting up such systems to avoid such errors and to reduce workload.

Course selection error

4.6 Course selection error is the difference between the desired course setting and the course that is actually set.

5. ERROR BUDGETS FOR FTE

General

5.1 FTE refers to the accuracy with which the aircraft is controlled, as measured by the indicated aircraft position with respect to the indicated command or desired position. It does not include procedural blunders which are gross errors in human judgment, or inattentiveness that cause the pilot to stray significantly from the intended track.

5.2 It is difficult to completely characterize FTE. Equipment design and ambient environment variables affect FTE directly and measurably by affecting the processing of the basic display inputs. This includes determining the display scale factors and other display configuration variables which affect how guidance information is displayed. Compensating for aircraft control dynamics and air turbulence are examples of environmental variables which affect FTE. These factors must be taken into account in arriving at empirical values for FTE contribution to system use accuracy.

5.3 Guidance signals can be coupled to the aircraft in one of three modes: manual (raw CDI deviations), flight director or autopilot. Each of these modes has an error budget for FTE.

Manual FTE

5.4 The FTE, which is associated with manual modes, will vary widely depending on such factors as wind conditions and the experience, workload, fatigue and motivation of the pilot. The currently used 95 per cent probability for manual FTEs for the various phases of flight based on 1978 United States Federal Aviation Administration (FAA) tests of VOR/DME are as follows:

Oceanic	3.7 km	2.0 NM
En-route	1.85 km	1.0 NM
Terminal	1.85 km	1.0 NM
Approach	0.93 km	0.5 NM

5.5 Experience has shown, however, that FTE is related to navigation system and course sensitivity. Data collected to date from flight tests and flight simulations for microwave landing system (MLS) RNAV straight-line segments under varying wind conditions and aircraft types indicate a value of 0.216 NM (400 m) may be appropriate for the approach phase at a 95 per cent probability. Curved approach path data indicate larger FTEs. The difference between the VOR/DME values and MLS RNAV values indicates that the current manual 95 per cent probability values may be too conservative.

Coupled FTE

5.6 The RNAV system may be coupled to the AFCS or the flight director. When RNAV is coupled to the AFCS, the tracking accuracy (FTE) is a function of the autopilot gain and the AFCS guidance loop bandwidth. Autopilot gain and bandwidth are in turn dependent on the phase of flight. When RNAV is coupled to the flight director, the additional error source of flight director needle sensitivity must be considered.

5.7 There is very little published data on AFCS-coupled FTE. EUROCONTROL Experimental Centre Report No. 216, June 1988, entitled *Navigational Accuracy of Aircraft Equipped with Advanced Navigation Systems* determined that en-route AFCS-coupled system use accuracy is approximately 1 200 m (0.66 NM) (95 per cent probability). This would suggest that AFCS-coupled FTE could be as high as 400 m (0.22 NM) based on 1 000 m (0.5 NM) computation error for RNAV-DME-DME which includes inaccuracies due to the geometry of the DME station, and a 50:50 weighted mix of analog and digital DME sensor accuracy (685 m (0.37 NM)(2-sigma)).

5.8 A second value of AFCS-coupled FTE may be obtained from manufacturers' specifications. A limited review of manufacturers' specifications indicates track accuracy requirements of 463 m (0.25 NM) (95 per cent probability) for equipment.

5.9 A value of AFCS-coupled FTE for approaches may be obtained from MLS RNAV flight tests and simulations for straight-line segments. These indicate that AFCS-coupled FTE could be as low as 0.030 km (0.016 NM) for approaches.

5.10 Limited data exist on flight director autocoupled FTE from flight tests and flight simulations for MLS RNAV straight-line segments. These data indicate that an FTE value of 0.061 km (0.033 NM) may be appropriate for the approach phase at a 95 per cent probability. This value was determined under varying wind conditions and with different aircraft types.

RNAV FTE

5.11 RNAV FTE cannot be completely characterized at this time for all three aircraft modes, as extensive data must be obtained with a variety of sensors and conditions before a complete statistical representation of FTE can be defined.

Table C-1. Assumed FTE values (95 per cent probability)

			Coupled			
	Manual		*Flight director*		*Autopilot*	
Flight phase	*km*	*NM*	*km*	*NM*	*km*	*NM*
Oceanic	3.7	2.0	0.93	0.50	0.463	0.25
En-route	1.85	1.0	0.93	0.50	0.463	0.25
Terminal	1.85	1.0	0.93	0.50	0.463	0.25
Approach	0.93	0.5	0.463	0.25	0.231	0.125

The purpose here is to use preliminary findings to establish an assumed system error budget based on various data sources, fully recognizing that the database is incomplete. This assumed FTE should satisfy the requirements of system users and system planners.

5.12 Table C-1 presents assumed FTE values. Manual FTE figures in Table C-1 are those currently used in FAA, RTCA and ICAO documents.

5.13 AFCS-coupled FTE of 463 m (0.25 NM) for en route appears to be substantiated by the EUROCONTROL data and manufacturers' specifications. Assuming that the approach FTE will be at least twice as accurate as en-route FTE, an approach FTE of 231 m (0.125 NM) is derived. This may be compared to the MLS RNAV value of 30 m (0.016 NM).

5.14 Flight director-coupled FTE is derived from the manual and AFCS-coupled FTE and MLS RNAV data. Based on the MLS RNAV tests, it is assumed that a flight director has at least a sixfold increase in FTE accuracy over manual flight, but has twice the error of an autopilot. Since the AFCS-coupled FTE values are reasonable with respect to available data, the assumption is made that flight director FTE will have at least twice the error of AFCS-coupled flight. This resultant flight director FTE of 463 m (0.25 NM) for the approach phase may be directly compared to the MLS RNAV value of 61 m (0.033 NM). The factor of 7.5 difference is comparable to the factor 7.8 difference for assumed AFCS-coupled FTE and the MLS RNAV value of 30 m (0.016 NM). This approximate order of magnitude difference between assumed FTE values and measured FTE values indicates that the assumed values may be conservative.

Appendix D

REFERENCE DOCUMENTATION RELATED TO AREA NAVIGATION

Australia

1. CAA Doc. ON 10, *Operational Notes on Area Navigation Systems*

2. CAA Publication Number 50, *Airborne Radio Equipment Classification*

3. CAA Publication, *Flying Operational Standards and Instructions*

4. CAA Publication, CAAP B-RNAV-1, *Approval of Australian Operators and Aircraft to Operate under Instrument Flight Rules in European Airspace Designated for Basic Area Navigation (RNP 5)*

5. CAA Publication, CAAP RNP 10-1, *Required Navigation Performance 10 Operational Approval*

Canada

1. *Guidance material on the application of Area Navigation (RNAV) in Canadian domestic airspace* — TP 9064E.

2. *ATC RNAV Control Procedures — Manual of Operations* — TP-703

Europe

1. National Civil Aviation Legislation

2. Aeronautical Information Circulars

3. Airworthiness Notices

4. EUROCAE ED-39, *Minimum Operational Performance Requirements (MOPR) for Airborne RNAV Systems based on two DME as sensors*

5. EUROCAE ED-40, *Minimum Performance Specification (MPS) for Airborne RNAV Computing Equipment based on two DME as sensors*

6. EUROCAE ED-27, *MOPR for Airborne Area Navigation System based on VOR and DME as sensors*

7. EUROCAE ED-28, *MPS for Airborne RNAV Computing Equipment based on VOR and DME as sensors*

8. EUROCAE ED-12A/RTCA DO-178A, *Software Consideration in Airborne Systems and Equipment Certification*

9. EUROCAE ED-14B/RTCA DO-160B, *Environmental Conditions and Test Procedures for Airborne Equipment*

10. EUROCAE ED-58 (Draft), *MOPR for Airborne RNAV Equipment using Multi-sensor Inputs*

11. EUROCAE ED-75, *Minimum Aviation System Performance Standards (MASPS) for RNP Area Navigation*

12. CAP360, *Guidance to UK AOC Holders*

13. NAT Doc. 001, T13.5N/5, *Guidance and Information Material concerning Air Navigation in the NAT Region*

14. EUR Doc. 001, RNAV/4, *Strategy for the Implementation of RNAV in the European Region* (4th Edition)

15. SAE ARP 1570 (Proposed), *Flight Management Computer System*

16. EUROCONTROL *Standard on Area Navigation, Operational and Functional Requirements*

17. Joint Airworthiness Authorities, AMJ 20-X2, *JAA Guidance Material on Airworthiness Approval and Operational Criteria for the Use of Navigation Systems in European Airspace Designated for Basic RNAV Operations (RNP 5)*

United States

1. AC 20-115A, *Radio Technical Commission for Aeronautics (RTCA) DO-178A* (8/12/86)

2. AC 20-121A, *Airworthiness Approval of Airborne LORAN-C Navigation Systems for Use in the U.S. National Airspace System (NAS)* (8/24/88)

3. AC 20-129, *Airworthiness Approval of Vertical Navigation (VNAV) Systems for Use in the U.S. NAS and Alaska* (9/12/88)

4. AC 25-4, *Inertial Navigation Systems (INS)* (2/18/66)

5. AC 90-45A, *Approval of Area Navigation Systems for use in the U.S. National Airspace System* (2/21/75)

6. AC 90-76B, *Flight Operations in Oceanic Airspace* (1/29/90)

7. AC 90-79, *Recommended Practices and Procedures for the Use of Electronic Long Range Navigation Equipment* (7/14/80)

8. AC 90-82B, *Direct Routes in the Conterminous U.S.* (7/15/90)

9. AC 91-49, *General Aviation Procedures for Flight in North Atlantic Minimum Navigation Performance Specifications Airspace* (8/23/77)

10. AC 120-33, *Operational Approval of Airborne Long Range Navigation Systems for Flight Within the North Atlantic Minimum Navigation Performance Specifications Airspace* (6/24/77)

11. AC 121-13, *Self-contained Navigation Systems (Long Range)* (10/14/69)

12. Federal Aviation Administration Order 8400.10, *Air Transportation Operations Inspector Handbook*, Volume 4 — Aircraft Equipment and Operational Authorizations, Chapter 1 — Air Navigation

13. Federal Aviation Administration Handbook, 8260.3B, *U.S. Standard for Terminal Instrument Procedures (TERPS)*, Chapter 15 — Area Navigation (RNAV)

14. AC 20-130, *Airworthiness Approval of Multi-sensor Navigation Systems for use within the U.S. NAS and Alaska* (9/12/88)

15. RTCA/DO-180 A, *Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using a Single Collocated VOR/DME Sensor Input* (5/24/90)

16. RTCA/DO-187, *Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using Multi-sensor Inputs* (11/13/84)

17. RTCA/DO-194, *Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using LORAN-C Inputs* (11/17/86)

18. RTCA/DO-236, *Minimum Aviation System Performance Standards (MASPS) for RNP Area Navigation*

19. ARINC Characteristics 702-1, *Flight Management Computer System*

20. TSO C115, *Airborne Navigation Equipment using Multi-sensor Inputs*

21. Federal Aviation Administration Order 8400.12A, *Required Navigation Performance 10 (RNP 10) Operational Approval*

22. AC 90-96, Approval of U.S. *Operators and Aircraft to Operate under Instrument Flight Rules (IFR) in European Airspace Designated for Basic Area Navigation (BRNAV/RNP 5)*

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