APPENDIX A. AIRBORNE AREA NAVIGATION SYSTEMS: ACCEPTABLE MEANS OF COMPLIANCE WITH AIRWORTHINESS REGULATIONS

1. INTRODUCTORY REMARKS.

a. Area navigation systems based on VORTAC stations have four sources of error: (1) ground VOR/DME radiated signal; (2) airborne VOR/DME equipment; (3) flight technical (pilotage); and (4) the air navigation equipment itself. It is assumed further that these are independent errors having such distribution that they may be combined root-sum-square (RSS) fashion. See Appendix C.

b. The means of compliance presented herein apply to systems that use VOR/DME sensor signals either for direct aircraft position determination or for updating aircraft position derived from other sources such as air data computers and magnetic compasses, inertial navigation systems, and doppler radar navigation systems. However, RNAV systems may employ sensor inputs other than VOR/DME without VOR/DME updating if equivalent accuracies can be demonstrated by means suitable to such systems.

c. The problem of slant range error takes on particular significance under the area navigation concept because of a direct effect upon the intended route of flight. Airborne systems that are dependent upon ground station signals for course guidance are subject to this error, while self-contained systems are not. Of the former, some systems are designed to compensate for slant range error and others are not. The problem is even more significant above FL 180, where airspace buffers are not planned.

2-D airborne systems affected by slant range error are accommodated through procedural compensation by the airspace planning and air traffic control systems outside the terminal area below FL 180. Route design compensations will take the form of limitations of the proximity of route centerlines to the reference facility, increased lateral dimensions for routes that must pass in proximity to reference facilities and increased lateral spacing of dual or parallel routes.

Air traffic control compensation is in the form of longitudinal and lateral separation criteria that encompasses the extremes of slant range error possibilities.

3-D Systems are expected to incorporate slant range correction because the input data for the correction is normally available, therefore, 3-D route planning and traffic control will NOT allow for slant range error.

Elimination of slant range error and its attendant compensating procedures is prerequisite to the development of optimum routes and separation criteria. FAA plans to initiate rulemaking action in the near future requiring slant range correction in terminal hubs and at FL 180 and above. This level may be lowered as operational experience is gained.

2. ACCETPABLE MEANS OF COMPLIANCE (FOR USE UNDER INSTRUMENT FLIGHT RULES) An acceptable means of compliance with Section -.1301, -.1309, -.1431, and -.1581, of Part 23, 25, 27 or 29 (as applicable), with respect to area navigation systems, provided for use under IFR conditions, is to satisfy the criteria set forth in this paragraph.

a. Accuracy.

(1) 2-D RNAV System using Reference Facility for continuous navigation information. The total of the error contributions of the airborne equipment (receivers plus area navigation - including desired track setting as well as waypoint setting errors) when combined RSS with the following specific error contributions should not exceed the error values shown in Table 1, Appendix A

VOR ground station	± 1.9°
DME ground station	± 0.1 NM

(2) 2-D RNAV systems which use VOR/DME information from other than the Reference Facilities must show that the algorithm used will always select a station that will provide cross track/along track errors equal to or less than the greater of the RNAV system errors of the reference facility for any RNAV track (Table 1) or the errors shown in paragraph 2.a.(3).

(3) 2-D RNAV System not using VOR/DME for continuous navigation information. The total of the error contributions of the airborne equipment (including update, aircraft position and computational errors), when combined with appropriate flight technical errors listed in 2.a.(4) below, should not exceed the following with 95% confidence (2-sigma) over a period of time equal to the update cycle:

	Cross Track	Along Track
Enroute	2.5 NM	1.5 NM
Terminal	1.5 NM	1.1 NM
Approach	0.6 NM	0.3 NM

(4) 2-D Flight Technical Errors (FTE) when combined RSS with the errors discussed in (1) and/or (a) above determine the Total

System error. The Total System error is used by airspace planners and includes the following specific FTE values for determining cross-track position accuracies. Values larger than these must be offset by corresponding reduction in other system errors. (See Appendix C) No FTE is used in determining the along-track accuracy.

Enroute	± 2.0 NM
Terminal	± 1.0 NM
Approach	± 0.5 NM

(5) 3-D RNAV Systems. The total of the error contributions of the airborne equipment, including sensors and area navigation:

(a) Should not contribute any new horizontal error, and

(b) When combined RSS with the specific vertical error contributions for "Flight Technical" listed in Table B of this Appendix, should not exceed the total RSS accuracy requirements of Table B, Appendix A.

(c) Vertical Navigation Equipment (VNAV)

Total vertical navigation system accuracy criteria are based largely on the satisfactory experience of many years with the present separation standard of 1000 feet, while also anticipating the probable needs of the air traffic system in the future.

The total 3-D system accuracy requirements for level flight are stated in Table A. The requirements are based on final approach, terminal area, and enroute operations in level flight. The specific requirements are based on the obstacle clearance standards for final approach and on airspace protection standards up to FL 290. The requirements for operations above FL 290, where separation standards change, are based on performance levels typical of altimetry systems meeting accuracy requirements for final approach and enroute operations up to FL 290.

The 3-D system accuracy for other than level flight varies with the ascent/descent angle. This variance is due to the flight technical error which has been shown to vary with the angle of ascent or descent. These variations are shown in Table B.

MINIMUM ACCURACY REQUIREMENTS FOR VERTICAL GUIDANCE EQUIPMENT EMPLOYED IN AIRBORNE VERTICAL NAVIGATION SYSTEMS

Level Flight

Flight Segment	Altitude Region	Total Vertical Error in Feet (3σ) (99.7% confidence)	Remarks
Final Approach	At or below 5000' MSL	200	Meets the obstacle clearance requirements of 250'.
Terminal Area	At or below 10000' MSL	350	Meets the 1000' level flight vertical separation requirement.
Enroute	All altitudes	350	Meets the 1000' level flight vertical separation requirement.

TABLE A

Table B illustrates typical error budgets where errors are assumed to be independent and are combined by the root-sum-square (RSS) method. These accuracy requirements provide an adequate buffer zone to accommodate all normally encountered atmospheric anomalies and reference discrepancies without jeopardizing the validity of the 1000 foot vertical separation standard in level flight.

The table lists vertical position error budgets without regard for horizontal position uncertainty. In a dynamic situation, additional vertical errors must be considered during ascending and descending flight because the aircraft may be either ahead of or behind its assumed position along track. For systems meeting minimum horizontal position accuracy requirements, this additional error is generally larger than the non position-dependent vertical position errors shown. The airborne computer calculates the descent angle and commands an altitude for the assumed position. If the aircraft is behind the assumed position, the aircraft is below the intended track by an amount proportional to the along-track error. This error must be added (RSS) to the basic vertical position errors shown when calculating airspace protection and obstacle clearance during descent.

SUMMARY OR REPRESENTATIVE VERTICAL GUIDANCE ERROR BUDGET IN FEET 99.7% (3σ)						
Error Source	*Final Approach 5000 feet MSL and below		*Terminal 10,000 feet MSL and below		Enroute (1) All altitudes	
	Level Flight	Ascent or Descent	Level Flight	Ascent or Descent	Level Flight	Ascent or Descent
Altimetry (3)	90	140	200	265	250	350
VNAV Equipment (4)	100	100	150	150	0 (2)	220
Flight Technical (5)	150	200	250	300	250	300
TOTAL RSS (3σ)	200	265	350	430	350	510

TABLE B

NOTE 1. Maximum operating altitudes to be predicated on compliance with total accuracy tolerance.
*When final approach and terminal area procedures are developed above altitudes shown, error is increased proportionately in the altimetry and RNAV parameters to provide airspace and obstacle clearance protection.

NOTE 2. In the event that VNAV guidance is used in level flight enroute the incremental error component contributed by the VNAV equipment must be offset by a corresponding reduction in other error components, such as flight technical error, to ensure that the total error budget is not exceeded.

NOTE 3. Altimetry Error. Refers to the electrical output and includes all errors attributable to the aircraft altimetry installation including position effects resulting from normal aircraft flight attitudes. In high performance aircraft, it is expected that altimetry correction will be necessary to meet these requirements. Such correction should be done automatically. In lower performance aircraft, upgrading of the altimetry system may be necessary. The larger errors shown for ascent/descent are typical of automatically corrected altimeter systems which meet the level flight error budget.

NOTE 4. VNAV Equipment Error. Includes all errors resulting from the vertical guidance equipment installation. Does not include errors of altimeter system but does include any additional errors resulting from the addition of the VNAV equipment. This error component may be disregarded in level enroute flights if the operation is limited to guidance by means of the altimeter only. It should not be disregarded in the terminal and approach operations, where the pilot is expected to follow the VNAV indications.

NOTE 5. Flight Technical Error. Includes errors in pilot interpretation of vertical guidance instrumentation, pilot activation of aircraft vertical controls, and deviations caused by aircraft response characteristics. Consideration is given to the relatively high pilot proficiency and good aircraft characteristics expected to be found in most operations at the higher altitudes. These values represent consensus estimates based upon experience and some limited testing; and for cases in which there is no relevant experience, they are conservative estimates. It is recognized that there are several design and operational parameters that could affect those values including display configuration, autopilot coupling versus manual control, pilot workload, and variation of aircraft response with increasing gross weight and altitude. As operational experience and experimental data are accumulated and analyzed, the values will be suitably adjusted.

(6) All RNAV equipment approved for use under Instrument Flight Rules (IFR) must meet the appropriate accuracy criteria. Should it not meet these criteria, a placard must be installed in the aircraft which reads "IFR Operation Not Authorized."

(7) Equipment presented will be approved by issuance of an STC or, upon prior approval from the appropriate regional office, may be approved by a properly processed Form 337 in the field.

b. Area Navigation System Design.

(1) General. The systems will normally use VOR/DME input sensor signals (or use combinations of VOR and DME for updating purposes) and indicate aircraft positions relative to the RNAV route and selected waypoint. Systems may be designed to utilize other

sensor inputs if equivalent accuracy can be demonstrated. Installations intended for final approach should use position information that is essentailly continuous with interruptions no longer than would result from switching from one preprogramed waypoint to another. The system should give no operationally significant misleading information.

(2) Vertical Guidance Input Controls.

In the absence of pre-stored or automatically inserted flight profile parameters, pilot controls shall provide for at least the following inputs:

(a) Station Elevation. For systems employing slant range error correction, elevation of the VOR/DME ground station in increments not greater than 100 feet if used during final approach, and for other phases in increments not greater than 1000 feet.

(b) Waypoint. Waypoint altitude in increments not greater than 10 feet if used during final approach, and for other phases in increments not greater than 100 feet. Waypoint horizontal position shall be entered in increments not greater than 0.1 nautical mile or 0.2 degree bearing from the station or the equivalent.

(c) Flight Path Angle. Vertical gradient from a zero degree origin in increments not greater than 0.1 degree or the equivalent.

(3) Checking of Input. Provisions should be made to enable the pilot to check the correctness of the inputs.

(4) Altimeter Setting. The system shall be so designed that there is no requirement to insert separate barometric correction inputs into the vertical guidance computer. Adjusting one of the barometric pressure altimeters in the cockpit should automatically provide the corrected input to the vertical computer. In order to avoid the abrupt irregularity in the computer vertical flight path at the transitional level, the pilot will make altimeter setting changes between local and standard 29.92" Hg. above the transitional level. Airspace will be buffered above this level to account for the discontinuities in the vertical flight path and the pilot will be expected to make the change gradually so as not to introduce unacceptably abrupt flight path requirements.

(5) Vertical Guidance Display. The equipment shall provide a vertical guidance presentation compatible with the aircraft's flight instrumentation such that the pilot is continuously furnished vertical deviation of the aircraft with respect to a preprogramed ascent/descent or level flight profile.

(6) Failure Warning. Provision should be made to alert the crew upon occurrence of any probable failure of major system functions or loss of inputs, including those that would affect aircraft position, heading, command course, command heading, altitude, or vertical guidance indications.

(7) Performance Check. Provision should be made for checking the system's performance on the ground and in flight. This may be a built-in check, an auxiliary test system or a procedural check.

(8) Response Time. The navigation display should indicate aircraft position, to the accuracy specified in Paragraph 2.a., assuming that navigation sensor outputs are available:

(a) During flight in any direction at the maximum ground speed declared by the equipment manufacturer, and

(b) During ascent or descent at the maximum rates declared by the equipment manufacturer, and

(c) Within five seconds after any normal maneuver, assuming sensor inputs are not lost during the maneuver.

(d) The time lag between time of data input and guidance derived from the display of the data should not be operationally significant.

NOTE: Terminal area speed limitations are taken into account in connection with this provision. Moving elements of the navigation display may be damped.

(9) Coordination of Displays. In installations incorporating both horizontal and vertical guidance, there should be no operationally significant difference between the various displays used by the flight crew. For example, if a descent is programmed to end at a waypoint, the command to level off should be operationally coincidental with the waypoint indication. This is not intended to preclude maneuver anticipation.

(10) Environmental Conditions. The area navigation equipment should be capable of satisfying the criteria set forth in Paragraph 2.a. and 2.b. above over the environmental ranges expected to be encountered in actual aeronautical operations. In demonstrating compliance, the environmental conditions outlined in Radio Technical Commission for Aeronautics Document DO-138 titled "Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment and Instruments" dated June 27, 1968, or other appropriate environmental standards may be used.

(11) Auto Tune Systems. Systems which automatically tune/select VOR/DME facilities for navigation or update should be limited to a search range of 130 NM for high altitude facilities and 40 NM at 18,000 feet and below for low altitude facilities in keeping with the NAS frequency protection criteria unless through computer logic or a 'reasonableness test' faulty information is rejected.

(12) Turn Anticipation and Parallel Offset.

(a) RNAV systems which provide for parallel offset tracks must also limit the turning maneuver. Turns shall be anticipated and flown in such a way as to cause the aircraft to remain within ± 2.5 NM of the desired track centerline enroute and ± 1.5 NM of the centerline in the terminal area. Pilots flying systems which do not automatically anticipate the turn are expected to lead a turn by 1 NM per 100 knots true airspeed.

(b) 3-D systems shall not require additional controls to assure that the offset route is in the same horizontal plane as the parent route at the waypoint. The plane is measured on the bisector angle between centerlines of the adjacent route segments.

c. Area Navigation Equipment Installation.

(1) Location of the RNAV display. Each display element to be used as a primary flight instrument in the guidance and control of the aircraft should be located where it is clearly visible to the pilot with the least practicable deviation from his normal position and from his line of vision when he is looking forward along the flight path.

(2) Failure protection. Any probable failure of the airborne area navigation equipment should not derogate the normal operation of required equipment connected to it, nor cause a flight hazard.

(3) Radio frequency interference. The area navigation equipment should not be the source of objectionable radio frequency interference,nor be adversely affected by radio frequency emissions from other equipment in the aircraft.

(4) Manufacturer's instructions. The area navigation equipment should be installed in accordance with instructions and limitations provided by the manufacturer.

d. Aircraft Flight Manual. If an aircraft flight manual is provided by the aircraft manufacturer, its FAA approved portion may contain the following information on the area navigation equipment:

(1) Normal procedure for operating the equipment;

(2) Equipment operating limitations; and,

(3) Emergency operating procedures (if applicable).

If not contained in the aircraft flight manual, information on equipment operating limitations should be provided to the pilot by means of placards. The aircraft flight manual or placard should state "RNAV Instrument Approaches Not Authorized" if the instrumentation is such that FTE cannot be resolved to meet appropriate criteria. Revisions or supplements to the flight manual must be approved by the Regional Chief of the Engineering and Manufacturing Branch.

3. TESTING PROCEDURE (FOR EQUIPMENT PROVIDED FOR USE UNDER INSTRUMENT FLIGHT RULES)

a. General. An applicant for approval of an area navigation system installation in an aircraft may show that he has satisfied the criteria in Paragraph 2 by a combination of bench tests of the individual components (including VOR and DME) and ground/flight tests of the entire installed area navigation system. The bench tests may have already been performed by the individual component manufacturer (during design and construction) or by the installer (on behalf of a previous customer). Such bench test data, if certified by the manufacturer or installer are acceptable. In addition, the applicant may refer to applicable TSO standards, if the manufacturer of the equipment certifies that his equipment meets those standards.

b. Bench Tests. The following tests may be performed on the bench or with the navigation system installed in the aircraft:

(1) Test equipment. Bench test equipment should be capable of simulating the input signals from VOR/DME and/or the altimeter or other sensors and of varying those signals over the ranges for which the equipment is designed.

(2) Accuracy testing.

(a) Variables to be considered. Each variable that has a significant effect on position error should be investigated over its entire range, and the error analysis should show the effects of reasonably probable variations of these variables on total system accuracy. The statistical technique described in RTCA Document No. DO-153 entitled "Minimum Performance Standards -- Airborne VOR Receiving Equipment Operating Within the Radio Frequency Range of 108-118 Megahertz" dated August 18, 1972, may be used as a guide.

(b) Static test. Horizontal and/or vertical position accuracy should be measured statically as the error in displayed position relative to the theoretical position obtained from perfect signal inputs (range and bearing from a known station location and/or altitude). Simulated range and bearing and/or altitude signals are introduced into the area navigation equipment. Combinations of ranges from zero up to the maximum distance for which the equipment is designed, bearings from zero to 360 degrees, and altitudes up to the maximum certificated altitude for the aircraft should be inserted as input signals. For each set of input signals, the corresponding display output should be compared to the theoretical position and recorded as an RNAV system error. The errors for each test point are then combined statistically to determine the 2σ (95%) probable error. When this value exceeds the RNAV system error element shown on Table 1, the total horizontal system error must be computed by adding the RNAV system error RSS to the other system errors. See Appendix C. They should be within the values shown in Table 1 if the system is to be used in IFR flight. Note that only one error table is provided. This represents the required accuracy for IFR of VOR/DME equipment using the reference facility. The only variable between enroute, terminal, and approach is FTE (shown in 2.a.(4) above). Separate tables are redundant.

The vertical system error is computed by adding RSS the values for FTE (Table B) and altimetry appropriate to the installation. The values shown in Table 1 and the RSS totals in Table B should not be exceeded.

(c) Dynamic test. In addition to the static test, a dynamic accuracy test should be performed utilizing simulated VOR/DME and/or altimeter inputs varied in range, bearing and/or altitude in order to assess the ability of the system to smooth variable input signals without incurring excessive lag. These tests should be performed with representative simulated airspeeds throughout the range for which the equipment is designed. During these tests the measured RNAV equipment error should be consistent with the total system accuracies specified in Paragraph 2. Alternatively, an in-flight demonstration of satisfactory dynamic characteristics may be accepted.

(d) Systems having map type displays. If the system uses a map type pictorial display of aircraft position as a primary means of steering guidance, the accuracy determination should take into account any error contribution by the cartography.

(e) Altimetry tests. The accuracy of the installed altimetry system should be determined by tests, evaluation of previously approved data, or both, to assure that the altimetry error budget of Table B is not exceeded. Static system error determined during aircraft certification or determined by currently recognized means may be combined RSS with scale error data for the altimeter.

c. Ground/flight tests.

(1) Ground tests. After the area navigation system has been installed, but before the aircraft is flown, an operational/functional check should be performed to ensure that the system has been installed in accordance with the installation criteria in Paragraph 2.c. (and with all applicable airworthiness regulations) and that it functions properly and safely.

(2) Determination of when flight tests are necessary. At least one flight test for accuracy in the approach case is necessary. Additional flight tests for accuracy are necessary if the system accuracy is not adequately determined by signal simulation as described in 3.b. above, or if it appears that the resolution of the pilot display is such

That the assumed FTE of 2.0 NM (enroute), 1.0 NM (terminal) or 0.5 NM (approach), will be exceeded.

NOTE: The "Approach" mode is defined as the flight operation between the final approach waypoint and the airport. The "Terminal" mode is defined as the ingress/egress flight operation between Enroute and Approach, normally below FL 180 within 50 miles of the airport. The "Enroute" mode is defined as the cruising flight operation between Terminal areas.

(3) Accuracy tests in flight. When the bench check data required by paragraph 3.b. above are not available, flight tests are necessary. Therefore, in addition to ground tests, to demonstrate satisfactory performance of the area navigation equipment, the airplane should be flown solely by reference to the RNAV display and other standard flight instruments, at a relatively low altitude under VFR conditions, with a safety pilot, and if practicable under ground radar surveillance as follows:

(a) Along the length of an FAA approved RNAV route segment.

(b) In accordance with an FAA approved RNAV terminal area procedure; and

(c) In accordance with an FAA approved RNAV approach procedure.

(d) During ascent and descent flight in terminal and/or final approach operation with theodolite observation or equivalent to check vertical angle performance of 3-D RNAV. Final approach performance may be compared against ILS signals.

In each case, the area navigation system is satisfactory if the equipment meets the accuracy requirements of Paragraph 2.a. as determined by direct visual reference or other suitable methods to identifiable ground check points and a large scale map of the area on which are shown route segment centerlines and boundary widths applicable to the distance from the reference facility.

(4) Functional test in flight. The area navigation system should be checked out in flight to determine whether the design and installation criteria in Paragraph 2.b. and 2.c. are satisfied.

4. ACCEPTABLE MEANS OF COMPLIANCE (FOR EQUIPMENT PROVIDED FOR USE UNDER VISUAL FLIGHT RULES ONLY)

a. An acceptable means of compliance with Sections -.1301, -.1309, -.1431 and -.1581, of Part 23, 25, 27, or 29 (as applicable), with respect to area navigation systems provided for use under VFR conditions only, is to satisfy the criteria in Paragraphs 2.c. and 3.c.(1) above, and to placrad the aircraft to limit the use of the area navigation system to VFR only.

b. Airborne area navigation equipment installed under Paragraph 4.a. may be approved by means of a Form 337 or Supplemental Type Certificate.

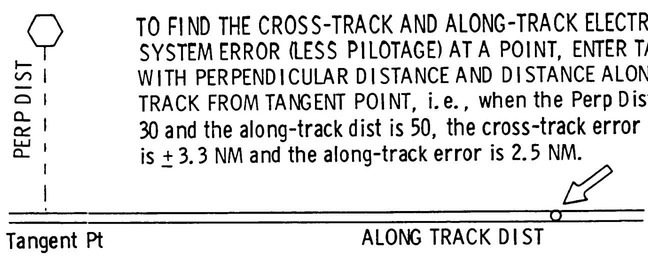
5. <u>MILITARY MEANS OF COMPLIANCE</u>. Military RNAV equipment approval procedures, the means for designating equipment for use under VFR flight conditions only, and methods by which pilots are to be informed of equipment limitations will be accomplished by the individual military services. Military use of TACAN azimuth and distance information is assumed where VOR/DME is required.

VOR/DME/TACAN STATION REFERENCED AREA NAVIGATION ERROR TABLE (95% PROBABILITY)

DISTANCE ALONG TRACK FROM TANGENT POINT

PERPENDICULAR DIST TO TANGENT POINT

	0	5	10	15	20	25	30	35	40	50	60	70	80	90	100	110	120	130	150	200
0(x trk)		.6	.8	1.1	1.3	1.6	1.9	2.2	2.5	3.1	3.7	4.4	5.0	5.6	6.2	6.8	7.4	8.1	9.3	12.4
(alg trk)		.7	.7	.7	.8	.9	1.0	1.2	1.3	1.6	1.9	2.2	2.5	2.8	3.0	3.3	3.6	3.9	4.5	6.0
5(x trk)	.7	.7	.8	1.1	1.4	1.6	1.9	2.2	2.5	3.2	3.8	4.4	5.0	5.6	6.2	6.8	7.5	8.1	9.3	12.4
(alg trk)	.6	.7	.8	.8	.9	1.0	1.1	1.2	1.4	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.6	6.1
10(x trk)	.7	.8	.9	1.1	1.4	1.7	2.0	2.3	2.6	3.2	3.8	4.4	5.0	5.6	6.2	6.9	7.5	8.1	9.3	12.4
(alg trk)	.8	.8	.9	.9	1.0	1.1	1.2	1.4	1.5	1.7	2.0	2.3	2.6	2.9	3.1	3.4	3.7	4.0	4.6	6.1
15(x trk)	.7	.8	.9	1.2	1.4	1.7	2.0	2.3	2.6	3.2	3.8	4.4	5.0	5.6	6.3	6.9	7.5	8.1	9.3	12.4
(alg trk)	1.1	1.1	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.9	2.1	2.4	2.7	3.0	3.2	3.5	3.8	4.1	4.7	6.2
20(x trk)	.8	.9	1.0	1.2	1.5	1.8	2.1	2.3	2.6	3.2	3.8	4.4	5.1	5.7	6.3	6.9	7.5	8.1	9.4	12.5
(alg trk)	1.3	1.4	1.4	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.3	2.6	2.8	3.1	3.4	3.6	3.9	4.2	4.8	6.2
25(x trk)	.9	1.0	1.1	1.3	1.6	1.8	2.1	2.4	2.7	3.3	3.9	4.5	5.1	5.7	6.3	6.9	7.5	8.1	9.4	12.5
(alg trk)	1.6	1.6	1.7	1.7	1.8	1.8	1.9	2.0	2.1	2.3	2.5	2.7	3.0	3.2	3.5	3.8	4.0	4.3	4.9	6.3
30(x trk)	1.0	1.1	1.2	1.4	1.7	1.9	2.2	2.5	2.7	3.3	3.9	4.5	5.1	5.7	6.3	6.9	7.6	8.2	9.4	12.5
(alg trk)	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.3	2.3	2.5	2.7	2.9	3.2	3.4	3.7	3.9	4.2	4.5	5.0	6.4
35(x trk)	1.2	1.2	1.4	1.5	1.8	2.0	2.3	2.5	2.8	3.4	4.0	4.6	5.2	5.8	6.4	7.0	7.6	8.2	9.4	12.5
(alg trk)	2.2	2.2	2.3	2.3	2.3	2.4	2.5	2.5	2.6	2.8	3.0	3.2	3.4	3.6	3.9	4.1	4.4	4.6	5.2	6.5
40(x trk)	1.3	1.4	1.5	1.6	1.9	2.1	2.3	2.6	2.9	3.4	4.0	4.6	5.2	5.8	6.4	7.0	7.6	8.2	9.5	12.5
(alg trk)	2.5	2.5	2.6	2.6	2.6	2.7	2.7	2.8	2.9	3.0	3.2	3.4	3.6	3.8	4.0	4.3	4.5	4.8	5.3	6.7
50(x trk)	1.6	1.6	1.7	1.9	2.1	2.3	2.5	2.8	3.0	3.6	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.3	9.5	12.6
(alg trk)	3.1	3.2	3.2	3.2	3.2	3.3	3.3	3.4	3.4	3.6	3.7	3.9	4.1	4.3	4.5	4.7	4.9	5.2	5.7	7.0
60(x trk)	1.9	1.9	2.0	2.1	2.3	2.5	2.7	3.0	3.2	3.7	4.3	4.8	5.4	6.0	6.6	7.2	7.8	8.4	9.6	12.6
(alg trk)	3.7	3.8	3.8	3.8	3.8	3.9	3.9	4.0	4.0	4.1	4.3	4.4	4.6	4.8	5.0	5.2	5.4	5.6	6.0	7.3
70(x trk)	2.2	2.2	2.3	2.4	2.6	2.7	2.9	3.2	3.4	3.9	4.4	5.0	5.5	6.1	6.7	7.3	7.9	8.5	9.7	12.7
(alg trk)	4.4	4.4	4.4	4.4	4.4	4.5	4.5	4.6	4.6	4.7	4.8	5.0	5.1	5.3	5.5	5.6	5.8	6.0	6.5	7.7
80(x trk)	2.5	2.5	2.6	2.7	2.8	3.0	3.2	3.4	3.6	4.1	4.6	5.1	5.7	6.2	6.8	7.4	8.0	8.6	9.8	12.8
(alg trk)	5.0	5.0	5.0	5.0	5.1	5.1	5.1	5.2	5.2	5.3	5.4	5.5	5.7	5.8	6.0	6.2	6.3	6.5	6.9	8.0
90(x trk)	2.8	2.8	2.9	3.0	3.1	3.2	3.4	3.6	3.8	4.3	4.8	5.3	5.8	6.4	6.9	7.5	8.1	8.7	9.9	12.9
(alg trk)	5.6	5.6	5.6	5.6	5.7	5.7	5.7	5.8	5.8	5.9	6.0	6.1	6.2	6.4	6.5	6.7	6.8	7.0	7.4	8.5
100(x trk)	3.0	3.1	3.1	3.2	3.4	3.5	3.7	3.9	4.0	4.5	5.0	5.5	6.0	6.5	7.1	7.6	8.2	8.8	10.0	12.9
(alg trk)	6.2	6.2	6.2	6.3	6.3	6.3	6.3	6.4	6.4	6.5	6.6	6.7	6.8	6.9	7.1	7.2	7.4	7.5	7.9	8.9
110(x trk)	3.3	3.4	3.4	3.5	3.6	3.8	3.9	4.1	4.3	4.7	5.2	5.6	6.2	6.7	7.2	7.8	8.3	8.9	10.1	13.0
(alg trk)	6.8	6.8	6.9	6.9	6.9	6.9	6.9	7.0	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.8	7.9	8.1	8.4	9.4
120(x trk)	3.6	3.7	3.7	3.8	3.9	4.0	4.2	4.4	4.5	4.9	5.4	5.8	6.3	6.8	7.4	7.9	8.5	9.0	10.2	13.1
(alg trk)	7.4	7.5	7.5	7.5	7.5	7.5	7.6	7.6	7.6	7.7	7.8	7.9	8.0	8.1	8.2	8.3	8.5	8.6	9.0	9.9
130(x trk)	3.9	4.0	4.0	4.1	4.2	4.3	4.5	4.6	4.8	5.2	5.6	6.0	6.5	7.0	7.5	8.1	8.6	9.2	10.3	13.2
(alg trk)	8.1	8.1	8.1	8.1	8.1	8.1	8.2	8.2	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0	9.2	9.5	10.4
140(x trk)	4.2	4.3	4.3	4.4	4.5	4.6	4.7	4.9	5.0	5.4	5.8	6.3	6.7	7.2	7.7	8.2	8.8	9.3	10.5	13.3
(alg trk)	8.7	8.7	8.7	8.7	8.7	8.8	8.8	8.8	8.8	8.9	9.0	9.1	9.2	9.3	9.4	9.5	9.6	9.7	10.0	10.9
150(x trk)	4.5	4.6	4.6	4.7	4.8	4.9	5.0	5.2	5.3	5.7	6.0	6.5	6.9	7.4	7.9	8.4	9.0	9.5	10.6	13.5
(alg trk)	9.3	9.3	9.3	9.3	9.4	9.4	9.4	9.4	9.5	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3	10.6	11.4



TO FIND THE CROSS-TRACK AND ALONG-TRACK ELECTRONIC SYSTEM ERROR (LESS PILOTAGE) AT A POINT, ENTER TABLE WITH PERPENDICULAR DISTANCE AND DISTANCE ALONG TRACK FROM TANGENT POINT, i.e., when the Perp Dist is 30 and the along-track dist is 50, the cross-track error is ± 3.3 NM and the along-track error is 2.5 NM.

ERROR ELEMENTS	
GROUND	
VOR	1.9^{0}
DME	0.1 NM
AIRBORNE	
VOR	3.0^{0}
DME	3% or 0.5 NM
RNAV SYSTEM	0.5 NM
PILOT	ZERO

TABLE 1

APPENDIX B. PROCEDURE FOR OBTAINING FAA DATA APPROVAL BY SUPPLEMENTAL TYPE CERTIFICATE (STC) OR MAJOR REPAIR AND ALTERATION (FORM 337) (FOR EQUIPMENT PROVIDED FOR USE UNDER INSTRUMENT FLIGHT RULES)

1. APPROVAL OF TECHNICAL DATA BY SUPPLEMENTAL TYPE CERTIFICATE (STC).

a. What the STC applicant does:

(1) Makes an application for STC at the FAA Regional Engineering and Manufacturing office. Early contact is wise, since scheduling may be critical. FAA evaluates the data submitted by the applicant (see Paragraph 1.b.), issues a Type Inspection Authorization (TIA), and participates in ground/flight tests outlined in Appendix A, Paragraph 3.c. An STC is issued when all airworthiness requirments are met. If the submitted data is adequate, the STC authorizes similar installations in the same aircraft type.

(2) Designs and constructs his area navigation system installation to the criteria set forth in Appendix A, Paragraph 2.

(3) Obtains, from the equipment manufacturer or the installer, the bench test data described in Appendix A, Paragraph 3.b., or an appropriate certification of accuracv per Paragraph 3.a., or conducts these bench tests himself.

(4) Makes available an aircraft (with the area navigation system installed) for ground inspection and flight test. The applicant is responsible for furnishing a qualified flight crew for conducting the required flight tests.

b. Data submitted by the STC applicant. The following kinds of data be submitted for FAA airworthiness evaluation:

(1) Equipment data, such as:

(a) Equipment schematics.

(b) Equipment manufacturer's operating instructions and installation instructions.

(c) Equipment manufacturer's quality control procedures.

NOTE: Equipment data is submitted for original installation only.

(2) Fault analysis covering installation.

(3) Installation information and/or photographs.

(4) Any needed structural substantiation.

(5) Electrical schematics.

(6) Any needed flight manual revision or supplement, or placard drawings.

(7) Evidence of previously approved data.

c. What the Equipment Manufacturer Can Do.

(1) Assist the STC applicant by supplying the data specified in Paragraphs 1.a.(3) and 1.b.(1).

(2) Perform the bench tests described in Appendix A, Paragraph 3.b. and certify (to the applicant and FAA) that the accuracy criteria in Appendix A, Paragraph 2.a., are satisfied.

2. APPROVAL OF TECHNICAL DATA BY FORM 337, Major Repair and Alteration (Airframe, powerplant, propeller or appliance) OMB 04-R060.1 (FOR USE UNDER INSTRUMENT FLIGHT RULES).

a. Data Submitted by the Applicant. The following alteration data for the equipment installation will be submitted with a properly executed Form 337.

(1) Data to confirm that the requirements of Appendix A, Paragraph 2, have been met.

(2) Data to confirm that the requirements of Appendix A, Paragraphs 3.b. and 3.c. have been met.

b. Additional Data Which May be Required. If required for FAA Airworthiness evaluation by the FAA District Office approving the technical data, the applicant may also be required to furnish a copy of the equipment schematics, manufacturer's operating and installation instructions, fault analysis for installation, installation details and/or photographs, substantiation of structural changes, electrical schematics, and any appropriate proposed flight manual revision and/or placards.

c. Inspection of Aircraft. Make the aircraft available for data conformity inspection.

APPENDIX C. SOURCES OF NAVIGATION SYSTEM ERROR

1. GENERAL. The establishment of relationships between navigation system accuracy and IFR aircraft separation criteria or route widths is a complex process. The first problem is to determine a reasonably achievable level of navigation system accuracy. This must be based not only on analysis of the measurable system error elements for state-of-the-art equipment but also on a series of intangibles judged primarily on the basis of experience.

   Current separation criteria, based on such analysis and experience, provide aircraft under IFR control a high degree of protection against collision with other aircraft or obstructions. These criteria take into account the measured accuracies of the VOR/DME ground facilities and airborne equipment and judgments as to how pilots actually fly their airplanes. Accumulating evidence shows that VOR/DME information, when used with area navigation computing and display devices and presented properly to the pilot, offers the potential for an even more efficient utilization of the airspace while maintaining current standards of in-flight safety.

2. CURRENT RELATIONSHIP BETWEEN NAVIGATION ACCURACY AND ROUTE WIDTH. The system of airways and routes used in the United States has widths of route protection used on a VOR system use accuracy of $\pm$ 4.5 degrees on a 95 percent probability basis. The $\pm$ 4.5 degrees for VOR justifies the application of $\pm$ 4 nautical mile route width out to a distance of 51 NM from the facility and a widening of route protection on the $\pm$ 4.5 degree basis beyond 51 miles.

3. CURRENT RELATIONSHIP BETWEEN VERTICAL NAVIGATION ACCURACY AND SEPARATION STANDARDS. The system of airways used in the United States allow for altimetry systems errors and atmospheric errors of various amounts dependent on mode of flight and altitude of the flight operations. Altimeter standards for accuracy (TSO C 10b) requires certain demonstrations of accuracy over a wide range of conditions including temperature, vibration and pressure. These accuracies combined with the expected changes in atmospheric pressure over the distances used and pilotage factors do not exceed a value which would interfere with other IFR aircraft operating with 1000' vertical separation below FL 290 and with 2000' vertical separation above FL 290. These are the vertical separation standards currently used. Efforts have been made to improve altimeter performance above FL 290 in order to permit application of 1000' vertical separation above, as well as below, this flight level. The accuracy requirements of the current altimeter standards are not stringent enough to meet this goal but the minimum accuracy requirements of Appendix A, Tables A and B are intended to support 1000' vertical separation at all flight levels.

4. SOURCES OF ERROR.

   a. Horizontal Errors. The basic assumption is that four sources of error - ground VOR and DME radiated signal, airborne VOR receiver equipment, area navigation equipment, and pilotage - contribute independent errors of such distribution that they may be combined in RSS fashion. This is the normal assumption used traditionally by the FAA and is required by the method recommended by ICAO Annex 10 for the determination of VOR system use accuracy (ICAO Annex 10, Second Edition, April 1968, Attachment C to Part I, Paragraph 3.6, VOR System Accuracy). All errors are based on a 95 percent probability basis.

Errors from the four major sources listed above are actually composite values including error contributions from various factors. For example, "Errors in radiated signals" include propagation errors as well as errors in the transmitted signals arising from geographical siting and magnetic alignment of the ground station.

(1) "Airborne VOR equipment errors," in accordance with common practice include not only errors in the receiver outputs, but also errors contributed by the converter and the conventional course selector and deviation indicator. In those cases in which an area navigation system accepts inputs directly from the receiver, the error components normally included for the converter and indicator are not incurred and, therefore, the appropriate value for "airborne VOR equipment error" can be correspondingly reduced. (NOTE: This factor is considered subsequently as one type of error compensation that may be afforded by area navigation equipment.) The errors for DME receivers to be used in conjunction with area navigation equipment, although small compared to the total system use error, are taken into account in Tables 1, 2, and 3, Appendix A.

(2) "Area navigation equipment error" includes error components contributed by any input, output, or signal conversion equipment used, by any computing element employed, 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 "area navigation equipment 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 waypoint definition directly attributable to errors in reference charts used in determining waypoint positions should be included as a component of "area navigation equipment error." This type of error is virtually impossible to handle and in general practice highly accurate published waypoint locations are used to the greatest extent possible in setting up such systems to avoid such errors (and to reduce workload).

(3) The 'flight technical error' refers to the accuracy with which the pilot controls the aircraft as measured by his success in causing the indicated aircraft position to match the indicated command or desired position on the display. Manual insertion errors are due to the human interface with the control and display units that affect the performance of an RNAV operation. The resulting error causes a deviation from the defined RNAV flight plan. These errors are usually recognized and corrected before developing in magnitude to a point where they may be considered blunders. However, "manual" errors also include undetected errors such as inaccuracies in track setting and in setting waypoint bearing information in some types of systems.

Blunder errors are gross errors in human judgment or attentiveness that cause the pilot to stray significantly from his area navigation flight plan, and are not included in the area navigation system error budget. Blunder tendency is, however, an important system design consideration.

Pilotage error will vary widely, depending on such factors as pilot experience, pilot workload, fatigue, and motivation. Equipment design and ambient environment variables also affect pilotage directly and measurably, such as:

Processing of the basic display inputs (i.e., smoothing and quickening), whether or not heading is presented integrally with position and/or command guidance indications, display scale factors, numerous display configuration variables, aircraft control dynamics, air turbulence, and many more. Strictly speaking, with autopilot coupling, "flight technical error" becomes "autopilot error." These factors must be taken into account in arriving at empirical values for pilotage contribution to system use accuracy.

Evaluation of area navigation equipment to the present time indicates that the flight technical error, using such equipment, is linear in nature. A value of ± 2.0 NM is typical for the enroute case and ± 0.5 is typical for final approach operations.

"Manual" errors, however, are not linear in nature. Track setting error, for example, is angular, and its effect on cross-track error is a function of distance from the waypoint.

The term "pilotage error" in the RNAV equipment error budget Appendix A includes ONLY the FLIGHT TECHNICAL ERROR element described above, and "manual" errors must be considered in the AIRBORNE EQUIPMENT ERROR BUDGET.

b. Vertical Errors. The sources of vertical error are listed in Appendix A, paragraph 2a(5)(c) Table B, of this advisory circular.

5. COMBINING THE ERROR ELEMENTS. Based on the assumptions that the variable errors from the various sources are normally distributed and independent, they may be combined in RSS (root-sum-squares) fashion. Thus, the standard deviations obtained from the various contributing sources may be combined geometrically rather than arithmetically by taking the square root of the sum of their squares:

$$\sigma\ \text{total} = \sqrt{\sigma 1^2 + \sigma 2^2 \ldots + \sigma n^2}$$

6. ERROR BUDGETING.

a. In optimizing a navigation system design, it is generally desirable to avoid having the error from one source much larger than those from the other sources since, by the RSS method of combination, it contributes disproportionately to the total error. However, it may be technically easier, cheaper, or operationally more desirable to reduce the error from one source rather than another in order to meet a total system use accuracy requirement.

b. In establishing an error budget, a system designer may trade off reduction in the errors from one or more sources against increases in the errors from others. Thus, in adding an area navigation computing and display capability to the basic VOR/DME system, it is necessary and possible to compensate for the errors introduced by the new equipment by means of reductions in errors from other sources. Any of the airborne error elements, including Flight Technical Error, may be traded provided the total system accuracy reflected in Appendix D, Tables 2, 3 and 4 are met.

(1) Assume that a company sells an airborne VOR system designed to fly within a ± 4 NM route width to a distance of 51 NM from a ground facility on the basis of the following error budget:

(2)

Ground VOR Station Error	±1.9° @ 51 NM = 1.7 NM cross-track error
Airborne VOR Equipment Error	±3.0° @ 51 NM = 2.7 NM cross-track error
Ground DME Error	±0.1 NM on radial = 0.0 NM cross-track error
Pilotage Error	±2.5° @ 51 NM = 2.2 NM cross-track error

(3) The error elements combine to make:

$$\text{Total Error} = \pm \sqrt{1.7^2 + 2.7^2 + 2.2^2}$$

$$= \pm 3.88$$

(4) In designing a new system containing area navigation devices contributing an error element of ±2 NM (equivalent to ±2.3° at 51 NM), the system engineer finds that the total error of the new system would not satisfy the requirement of a ±4 NM route width at 51 NM range if the other error elements remained the same. However, he also finds that he can compensate for the added error component in two ways:

(a) By picking off signals directly from the VOR receiver and using a digital course selector in the RNAV equipment the usual converter and indicator errors are not incurred so that the airborne VOR equipment error is reduced from 3° to 2° thus the cross-track error becomes ±1.8 NM.

(b) By employing a linear RNAV display which permits an assumed pilotage error of ±2.0 NM which is consistent with values shown in Appendix A, Paragraph 2.a.(4).

(5) The system engineer now recomputes the total system error on the basis of the following error budget:

$$\text{Total Error} = \pm \sqrt{1.7^2 + 1.8^2 + 2.0^2 + 2.0^2}$$

$$= \pm\ 3.76 \text{ NM at 51 NM from the facility (95\% probability)}$$

The new system meets the design accuracy requirement with an increased margin of safety. In this example, the DME errors did not contribute to cross-track error. With track orientation other than along a radial, an increase in DME contribution will be offset by a decrease in VOR effect.