

# Airport Surface RNP (Required Navigation Performance) - Implications for GNSS

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## BIOGRAPHIES

Rick Cassell, Scott Bradfield, and Alex Smith are systems engineers at Rannoch Corporation, and for the past several years have been supporting National Aeronautics and Space Administration (NASA) and Federal Aviation Administration (FAA) programs with the implementation of the Required Navigation Performance (RNP) concept for airport surface applications. Rick Cassell has a Bachelor's degree in Electrical Engineering from Villanova University. Scott Bradfield has a Bachelor of Science degree in Aerospace and Ocean Engineering from Virginia Tech University. Alex Smith has a Masters degree in Aerospace Engineering from Cranfield University, and is a registered Professional Engineer.

## ABSTRACT

One of the anticipated applications of Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS), is aircraft navigation on the airport surface. With the implementation of local area differential GNSS, technology will be available to enable aircraft to obtain accurate position information when taxiing on the airport. Currently, navigation performance standards do not exist for aircraft operations on the airport surface. Standards are under development by the International Civil Aviation Organization (ICAO) All Weather Operations Panel (AWOP) for Advanced Surface Movement Guidance and Control Systems (A-SMGCS) and by the RTCA Airport Surface Navigation and Surveillance subgroup of Special Committee 159. Under contract to NASA Langley Research Center as part of the Terminal Area Productivity Program, Rannoch is developing the RNP requirements for surface movement guidance. The results of this work are being coordinated with ICAO, RTCA and the FAA, and form the basis for surface navigation standards. This paper

presents a summary of RNP development including definition of the operation target level of safety and proposed requirements

for the four RNP parameters—integrity, continuity, accuracy and availability. In addition to definition of system level requirements the paper presents proposed allocations for navigation sensor performance, which defines the performance needed by a GNSS-based system to satisfy system RNP requirements.

## INTRODUCTION

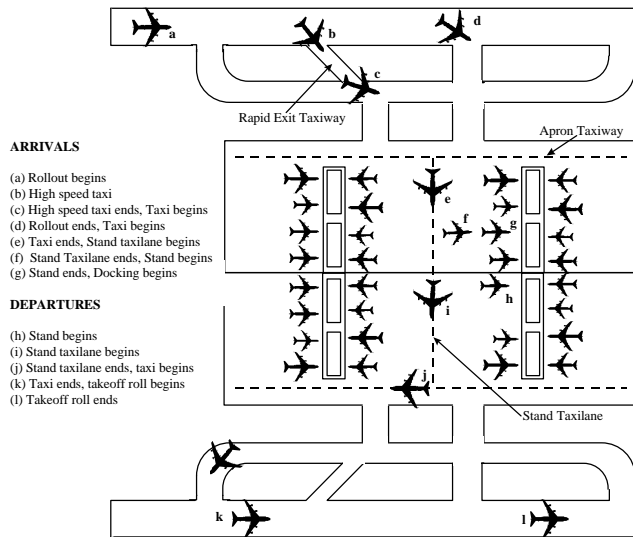
RNP is a relatively new concept that is being applied to develop guidance standards for all phases of aircraft operations, including en route, landing and surface operations. RNP is a probabilistic approach to evaluating an aircraft's deviation from its intended course. One of the benefits of the RNP approach is that it allows the design engineer to trade off elements of error budgets between subsystems; for example, a newer autopilot design may allow the use of a less accurate sensor or ground system. The RNP approach also goes beyond the accuracy of a system and provides quantitative requirements for a system's continuity and integrity. The RNP process is being applied to aircraft surface movements. The main components of the RNP are:

- Operation Classification
- Target Level of Safety (TLS) Risk Allocation
- Accident/Incident Ratio
- Risk Allocations
- Pilot Risk Factor
- Integrity and Continuity
- Containment Limit
- Accuracy
- Availability
- Validation

Each of these are discussed in the following sections (see Ref. 1).

## REQUIREMENTS DEVELOPMENT

**Operation Classification.** The surface operation is considered in phases, including rollout, high speed taxi exit, and normal taxi. The definition of phases is related to aircraft taxi speed and each phase of the operation is considered for different visibility conditions. Figure 1 shows a summary of the phases of operation selected for surface movement.



**Figure 1. Phases of Surface Operation**

Rollout is defined as touchdown to the point where the aircraft decelerates below 60 kts [2]. Operationally, rollout is considered to be a part of the aircraft landing, therefore the RNP for that phase of surface movement is defined by the Category III landing RNP. After completing rollout the aircraft will enter into the taxi phase, which is defined as either high speed, normal or apron taxi. For runways with a rapid exit taxiway, the aircraft will end rollout by taxiing at a high speed. After the aircraft has decelerated it enters the normal taxi phase. The aircraft then enters the apron area and initially will travel on an apron taxiway. When the aircraft enters the stand area it will be moving on a stand taxilane at its slowest taxi speed. In some operations there is also a docking maneuver.

For the departing aircraft, the order of the phases of operation are from the stand to normal/apron taxi to takeoff roll. The takeoff roll is covered in the RNP for aircraft departure and is therefore not included as part of the surface movement RNP. High speed taxi is at speeds between 30 and 50 kts, which occur with the use of rapid exits (also referred to as high speed exits). This is based

on measurements of operational speeds [3] and the ICAO aerodrome design manual [4]. Normal/apron taxiway

speeds range from 10 - 30 kts. The 30 kts maximum for normal taxi is based upon a U.K. study that found 95% of aircraft taxi speeds to be less than 30 kts, with the average being slightly under 20 kts [5]. When the aircraft enters the stand taxilane phase of surface movement it will have a ground speed between 0 and 10 kts. To determine the risk for each phase of operation, an associated exposure time must be assigned. Exposure times were determined by evaluating typical taxi distances for each phase for nine major U.S. airports [6]. Table 1 summarizes the velocities and exposure times for the different phases.

Taxi Phase	Taxi Speed (knots)	Exposure Time (minutes)
Rapid Exit (High Speed)	30-50	0.5
Normal/Apron Taxiway - straight	10-30	6
Normal/Apron Taxiway - curve	10-20	
Stand/Stand Taxilane	0-10	3

**Table 1. Taxi Speeds and Exposure Times**

As stated earlier, each phase of the surface operation must be considered for different visibility conditions. Currently, visibility conditions have three classifications according to ICAO [7] and are shown below. Levels 3 and 4 are essentially equivalent to the approach and landing Category III.

- Level 1, 2: RVR > 400 m (1300 ft)
- Level 3: 75 m (250 ft) < RVR < 400 m (1300 ft)
- Level 4: RVR < 75 m (250 ft)

**TLS Risk Allocation.** The target level of safety established by ICAO for the entire operation or mission is one accident per  $10^7$  operations [7]. It is necessary to allocate a portion of this to the taxi phase. One method of determining an appropriate TLS for an operation is to base it upon the historical accident rate. Two sources of accident data are used here—worldwide data, and National Transportation Safety Board (NTSB) data for aircraft operations in the U.S. Worldwide accident data reveals the following:

- Overall fatal accident rate (1985-94) =  $1.8 \times 10^{-6}$  per operation [8,9]
- Taxi accidents (including load and unload) account for 5% of fatal accidents [10]

- Therefore the fatal taxi accident rate =  $9.0 \times 10^{-8}$  per operation.

NTSB accident data is summarized as follows:

- Overall fatal accident rate (1985-94) =  $0.56 \times 10^{-6}$  per operation [11]
- Fatal taxi accidents account for 11% of all fatal accidents [11]
- Therefore the fatal taxi accident rate =  $6.2 \times 10^{-8}$  per operation.

The ICAO and NTSB fatal taxi accident rates are similar ( $9.0$  vs.  $6.2 \times 10^{-8}$  per operation). The final approach and landing phase was allocated  $1.0 \times 10^{-8}$  [2,12]. Similarly, the other phases of flight have allocations that use only a small portion of the overall TLS. Therefore, the taxi phase should be allocated a comparable portion. Based on the above, the surface movement TLS was established at  $1.0 \times 10^{-8}$  per operation. This provides a margin of  $6-9$  over the historical accident rate and is in line with the

allocations used for the approach and landing RNP. It should be noted that this TLS applies to all visibility conditions of surface operations. Figure 2 shows the allocation of risk from the TLS to integrity and continuity requirements for the guidance function. The TLS is initially divided between the four functions associated with surface movement (surveillance, guidance, control and routing). The risks were divided equally except for routing, which was assigned a lower risk because it is a less complex function. Following is an explanation of the allocation process for the guidance (or navigation) risk.

**Accident/Incident Ratio.** As not all incidents translate to accidents there is a ratio assigned. An incident is defined as any time the aircraft leaves the containment region. There are actually two ratios used: fatal accident/accident and accident/incident. These ratios were based primarily on NTSB data for accidents on the airport surface.

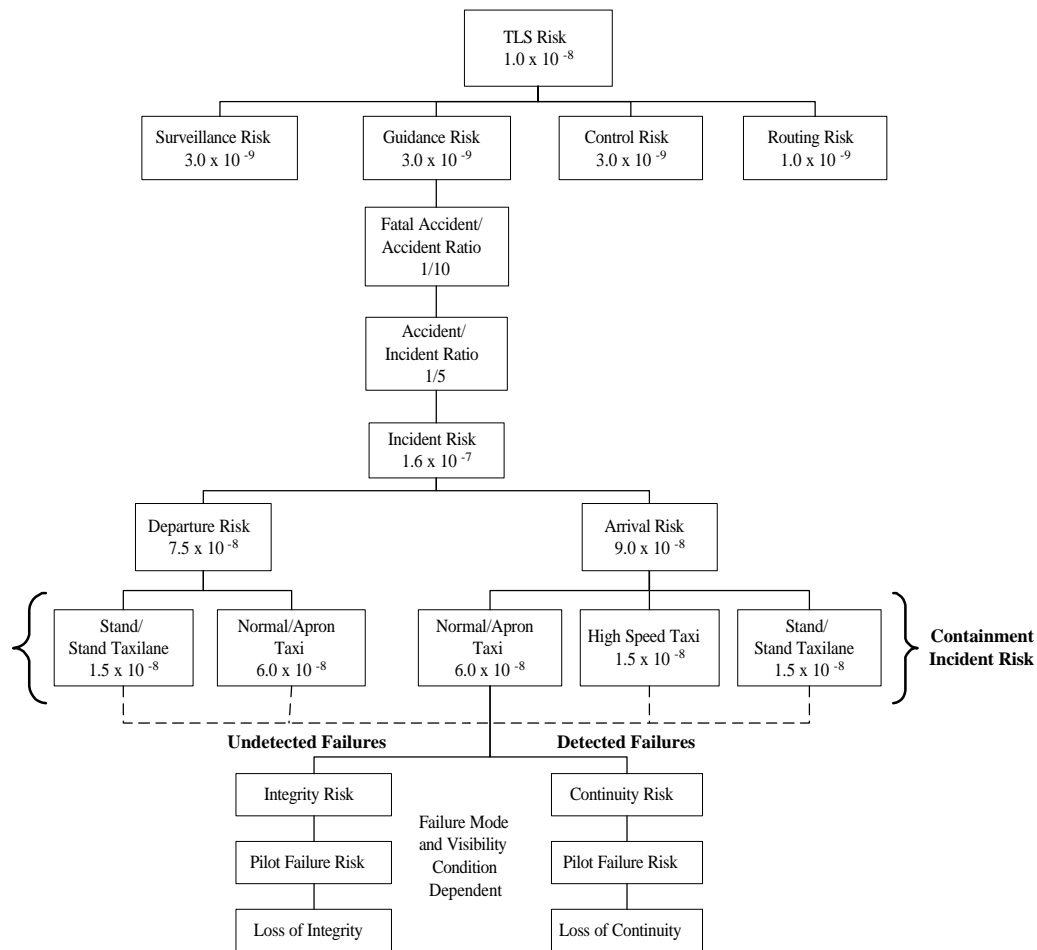
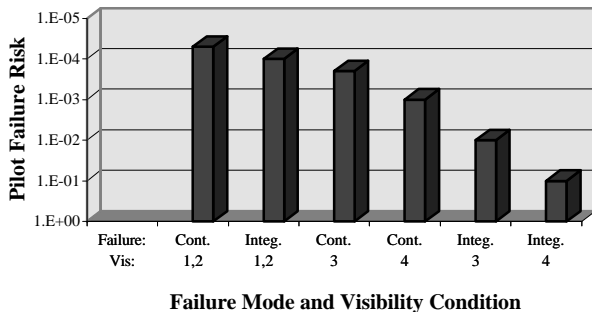


Figure 2. RNP Risk Allocation

**Risk Allocations.** The overall TLS is then allocated to each phase of the surface operation. The TLS includes all phases of an operation, so for surface both departure and arrival must be included. Risk levels are assigned to each phase—high speed taxi, normal taxi, etc. Failures are identified as continuity or integrity. The reason for different allocations is different exposure times. The values shown in Figure 2 are on a per operation basis. The requirements have been allocated such that when normalized to a per hour basis they are roughly equal over all phases of the operation.

**Pilot Risk Factor.** Figure 3 shows the pilot failure risk for various failure mode and visibility conditions at normal taxi speeds. This risk factor is dependent on several variables, all of which affect the outcome. The mode of failure determines whether the crew receives a warning that a failure has occurred. If a continuity failure occurs the crew will receive a warning immediately following the failure. An integrity failure will yield no warning and will be dependent on the crew realizing a failure has occurred based on visual cues.



**Figure 3. Pilot Risk Allocations at Normal Taxi Speeds**

Consequently, longer response times can be expected for integrity failures. Since the crew is relying on visual, out-the-window views, visibility will primarily drive the pilot risk for the integrity failure mode. Low visibility can also be expected to generate longer pilot response times and higher risk. The velocity the aircraft is traveling when the failure occurs affects the amount of time the crew has to respond to the failure. The greater the aircraft velocity, the longer the braking distance, and consequently, the less time the crew has to respond to the failure. Crew response time will also be longer because of an increased crew workload when traveling at high speeds on the airport surface (i.e., high speed exit taxiing).

**Integrity and Continuity Requirements.** Incident risk is allocated to integrity and continuity. Integrity relates to the trust which can be placed in the correctness of the

guidance information. Integrity risk is the probability of an undetected failure that results in the TSE exceeding the containment limit. Continuity is the capability of the system (comprising all elements necessary to maintain the aircraft position within the containment region) to perform the guidance function without nonscheduled interruptions during the operation. Continuity risk is the probability that the system will be unintentionally interrupted and not provide guidance information for the intended operation. More specifically, continuity is the probability that the system will be available for the duration of an operation, presuming that the system was available at the beginning of the operation. The risk allocations are determined after accounting for the pilot risk factor. Table 2 summarizes the most stringent integrity and continuity requirements for the different visibility conditions. Each phase of surface operation is theoretically allocated a different risk, but in order to simplify the standards only the most stringent requirement is used.

	Visibility Condition		
	1,2	3	4
Integrity	$3.0 \times 10^{-3}$	$3.0 \times 10^{-5}$	$3.0 \times 10^{-6}$
Continuity	$6.0 \times 10^{-3}$	$1.5 \times 10^{-3}$	$3.0 \times 10^{-4}$

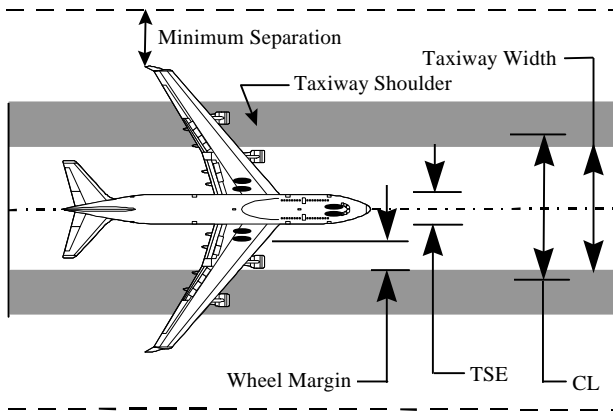
**Table 2. Integrity and Continuity Risk (per hour)**

**Containment Limit.** Figures 4 and 5 illustrate key taxiway design standards [4,13]. The two parameters of concern are the relationship of the main wheels to the edge of the taxiway and its shoulder, and the margin between the wing tips and the closest allowable objects. Figure 4 shows straight sections of taxiways and Figure 5 curved sections.

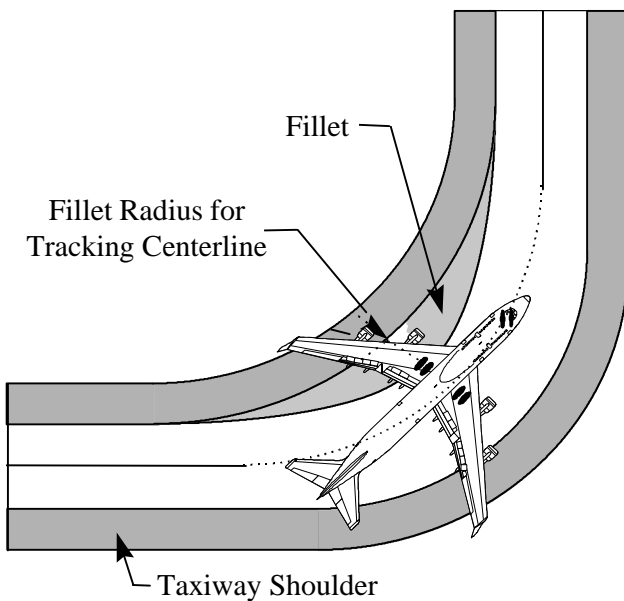
The difference with curved sections is that normally there is additional pavement added to the inside of the curve in the form of a fillet. This compensates for the fuselage of the aircraft deviating to the inside when making a turn, assuming that the pilot steers by maintaining the cockpit (and nosewheel) over the centerline of the taxiway. The amount of extra fillet required is sufficient to maintain the same margins between the wheels and taxiway edge. At airports where there is no fillet the pilot is required to use “judgmental oversteering” to maneuver the aircraft, where the nosewheel is purposely steered outside the centerline, thus keeping the fuselage from deviating to the inside of the curve.

The containment limit (CL) definition assumes operation at an aerodrome that meets the taxiways widths and the minimum separation distances specified in Annex 14 [13]. Table 3 indicates the taxiway widths categorized according to aerodrome code. For code E, there is a 15.5 m margin between the wing tips and any objects,

including wings of aircraft on parallel taxiways. The minimum margin between the main wheels and taxiway edge is 4.5 m. The standards also recommend a 10.5 m shoulder, thus yielding a 15 m margin between the wheels and outer edge of the shoulder. The result is that the aircraft can deviate by 15 m from the taxiway centerline before there is risk of an incident, and therefore the CL is defined to be this value. For our purposes it is assumed that all deviations are referenced to the nosewheel of the aircraft.



**Figure 4. Taxiway Design Standards (straight segments)**



**Figure 5. Taxiway Design Standards (curved segments)**

Table 3 lists the CL values based on minimum separation distances for aircraft for all of the different taxiway design codes. The CL of 15 m is applicable only to codes D and E. Since the margin is less for codes A, B and C, the CL for those cases is defined accordingly as 8 m. This table addresses only the normal taxiways. The dimensions change as we move into the stand taxilanes and stand regions. In the stand taxilanes, the boundary is dependent on the minimum clearance between the aircraft's wing tips and other objects. In the stand area, the relationship of the main wheels to the edge of the taxilane is not of concern because there is a continuous pavement area; therefore, only the wing tip margins determine the CL. As would be expected, the safety margins and associated CLs decrease in the stand areas since it is assumed the aircraft is moving slower and is able to track the centerline more accurately. The probability of an aircraft deviating outside the boundary of the containment region is equal to the incident risk for the appropriate surface operation. These are indicated in Figure 2, and are either  $1.5 \times 10^{-8}$  (high speed taxi and stand/stand taxilane) or  $6.0 \times 10^{-8}$  (normal and apron taxi).

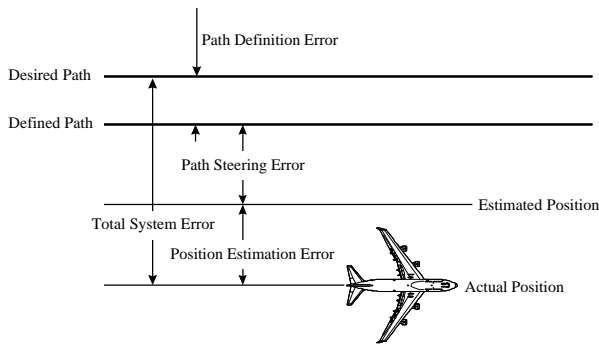
Aero-drome Code	Taxiway width (meters)	CL (meters)	95% TSE (meters)	Vis 4 - 95% PEE (meters)
A	7.5	8	0.7	0.4
B	10.5	8	1.1	0.6
C	15	8	1.5	0.8
C	18	8	2.2	0.8
D	18	15	2.2	1.1
D	23	15	2.2	1.1
E	23	15	2.2	1.1

Notes:

1. Aerodrome reference code is according to the code letter definition in ICAO Annex 14, paragraph 1.3 [13].
2. All values for CL, TSE, and PEE are  $\pm$ .

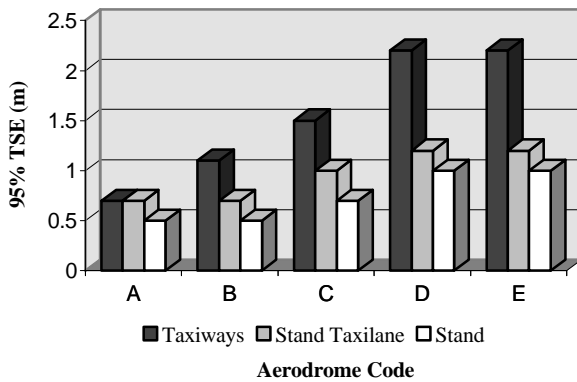
**Table 3. Containment Limits and Normal Performance Requirements**

**Accuracy.** The accuracy requirement establishes the normal performance or 95% Total System Error (TSE), defined as the difference between actual aircraft position and desired path (see Figure 6). The constraining limit used in establishing the accuracy requirement is the margin between the aircraft wheels and taxiway edge (4.5 m for codes D and E). The normal performance limit should be established to minimize the probability of the wheels leaving the taxiway.



**Figure 6. Components of Total System Error**

The probability allocated for this is the equivalent of  $4\sigma$  or  $6.3 \times 10^{-5}$ , based on the assumption that the TSE distribution is gaussian. Having the deviation to the taxiway edge established as a  $4\sigma$  value and the normal performance equivalent to  $2\sigma$  (approximately 95%), the accuracy requirement is obtained by dividing the wheel margin by two. For aircraft with 4.5 m wheel margins the resulting accuracy requirement is  $\pm 2.2$  m. The resulting TSE requirements are shown in Figure 7.



**Figure 7. Guidance Accuracy Normal Performance Requirements**

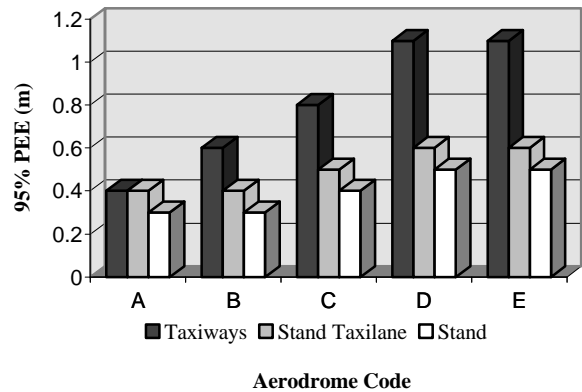
The process for establishing the TSE limit is analogous to that used in establishing the relationship between the 95% TSE and the CL for other RNP applications. For en route and terminal area navigation the containment limit is set to two times the 95% value [14], while for approach and landing the relationship is a factor of three [2]. The difference is the direct relationship between normal performance and the boundary for wheel excursions, not the CL. Referring again to Figure 6, the TSE is composed of Path Definition Error (PDE), Path Steering Error (PSE) and Position Estimation Error (PEE), represented mathematically as:

$$\text{Instantaneous RNP accuracy} = \text{TSE} = \text{PDE} + \text{PSE} + \text{PEE}$$

PSE has traditionally been referred to as flight technical error and PEE is usually referred to as navigation sensor

error. Since they are statistically independent, PEE, PSE and PDE are Root Sum Squared (RSS) to compute TSE.

For approach and landing calculations, it is always assumed that the pilot or flight control system attempt to fly the course provided by the guidance system. For surface movement this is not necessarily true. When visibility conditions are such that the pilot is able to track the actual centerline by visual reference, the track defined by the guidance system may be different from the desired track without any effect on overall performance. In practice, during good visibility the role of electronic guidance is mainly for enhancing situational awareness. Accordingly, PEE, PSE and PDE are not necessarily additive. Only under the lowest visibility conditions, when the pilot is completely reliant on the guidance system should PEE, PSE and PDE be additive as in normal flight. Here we only address the PEE allocations for visibility condition 4. The PEE allocations are shown in Figure 8.



**Figure 8. Lateral and Longitudinal Position Estimation Errors**

The process used in determining the allocations was based on maximizing the PSE allocation. Table 6 lists available data on centerline tracking performance. Since these represent visual taxi (with two exceptions of electronic maps) the values can be considered primarily PSE. Therefore, allocated PSE values should be consistent with measured performance. The PEE was assigned a value equal to 50% of TSE, and PSE was assigned the remaining portion on an RSS basis.

**Availability.** Guidance availability is an indication of the ability of the guidance function to provide usable service within the specified coverage area. Availability is defined as the portion of time the system is to be used for navigation. During this time reliable navigation information is presented to the crew, autopilot, or other system managing the movement of the aircraft. Guidance availability is specified in terms of the

probability of the guidance function being available at the beginning of the intended operation.

The availability required for surface movement should not limit the overall operations of the aerodrome. As an example, for low visibility operations the guidance function should have at least the same availability as the landing system guidance function, otherwise the total operation cannot be performed. For providing service in visibility conditions 3 and 4, the availability requirement is equal to that of an associated Category III landing system and is 0.999. For visibility conditions 1 and 2, the availability is equal to that of an associated Category I landing system and is 0.9975 [2].

### GNSS IMPLICATIONS

**Integrity and Continuity.** The requirements contained in Table 2 are system level. To assess the implications of these requirements on a GNSS based system, the RNP risk is allocated to aircraft and non-aircraft components (see Figure 9). Preliminary allocations are contained in Tables 5 and 6. Where possible, allocations have been made consistent with existing GNSS standards (RTCA SCAT-I [15], FAA LAAS [16]). In general, the conclusion is that requirements for visibility conditions 1 and 2 are slightly less stringent than Category I precision approach. Similarly, visibility conditions 3 and 4 requirements are slightly less stringent than required for Category II and III, respectively. Therefore, a GNSS based system installed to provide Category I service should meet the integrity and continuity requirements for visibility conditions 1 and 2 surface operations. A GNSS based system installed to provide Category II/III service should meet the integrity and continuity requirements for visibility 3 and 4 conditions.

**Accuracy.** The PEE values specified in Table 3 and Figure 8 are equivalent to navigation sensor error, and therefore would be the accuracy requirements imposed on GNSS for visibility condition 4 (less than 75 m). It is possible these may be relaxed slightly for visibility condition 3. When comparing these values to those required for a Category III local area differential system they are significantly more stringent than the lateral requirements for landing, while the least stringent values in Figure 8 (codes D and E normal taxiways) are comparable to the vertical requirements [16]. The most stringent values (codes A and B and stand regions) are more demanding than Category III vertical requirements, implying these operations require accuracy better than that guaranteed by a local area differential system. In conclusion, a local area differential system will be necessary to meet the accuracy required for the lowest visibility operations, but still may not satisfy all surface operations, particularly those in the stand or gate areas. Regarding visibility conditions 1 and 2, further research is required to define PEE requirements. It is apparent, however, that it does not need to be as stringent as for low visibility since the pilot will be navigating primarily by visual out-the-window references. When the pilot has visual cues the position information is used mainly for situational awareness, and would require less stringent accuracy.

### VALIDATION

Several methods are being used to validate the proposed RNP. These include use of operational data, simulations, field demonstrations, and analysis.

**Operations.** Several sources of data were used to validate the accuracy allocations. One source was operational data from London Heathrow Airport consisting of over 77,000 aircraft taxiing movements on the airport surface and a statistical analysis [5]. Aircraft taxi centerline deviations recorded for various aircraft in the U.K. study are shown below in Table 4 and correlate well with RNP requirements.

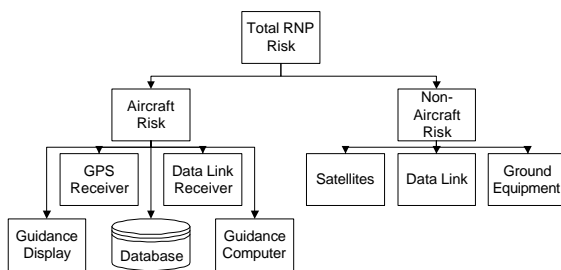


Figure 9. Allocation of GNSS Risk

<b>Aircraft Type</b>	<b>Straight Sections 95% (m)</b>	<b>Curved Sections 95% (m)</b>	<b>Data Source</b>
A310	1.4	1.9	1.
B72S	1.4	1.9	1.
B73S	1.6	1.8	1.
B747	1.2	2.5	1.
B757	1.4	1.8	1.
BAC1-11	1.5	1.9	1.
DC9S	1.5	2.3	1.
DC9	1.4	2.0	1.
F27	1.5	1.9	1.
F28	4.6	2.0	1.
S360	1.4	1.9	1.
L1011	1.1	2.3	1.
B737	1.4	N/A	2. VFR/day
B737	1.2	N/A	2. VFR/night
B737	1.5	N/A	2. RVR 1200'
B737	1.5	N/A	2. RVR 600'
B737	3.9	6.8	3. VFR
B737	3.7	6.2	3. RVR 150'
B737	3.9	5.2	3. VFR with map
B737	3.7	5.0	3. RVR 150' with map
<p>Note: Data collected on normal and apron taxiways only.</p> <p>Data Sources:</p> <ol style="list-style-type: none"> <li>1. Heathrow Airport operational data [5]</li> <li>2. RSLs simulator data [17]</li> <li>3. Moving map display simulator data [18,19]</li> </ol>			

**Table 4. Summary of Aircraft Taxi Centerline Tracking Performance**

Element	Visibility Conditions		
	1,2	3	4
1. Total Risk	$6.0 \times 10^{-3}$	$1.5 \times 10^{-3}$	$3.0 \times 10^{-4}$
2. Aircraft	$4.5 \times 10^{-3}$	$6.2 \times 10^{-4}$	$< 10^{-6}$
2a) GNSS Receiver	$0.9 \times 10^{-3}$ (2)	$< 10^{-6}$ (9)	$< 10^{-6}$ (9)
2b) Data Link Receiver	$0.9 \times 10^{-3}$	$1.55 \times 10^{-4}$	$< 10^{-6}$ (9)
2c) Guidance Computer	$0.9 \times 10^{-3}$	$1.55 \times 10^{-4}$	$< 10^{-6}$ (9)
2d) Cockpit Displays	$0.9 \times 10^{-3}$	$1.55 \times 10^{-4}$	$< 10^{-6}$ (9)
2E) Database	$0.9 \times 10^{-3}$	$1.55 \times 10^{-4}$	$< 10^{-6}$ (9)
3. Non-Aircraft	$1.5 \times 10^{-3}$ (3)	$8.8 \times 10^{-4}$ (5)	$3.0 \times 10^{-4}$ (7)
3a) Satellites	$2.6 \times 10^{-4}$ (1)	$2.6 \times 10^{-4}$ (1)	$0.5 \times 10^{-4}$ (8)
3b) Ground Equipment	$1.1 \times 10^{-3}$ (4)	$4.8 \times 10^{-4}$ (6)	$2.0 \times 10^{-4}$
3c) Data Link	$1.4 \times 10^{-4}$ (1)	$1.4 \times 10^{-4}$ (1)	$0.5 \times 10^{-4}$
Risk Allocations are on a per hour basis.			
Notes:			
1) SCAT-I allocations [15].			
2) SCAT-I aircraft avionics is $1.1 \times 10^{-3}$ . Requires 1000 Hr MTBF.			
3) LAAS Category I non-aircraft requirement is $6.6 \times 10^{-4}$ [16].			
4) SCAT-I ground equipment is $9.1 \times 10^{-4}$ .			
5) LAAS Category II non-aircraft requirement is $6.0 \times 10^{-4}$ .			
6) Same as AWOP Category III RNP ( $4 \times 10^{-6}$ for 30 sec) [2].			
7) LAAS Category IIIb requirement is $2.3 \times 10^{-4}$ .			
8) Assumes additional ranging sources.			
9) Assumes redundancy with 1,000 Hrs MTBF = Failure probability of $(10^{-3})(10^{-3}) = 10^{-6}$ .			

**Table 5. GNSS Continuity Allocations**

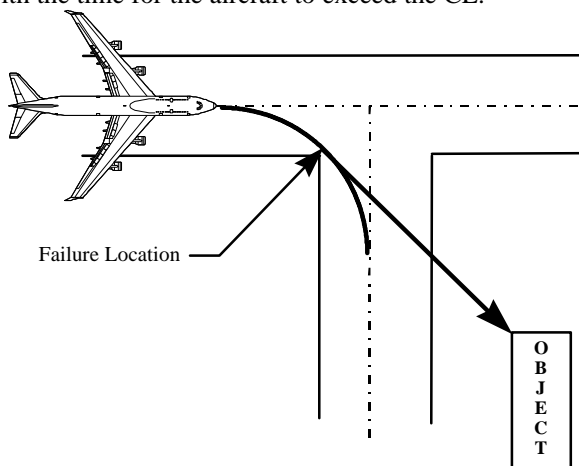
Element	Visibility Conditions		
	1,2	3	4
1. Total Risk	$3.0 \times 10^{-3}$	$6.0 \times 10^{-6}$	$6.0 \times 10^{-7}$
2. Aircraft	$2.0 \times 10^{-3}$	$4.0 \times 10^{-6}$	$4.0 \times 10^{-7}$
2a) GNSS Receiver	$0.4 \times 10^{-3}$ (3)	$2.5 \times 10^{-6}$ (3)	$2.5 \times 10^{-7}$ (5)
2b) Data Link Receiver	$0.4 \times 10^{-3}$	$0.375 \times 10^{-6}$	$0.375 \times 10^{-7}$
2c) Guidance Computer	$0.4 \times 10^{-3}$	$0.375 \times 10^{-6}$	$0.375 \times 10^{-7}$
2d) Cockpit Displays	$0.4 \times 10^{-3}$	$0.375 \times 10^{-6}$	$0.375 \times 10^{-7}$
2e) Database	$0.4 \times 10^{-3}$	$0.375 \times 10^{-6}$	$0.375 \times 10^{-7}$
3. Non-Aircraft	$1.0 \times 10^{-3}$ (1)	$2.0 \times 10^{-6}$ (4)	$2.0 \times 10^{-7}$ (6)
3a) Ground Equipment	$1.0 \times 10^{-3}$	$2.0 \times 10^{-6}$	$2.0 \times 10^{-7}$
3b) Data Link	$< 10^{-8}$ (2)	$< 10^{-8}$ (2)	$< 10^{-8}$ (2)
Risk Allocations are on a per hour basis.			
Notes:			
1) SCAT-I [15] and LAAS [16] Category I non-aircraft are $7.2 \times 10^{-7}$ and $9.6 \times 10^{-7}$ , respectively.			
2) SCAT-I requirement.			
3) SCAT-I and AWOP Category I avionics are $1.4 \times 10^{-6}$ and $2.4 \times 10^{-6}$ , respectively.			
4) LAAS Category II requirement is $8.7 \times 10^{-7}$ .			
5) AWOP CAT III RNP avionics requirement is $1.2 \times 10^{-7}$ .			
6) LAAS Category III and AWOP Category III non-aircraft are $3.0 \times 10^{-8}$ and $1.8 \times 10^{-7}$ , respectively.			

**Table 6. GNSS Integrity Allocations**

**Simulations.** Data from several NASA simulator tests were analyzed, including a Runway Status Light System (RSL) evaluation [17] and a moving map display study [18,19]. Centerline deviations collected from the RSL simulation study are consistent with the Heathrow data (see Table 4). However, the moving map study showed straight section 95% centerline deviations significantly greater than the others. It is not clear if this was due to a limitation of the map display or some other factors were involved. Further simulations are planned, including validation of the failure mode analysis discussed below.

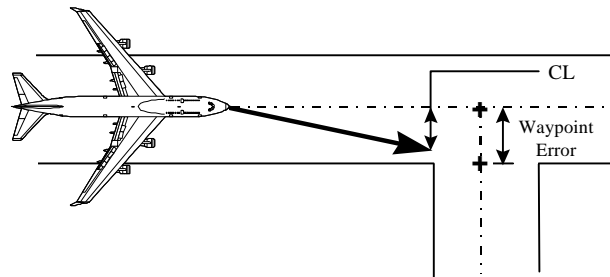
**Field Demonstrations.** A source of field validation data is a flight demonstration conducted at the Atlantic City International Airport by NASA in cooperation with the FAA Technical Center [20]. Flight trials demonstrated that the integration of several technologies, including electronic moving map displays in the cockpit, and a Differential Global Positioning System (DGPS) receiver, could provide the pilot and controller with sufficient situation awareness information. Specifically, DGPS could be used to enhance navigation and guidance accuracy. These results yielded an overall DGPS sensor accuracy of  $\pm 0.9$  m (mean plus  $2\sigma$ ), which would meet the PEE required for standard taxiways. Further demonstrations are planned by NASA at Atlanta Hartsfield Airport in 1997.

**Failure Mode Analysis.** To evaluate pilot and aircraft response to the failure modes previously identified, several scenarios were created and analyzed. These scenarios represent possible “real-world” situations aircraft may encounter when operating on the airport surface. As shown in Figure 10, the aircraft encounters a loss of navigation signal (continuity failure) at the midpoint of a turn. This error is detected and the crew is notified to begin immediate braking. The time to bring the aircraft to a stop is then calculated and compared with the time for the aircraft to exceed the CL.



**Figure 10. Continuity Failure Mode, Normal Speed**

In Figure 11, the aircraft encounters an undetected (integrity failure) waypoint error which proceeds to direct the aircraft off the pavement. The time for the aircraft to exceed the CL is then calculated, and compared with the time required to stop the aircraft. Initial results from this analysis have substantiated the allocated pilot risk factors.



**Figure 11. Integrity Failure Mode, Normal Speed**

The failure mode analysis includes validation with the aircraft system design standards contained in Federal Aviation Regulation (FAR) 25-1309, FAA Advisory Circular 25.1309-1A [21] and Joint Aviation Requirement (JAR) 25 [22]. These relate the consequences and severity of effects of system failures and required probabilities (see explanations in references 1 and 12).

## CONCLUSIONS

The use of RNP for aircraft approach and landing is accepted by the aviation community, in the U.S. and internationally. The approach and landing RNP has pioneered the process and analytical techniques used to define aviation standards and requirements for accuracy, continuity, integrity, and availability. Application of the RNP to the runway surface has used the same process, but for a two-dimensional surface with unique guidance requirements.

For the surface RNP, work to date has focused on the analytical aspects of the process, the classification of operations, the allocation of risks to each operational phase, and the calculation of containment limits, integrity and continuity requirements. Operational and simulator data have been used to validate the analyses; however, validation in some areas is limited, and further simulation and field trials are required. The process and data used to develop the surface RNP have been coordinated with aviation standards organizations including ICAO All Weather Operations Panel and RTCA. The All Weather Operations Panel is scheduled to complete the operational requirements for A-SMGCS operations by June 1997. This will include the provisional RNP requirements for the guidance function

described in this paper. RTCA is in the process of developing the Minimum Aviation Systems Performance Standard (MASPS) for airport surface navigation and surveillance. The RNP requirements presented in this paper will be a primary input to the navigation portion of this MASPS.

ICAO, FAA and RTCA are all currently developing requirements for local area differential GNSS to support Category I, II, and III approach and landing. It is intended that local area navigation systems be capable of supporting surface operations. The requirements described in this paper should be considered in the development of local area differential GNSS standards to be sure that these systems will adequately support surface operations.

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