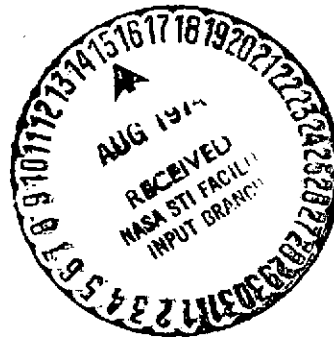2miy

NAVIGATION AND GUIDANCE REQUIREMENTS FOR COMMERCIAL VTOL OPERATIONS

INTERIM TECHNICAL REPORT

William C. Hoffman
Walter M. Hollister
Jack D. Howell

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ASI | AEROSPACE SYSTEMS, INC.

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FOREWORD

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SECTION 1

INTRODUCTION

Vertical takeoff and landing (VTOL) systems have been recommended by many experts in the aeronautical and transportation fields, including members of the President's Scientific Advisory Committee, as the logical form of transportation for the high-density, short-haul transportation markets in the 1980s. Such systems span a broad range of operations, from the intra-urban, typified by New York Airways, to the inter-city shuttles operating between downtown or nearby vertiports as well as to conventional airports.

In addition to the extreme convenience afforded by VTOL, the unique vertical flight capability requires a much smaller landing area than either conventional takeoff and landing (CTOL) or short takeoff and landing (STOL) aircraft. Also, significant buffer zones are required at each end of a CTOL or STOL runway for safety and noise considerations. Thus, even though VTOL aircraft have higher direct operating costs than conventional fixed-wing aircraft, the VTOL system is more attractive for many short-haul markets when all other factors (indirect costs, noise, convenience, etc.) are considered.

Before a viable VTOL system can become a reality, technology developments are needed in several areas. For example, the technology for an economical, 150-passenger class VTOL with reasonably high cruise speed and acceptable passenger ride qualities for the inter-city market must be developed. At the other end of the spectrum, advanced helicopter development is needed to improve ride comfort and reduce maintenance requirements for the very short-haul, medium-density market. These vehicle design areas are receiving considerable attention in various programs sponsored by NASA, the U.S. Army, and the aircraft industry. However, to effectively utilize these vehicles, and to exploit their unique characteristics for minimizing noise and both air and ground space requirements, corresponding advances must be made in handling qualities, operating procedures and techniques, and avionics.

The NASA Langley Research Center (LaRC) has undertaken a research program to develop the navigation, guidance, control, and flight management technology base

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needed by Government and industry in establishing systems design concepts and operating procedures for VTOL short-haul transportation systems in the 1980 s time period. The VALT (VTOL Automatic Landing Technology) Program encompasses the investigation of operating systems and piloting techniques associated with VTOL operations under all-weather conditions from downtown vertiports; the definition of terminal air traffic and airspace requirements; and the development of avionics including navigation, guidance, controls, and displays for automated takeoff, cruise, and landing operations. The program includes requirements analyses, design studies, systems development, ground simulation, and flight validation efforts. System designs will be made and evaluated for selected vehicles during the program.

Previous LaRC research studies have concluded that meeting the VTOL challenge will require extensive automation to permit all-weather operation along flight paths that minimize noise, airspace, and fuel. Flight studies will be conducted to define automation requirements, develop satisfactory pilot/vehicle interfaces, and identify operating and control techniques associated with specific, promising vehicle types. Also, to maximize the potential of VTOL aircraft for relieving air and ground congestion, an efficient and safe interface between VTOL aircraft and other traffic must be developed.

Previous studies of the requirements for advanced VTOL avionics technology have also indicated several specific areas in which developments are required. Reliable, low-cost inertial navigation and guidance systems are needed both for primary navigation and to provide short-term stability for radio navigation systems. Improved terminal area navigation systems must be capable of operating at low altitude in congested urban areas, ensuring obstacle avoidance, and providing information for the final approach and landing guidance system. The landing guidance system must provide sufficient coverage to take advantage of the VTOL ability to approach from any direction, independent of wind, and make a vertical landing.

A major element in the VALT Program is the Automated Avionics Development task. The overall objective is to develop avionics technology for reliable, cost-effective, automated operation of civil VTOL aircraft. The specific objectives are:

- Definition of the navigation and guidance requirements for commercial VTOL operations.

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- Development of control algorithms and technology for automated and manual control functions.
- Development of low-cost, easily maintainable, inertial and radio inertial navigation systems.
- Development of RF navigation and guidance technology for terminal area, approach, and landing operations.
- Development of display technology for automated flight-control monitoring and manual take-over requirements.
- Development of sensors for low-speed velocity and precision low-altitude altimetry requirements.
- Definition, development, and flight test of an advanced, integrated avionics system for VTOL automated operations.

Aerospace Systems, Inc. is conducting a research effort for LaRC in support of the Automated Avionics Development task. The objective of this work is to define the navigation and guidance requirements for commercial VTOL operations in the takeoff, cruise, terminal area, and landing phases of flight in weather conditions up to and including Category III. This interim report documents the results of the ten-month, Phase I contract work. In accordance with the contract requirements, the study was limited to two types of rotorcraft vehicles — pure helicopter and compound helicopter — and three types of services — intra-urban, inter-city, and conventional airports. Applicable navigation technology and systems (such as Omega, Loran, inertial, and microwave landing systems) were examined to define present system shortcomings, to identify areas where technology advances are required, and to select candidate systems and conceptual approaches. A multi-configuration "straw-man" system design was prepared, and representative operational procedures and trajectories defined. A limited flight evaluation program was conducted to investigate VTOL operational procedures and current navigation systems and to verify analytical results. A comprehensive digital computer simulation (Program VALT) was developed to provide a means for evaluation of VTOL guidance and navigation system performance. Program VALT was developed and checked out on a Boston area computer and demonstrated on the NASA LaRC CDC 6400/6600 computer facility.

In Phase II of the contract, Program VALT and the LaRC computer will be used to conduct parametric studies and error analyses of navigation sensors, and evaluations of estimator algorithms. This work will be documented in a subsequent report to be prepared upon the completion of the six-month Phase II effort.

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The material presented in this report is organized in accordance with the major task areas completed during Phase 1. Section 2 describes commercial VTOL operations, rotorcraft, procedures and navigation requirements. The capabilities and limitations of available and near-future navigation systems are presented in Section 3. Section 4 describes the straw-man hybrid navigation system, error models and performance evaluation. The flight evaluation program is discussed in Section 5. Conclusions and recommendations are summarized in Section 6. A comprehensive bibliography of VTOL navigation, guidance and operations follows the list of references. Several appendices provide details of the point-mass VTOL dynamic model; the synthesis of a simple velocity-command guidance system; descriptions of the simulation program VALT, and a line-of-sight coverage prediction program COVER.

SECTION 2

COMMERCIAL VTOL OPERATIONS

This section discusses the important operational considerations which affect the feasibility of a commercial VTOL air transportation system.

2.1 RESEARCH GUIDELINES

The purpose of this study has been the development and analysis of the navigation and guidance requirements for VTOL aircraft in scheduled commercial operations. Navigation and guidance requirements are defined in the takeoff, cruise, terminal area and landing phase of flight, for fully automated and piloted operations, in both good and adverse weather up to and including Category III. A variety of candidate navigation and guidance systems were considered, including radio, Doppler, scanning-beam, inertial and mixes of these using modern filtering theory.

2.1.1 COMMERCIAL VTOL SERVICES

In the total transportation system, the stage length of 10 - 300 miles, which defines the short-haul operations sector, is of exceptional importance. It is in this sector that the conflict is most intense between society's need for "instant transportation" and society's rejection of the resultant damage to the environment by noise, pollution, land sterilization and unsightliness. The major high density market routes lie in this range creating an intense competition between road, rail and air transportation modes, and between operators within a common mode. Potential inter-city, short-haul market regions in the United States are shown in Figure 1.

Three types of short-haul operations can be defined for VTOL service: intra-urban, inter-city, and conventional airport. Guidelines for VTOL services are summarized in Table 1.

The intra-urban operations might utilize helicopters with a 20 to 50 passenger capability, over stage lengths up to 75 miles. Terminals would include city center, outlying, and airport locations. City center and outlying heliports may be elevated or at ground level such as in a parking lot or park. Approach paths to such heliports
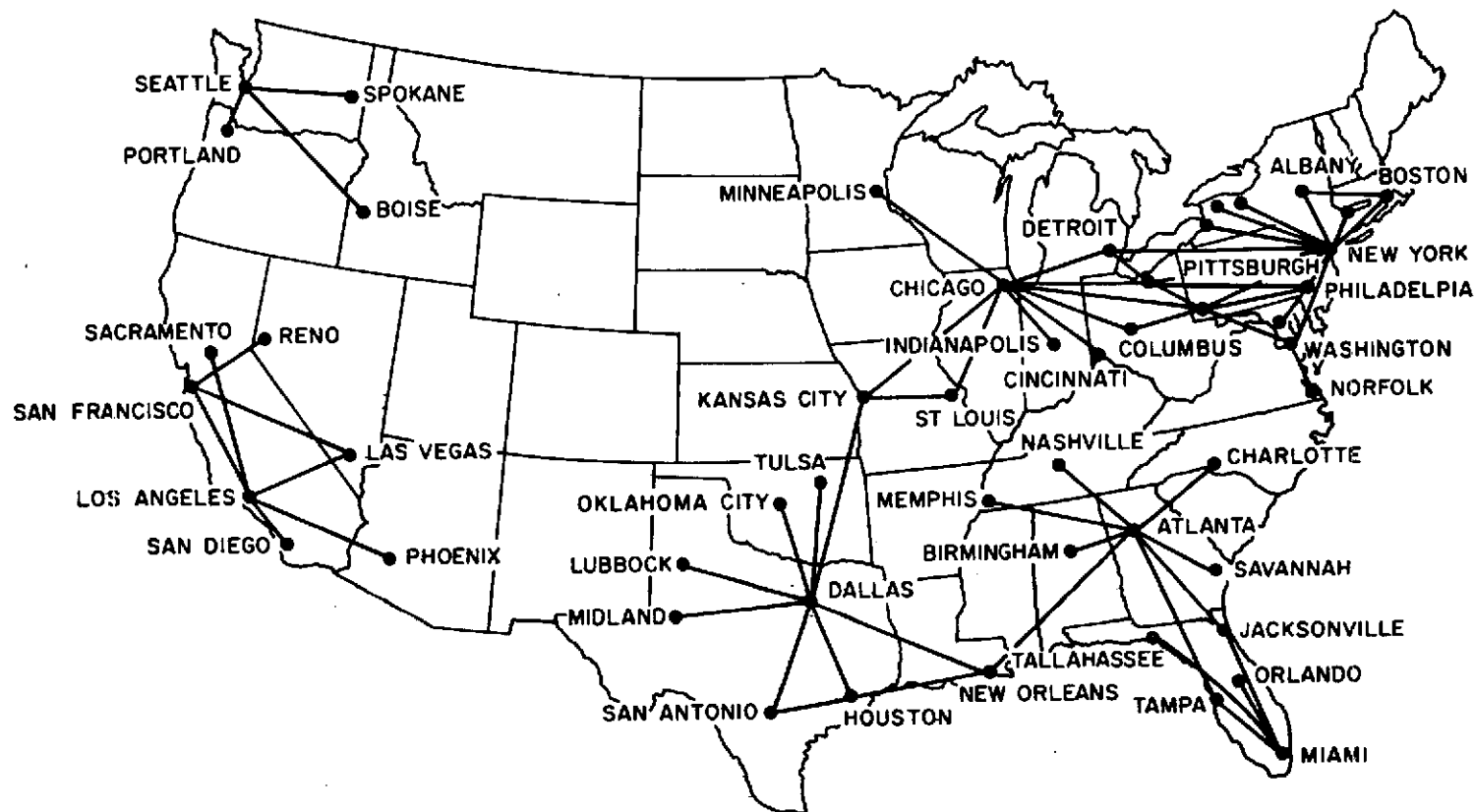
Figure 1. Potential Inter-City Short-Haul Market Regions.

Table 1. Guidelines for Commercial VTOL Services.

Type of Service	Intra-Urban	Inter-City	City-Center to Conventional Airport
Rotorcraft Cruise Speed Passenger Size	Helicopter 180 kt 20 to 50	Compound Helicopter 250 kt 50 to 100	Compound Helicopter 250 kt 50 to 100
Stage Length	75 miles	300 miles	300 miles
Terminals	City Center: Elevated or Ground Level Outlying: Elevated or Ground Level Airport: Ground Level	City Center: Elevated or Ground Level	City Center: Elevated or Ground Level Airport: Ground Level
Pad Size	200 ft	300 to 400 ft	300 to 400 ft
Multi-Pad Operations	Yes	Yes	Yes in City
Approach/ Departure Paths	Any Azimuth Restricted for Noise & Safety Curved in Two Planes Up to 1000 ft Vertical Leg	Any Azimuth Restricted for Noise & Safety Curved in Two Planes Up to 1000 ft Vertical Leg	Any Azimuth Restricted for Noise & Safety Curved in Two Planes Up to 1000 ft Vertical Leg
Frequency of Operations	1 per min	1 per min	1 per min
Mode of Operations	Independent of CTOL/STOL ATC	Independent of CTOL/STOL ATC	Independent of CTOL/STOL ATC

may be restricted due to noise considerations and safety factors such as the avoidance of tall obstacles. Ideally, to avoid any flight safety problems, intra-urban feeder service to conventional airports should operate independent of the CTOL/STOL operations and air traffic control.

Pad size for heliport operations would be on the order of 200 feet square, with multi-pad operations capability at the high traffic-density locations. Frequency of operations would be commensurate with the traffic density and number of pads, with a one-operation-per-minute goal for high density multiple pad locations.

Advanced compound helicopters are contenders for the inter-city and city center to conventional airport services. Considerations of approach and ATC restrictions are the same as for the conventional helicopter service, with pad sizes of 300 to 400 feet square.

For all services, operations should be keyed to a fully automatic systems approach for all-weather navigation, guidance and control, with the pilot as a monitor-manager. The automatic systems should be capable of flying the curved approaches necessary for noise reduction and obstacle avoidance, and of handling vehicle approaches from any azimuth. Since VTOL vehicles normally come to zero velocity at the landing site, the general form of an approach-to-landing will be a decelerating flight path, curved in two planes. However, the use of a vertical leg of up to 1000 feet should be considered to reduce noise effects in the landing and takeoff phases.

2.1.2   VTOL AIRCRAFT CHARACTERISTICS

Performance characteristics for the pure helicopter and the advanced compound helicopter are listed in Table 2. The pure helicopter is a rotary wing aircraft which derives all lift and propulsive force from a rotor or rotors oriented in a substantially horizontal plane. This configuration is optimum for hovering and moderate forward speeds, but it has well-known performance limitations with regard to maximum speed and also with regard to altitude and maneuvering capability near maximum speed.

One reason for the performance limits of the pure helicopter is illustrated by Figure 2, which shows a typical curve of rotor lift capability as a function of airspeed. Because of the aerodynamics on the rotor in forward flight, maximum lift decreases steadily with increasing speed. The maximum speed for a pure helicopter is limited to

Table 2. Guidelines for Rotorcraft Characteristics.

Parameter	Helicopter	Compound Helicopter
Passenger Size	20 to 50	50 to 100
Cruise Speed	180 kts	250 kts
Stage Length	75 miles	300 miles
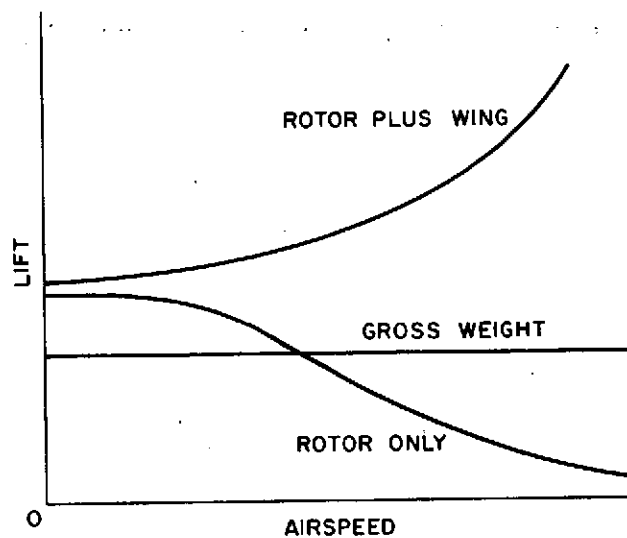
Figure 2. Effect of Wing on Lift Capability.

that value for which rotor lift is equal to the gross weight. At this speed limit no lift margin is available for maneuvering except by entering a retreating blade stall condition that results in high structural loads and vibrations. Increasing total rotor blade area will increase this speed limit, but it is not generally practical to extend the limit beyond about 200 knots.

The addition of a wing is a very efficient way of eliminating the lift-limited speed of the pure helicopter. Total lift capability now increases with airspeed, providing excellent maneuver and altitude capability at high speed. The rotor is not required to lift the gross weight except at low speeds, so that blade area may be reduced compared to that required for a pure helicopter, thus reducing rotor system weight.

Another limitation to speed of the pure helicopter is imposed by rotor propulsive force capability, as illustrated in Figure 3. This force capability is very high at low speeds, and is achieved by tip path plane tilt. Maximum available propulsive force drops rapidly with speed, becoming negative (drag) at speeds of about 250 knots or above. The propulsive force required to pull the airframe through the air, on the other hand, increases with the square of the forward speed. The point where the two curves cross depends on the specific design, but is almost always less than 200 knots. Some form of auxiliary propulsion system (propeller, fan, or jet) is mandatory for higher speeds.
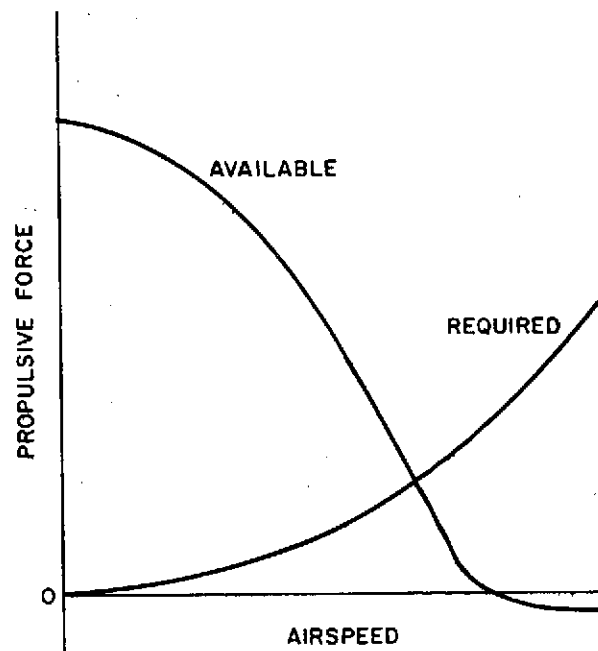
Figure 3. Rotor Propulsive Force.

The compound helicopter, by virtue of its wing and auxiliary propulsion, has many advantages over the pure helicopter. In addition to higher speeds, better altitude performance, and greater maneuverability, the wing-rotor combination has higher lift-drag ratios than a rotor alone, providing improved cruise efficiency. These factors combine to provide aircraft of higher productivity (payload times block speed), resulting in lower operating costs per ton mile or per passenger mile.

A survey of rotorcraft manufacturers was conducted to identify specific existing or projected designs with the guideline characteristics given in Table 2. It was concluded that two advanced Sikorsky designs were most suitable for the study. Figure 4 presents a three-view drawing of the Sikorsky Model S-65-40 commercial helicopter designed to carry 46 passengers (Ref. 1). Cruise speed for this configuration is 150 kts and maximum range is over 300 nm. A summary of the model S-65-40 characteristics is presented in Table 3. Two military forerunners of the S-65-40 have demonstrated the IFR capability of the aircraft. The CH-53 is fully equipped with radio and navigation equipment to conduct missions under instrument flight rules. The HH-53B/C ("Super Jolly Green Giant") is the Air Force primary rescue helicopter; this version of the S-65-40 has a self-contained Doppler navigation system that provides point-to-point, area navigation capability and an automatic approach and hover coupler which provides terminal guidance for the aircraft under non-visual conditions.

The Sikorsky Model S-65-200 compound helicopter design is shown in Figure 5 (Refs. 2 and 3). Its characteristics are given in Table 4. This vehicle has a maximum cruise speed of 261 kts, a maximum range of 580 nm and carries 100 passengers. The seven-bladed main rotor provides 100 percent of the lift in hover. In high speed flight, lift is provided primarily by the wing; for example, at 250 knots the wing carries 80 percent of the aircraft weight. The wing is equipped with simple flaps for adjustment of lift trim and increased maximum lift coefficient for low speed flight, and, by means of 90° deflection, for reduction of vertical drag in hover. The outboard flaps also function as ailerons to supplement roll control in high speed flight.

Power for the S-65-200 is supplied by three interchangeable shaft turbine engines, one on each wing and a third behind the main transmission in the fuselage. The propellers and rotors are all interconnected so that in the event of malfunction of any of the engines, the remaining power is available to all dynamic components. Twin fan-type turboprop

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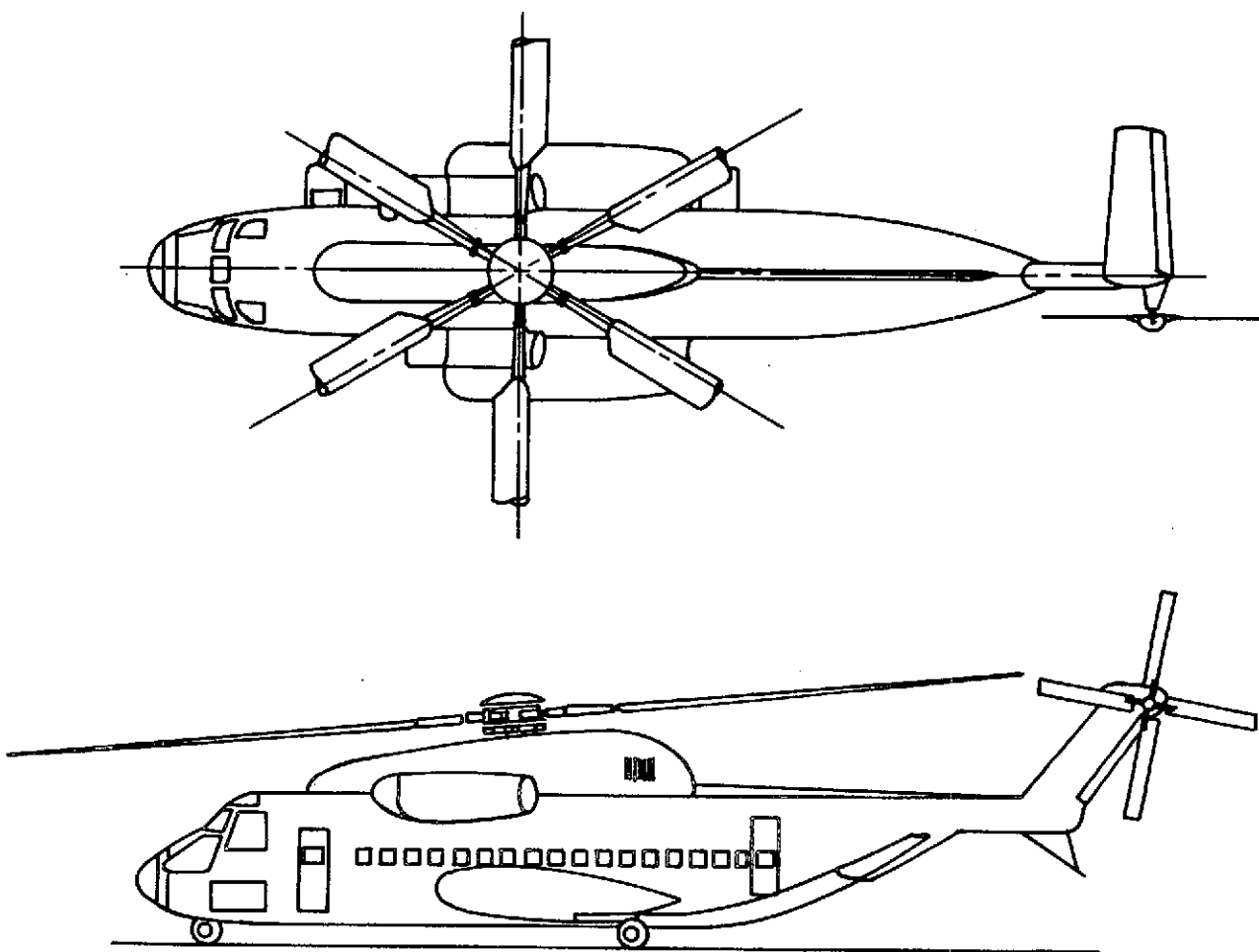
Figure 4. Sikorsky Model S-65-40 Helicopter.
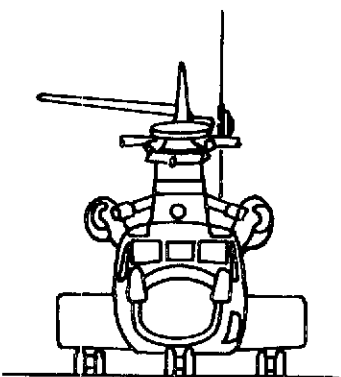
Table 3. Summary of Sikorsky Model S-65-40 Helicopter Characteristics.

WEIGHTS

Design Gross Weight (lb)	41,000
Manufacturer's Weight Empty (lb)	26,618
Operational Weight Empty (lb)	27,377

PERFORMANCE

Max. Recommended Cruise Speed (kt)	150
Max. Initial Rate of Climb (ft/min)	2,160
Max. Range with Reserve @ Design Gross Weight (nm)	308
Operational Ceiling (ft)	10,000

DIMENSIONS OR CAPACITIES

Overall Length (ft)	88.2
Overall Height (ft)	24.9
Overall Fuselage Width (ft)	17.7
Main Rotor Diameter (ft)	72.2
Tail Rotor Diameter (ft)	16.0
Passenger Capacity @ 32 in Seat Pitch	46
Baggage Capacity (cu ft)	138
Max. Useable Fuel Capacity (lb)	7,100

FEATURES

Primary Power Plant	(2) GE CT64-630-6
Auxiliary Power Plant	(1) Solar T62T-38A
Instrument Flight Capability	100 ft Ceiling; 1200 ft RVR
External Noise @ 500 ft	98 PNdB
Internal Noise	75 dB PSIL
Air Conditioning	(3) Ham Std R70-3W

Note: Fuel reserve includes allowance for 25 nautical miles at speed for best range, 45 minutes holding at speed for best endurance and 16.0 kts headwind.
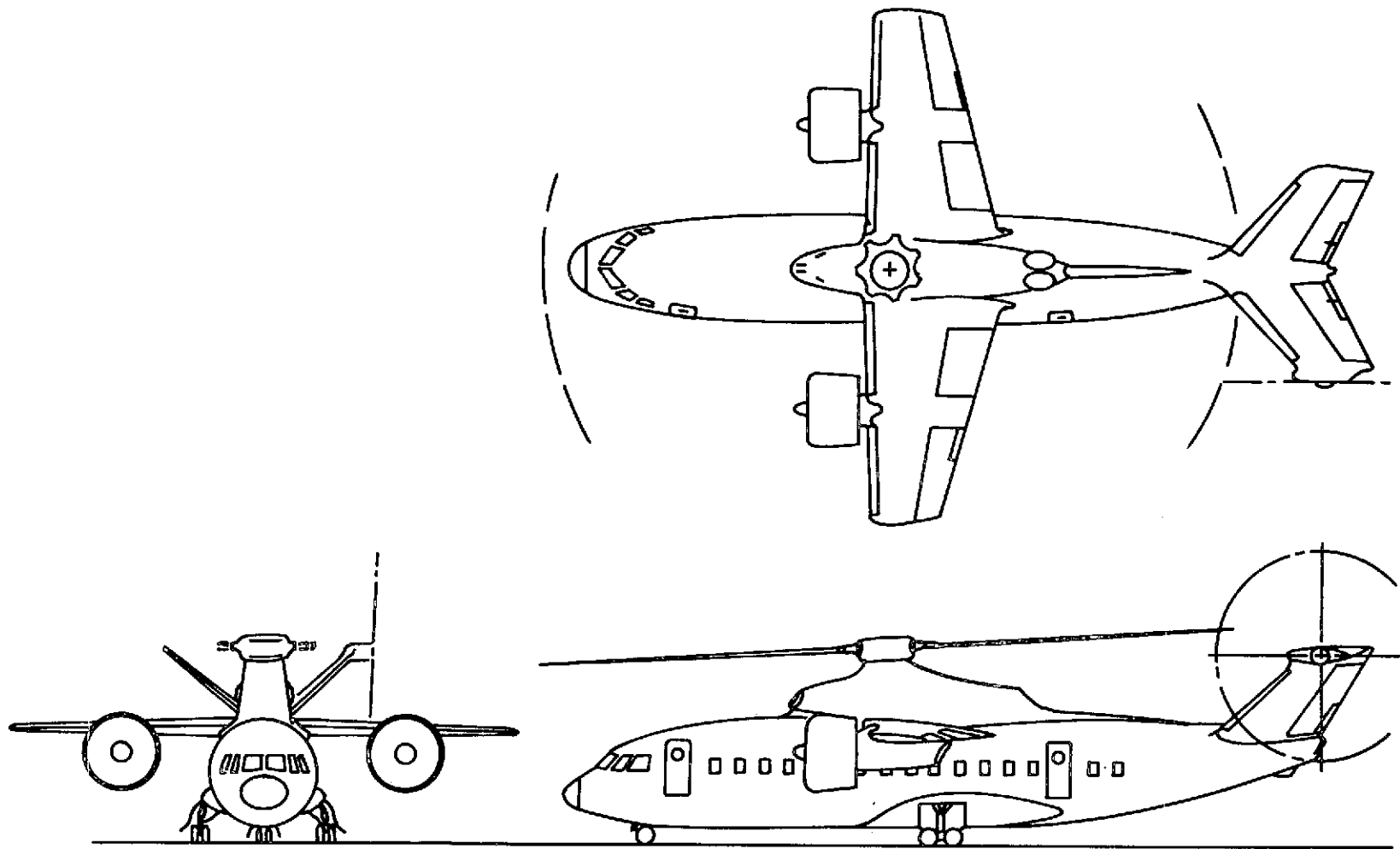
Figure 5. Sikorsky S-65-200 Compound Helicopter.

Table 4. Summary of Sikorsky Model S-65-200 Compound
Helicopter Characteristics.

WEIGHTS

Design Gross Weight (lb)	80,400
Manufacturer's Weight Empty (lb)	53,078
Operational Weight Empty (lb)	54,150

PERFORMANCE

Max. Recommended Cruise Speed (kt)	261
Max, Range with Reserve @ Design Gross Weight (nm)	580
Design Range (nm)	200
Cruise Altitude (ft)	15,000 std
VTO Condition @ Design Gross Weight	SL 90°

DIMENSIONS OR CAPACITIES

Overall Length (ft)	101.7
Overall Height (ft)	33.0
Overall Fuselage Width (ft)	12.3
Main Rotor Diameter (ft)	80.0
Tail Rotor Diameter (ft)	23.0
Passenger Capacity @ 34 in Seat Pitch	100
Baggage Capacity (cu ft)	500
Max. Usable Fuel Capacity (lb)	14,000
Wing Loading (psf)	110

FEATURES

Primary Power Plant	(4) 6800 hp Engines
Auxiliary Power Plant	Provided
Prop/Fans	(2) 8.5 ft Diameter
Instrument Flight Capability	0 Ceiling 0 RVR
External Noise @ 500 ft	95 PNdB
Internal Noise	68 dB PSIL
Air Conditioning	Provided
Pressurization	Provided

Note: Fuel Reserve Includes Allowance for 30 nautical miles at speed for best
range (559 lb), and 30 minutes holding at speed for best endurance (2400 lb).

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engines provide propulsive thrust at high speed. The engines can be decoupled from the drive train during hovering and low speed flight for reduced total power required and for reduced noise.

The V-tail incorporated in the S-65-200 design provides the required stability and control characteristics with minimum dependence on stability augmentation. Rudder-vator control surfaces provide both elevator control, linked to the longitudinal cyclic pitch control column, and rudder control, linked to the rudder pedals. These control surfaces, in conjunction with the ailerons, provide airplane type control about all three axes throughout the speed range.

2.2   OPERATIONAL CONSTRAINTS

From the standpoint of the navigation system, the critical portions of the flight profile are the takeoff and landing phases. During these phases, the trajectory of the rotorcraft is determined as a compromise among the requirements to minimize: 1) the intensity and duration of the noise heard by the community located beneath the flight path, 2) the fuel expended due to the high power required in low speed flight, and 3) the time spent in the vicinity of the terminal area. The problem is further compli-cated by the maneuvering required to avoid obstacles and CTOL traffic, the flow char-acteristics of the rotor during steep descents, and the fundamental control characteristics of rotorcraft in low speed flight. The following discussion outlines the operational characteristics of the rotorcraft with respect to the above considerations.

2.2.1   NOISE

Careful choice of the flight path of a rotorcraft near the terminal area leads to significant reductions in the intensity of ground measured noise levels (Ref. 4).   How-ever, vehicle performance characteristics, area navigation capabilities, and safety considerations constrain the choice of practical flight paths. Steeper approaches requir-ing lower power settings and larger distances between the rotorcraft and the ground reduce the noise impact area. However, the higher sink rates and lower power settings leave less margin for error, requiring greater pilot proficiency for manual operations and higher performance guidance and control system for automatic operations.

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A simple model for demonstrating the effect of descent angle on the noise footprint may be developed by assuming that the space contaminated by the aircraft noise to some specified sound level lies inside a sphere centered at the noise source. As the aircraft proceeds along its flight path, the sphere generates a cylinder in space. The intersection of the cylinder with the ground plane defines a footprint contour inside of which the noise contamination is equal to or greater than the specified level. Some representative contours are shown in Figure 6. Increasing the slope angle from 6° to 18° reduces the contaminated area by a factor of 3. Further increase from 18° to 30° gives a reduction in contaminated area of only 50 percent. However, increasing the descent angle from 30° to 90° does not provide any significant additional improvement.
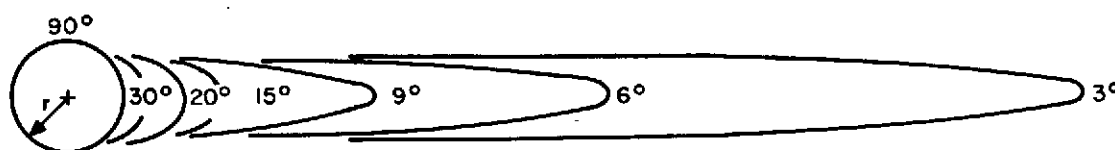
Figure 6. Noise Contours as a Function of Aircraft Descent Angle.

To illustrate the potential benefits of flight path control, a representative current rotorcraft was flown in a series of approach and climbout paths. Figure 7 illustrates the maximum perceived noise level contours for both a typical takeoff trajectory, and one utilizing a vertical ascent to 750 feet followed by a conventional climbout (Ref. 4). **The conventional takeoff has greatly increased perceived noise contour** areas in the direction of the flight path. However, although the ground noise footprint is reduced by the 750-foot vertical departure, the intensity of the noise near the takeoff point is virtually unchanged and the duration of the perceived noise, the fuel burned, and the climbout time are significantly increased.

It should be noted that landing of a rotorcraft can often be noisier than takeoff. Although the power settings are lower, blade/vortex interaction in certain descent conditions leads to the high-intensity noise known as "blade slap." Figure 7 also illustrates the maximum perceived noise level contours for both a conventional descent trajectory,

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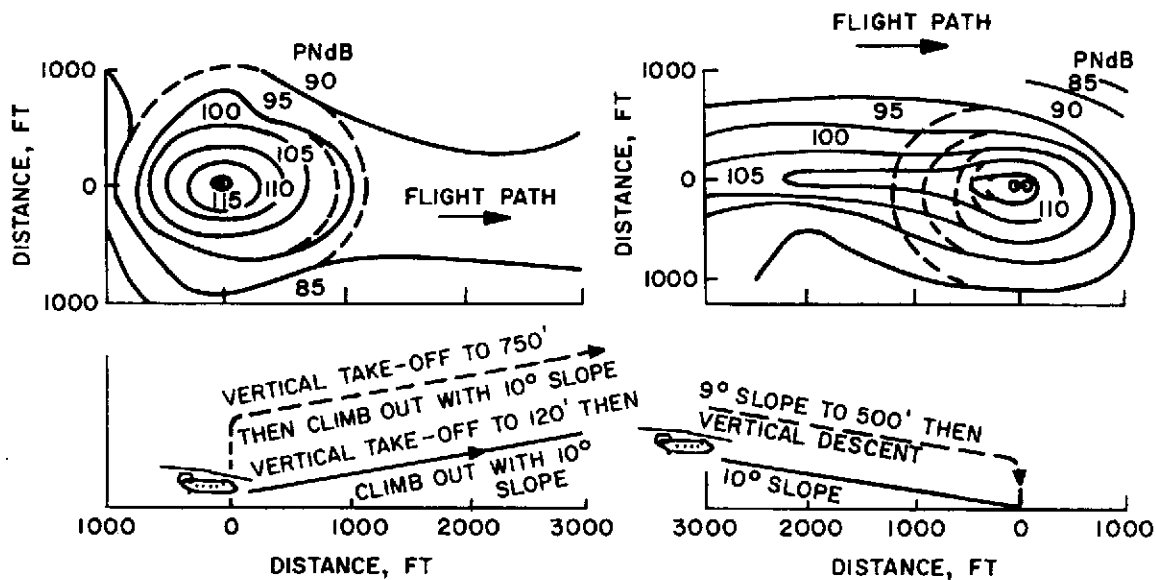
Figure 7. Noise Exposure Due to Different Takeoff and Landing Flight Profiles.

and a conventional approach to a point 500 feet above the landing area followed by a vertical descent to the ground. Again, the vertical descent substantially reduces the perceived noise contour areas in the direction of the flight path.

The power and flight path angle for the conventional descent case shown in Figure 8 illustrate other aspects of the terminal landing problem. Almost zero power was
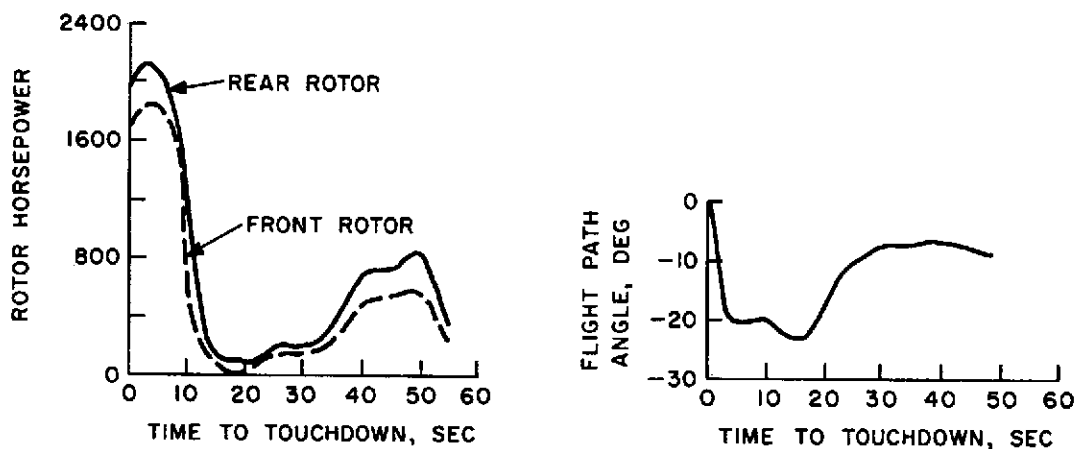
Figure 8. Power and Flight-Path Angle Time Histories in a 10° Descent to Hover.

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used for nearly 20 seconds, but even then the noise levels remained high due to blade/ vortex interaction. Also, the large deviations of the flight path angle from the desired value of 10°, indicate the necessity for improved guidance and control methods to implement even the relatively simple terminal trajectory considered.

2.2.2 AERODYNAMICS

In addition to noise considerations, certain fundamental aerodynamic effects limit the descent angle achievable by a rotorcraft. As shown in Reference 5, one of the most important parameters is the maximum obtainable drag/lift ratio as a function of airspeed. This parameter determines the descent and deceleration capability of the rotorcraft. The relationship between descent angle γ, deceleration $\dot{V}$, and the drag/ lift ratio D/L is given by

$$\tan \gamma = \frac{D}{L} - \frac{\dot{V}}{g \cos \gamma} \tag{1}$$

Note that increased deceleration at a given descent angle and speed requires an increase in drag at constant lift. Because the value of D/L that can be achieved at a given speed is limited, either the descent angle or the deceleration is also constrained. However, since the terminal landing phase must include both descent and deceleration, the manner in which these are combined greatly influences the time and fuel consumed during descent for a given value of $(D/L)_{max}$.

For rotorcraft, $(D/L)_{max}$ is limited by the flow conditions at the rotor(s). As shown in Figure 9, the possible combinations of descent angle and rates of descent are restricted by flight conditions known as the vortex-ring state and the autorotative state. The vortex-ring state is a condition of violently unsteady flow occurring on rotors operating with high D/L at low flight speeds. It limits the maximum achievable D/L. The autorotative state occurs when rotor flow conditions are such that the power required by the rotor is reduced to zero; steeper descent angles cannot be achieved without increasing the rate of descent. Autorotation is not normally used in IFR conditions since the rates of descent are excessive for the high disc loadings of current rotorcraft. The principal operational limitation on $(D/L)_{max}$ is therefore the vortex-ring state.

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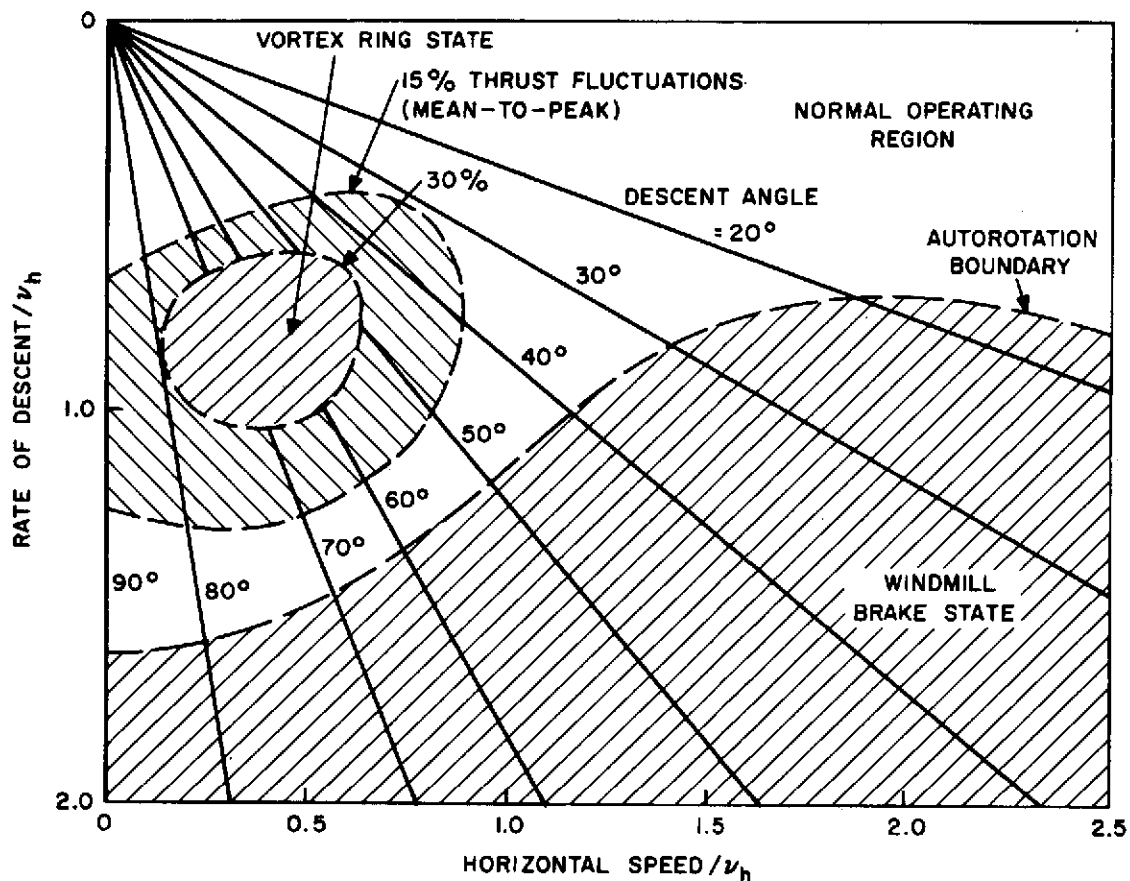
v_h = rotor induced velocity in hovering

Figure 9. Helicopter Approximate Descent Boundaries in Nondimensional Form.

2.2.3 STABILITY AND CONTROL

As was seen in Figure 8, the flight path descent angle can vary substantially from the desired value during steep descents, despite the best efforts of the pilot. These variations are due to difficulties arising from the fundamental control character-istics of rotorcraft, as shown by the following simple analysis.

Consider the problem of controlling the rotorcraft shown in Figure 10 during a steep descent at constant velocity. Neglecting aerodynamic effects, the linearized equations of motion with respect to inertial axes whose origin is translating at constant velocity along the nominal flight path are:

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$$\ddot{x} = \frac{T}{m} (\alpha + \delta_e) \qquad (2)$$

$$\ddot{\alpha} = \frac{Th_c}{I_{YY}} \delta_e \qquad (3)$$
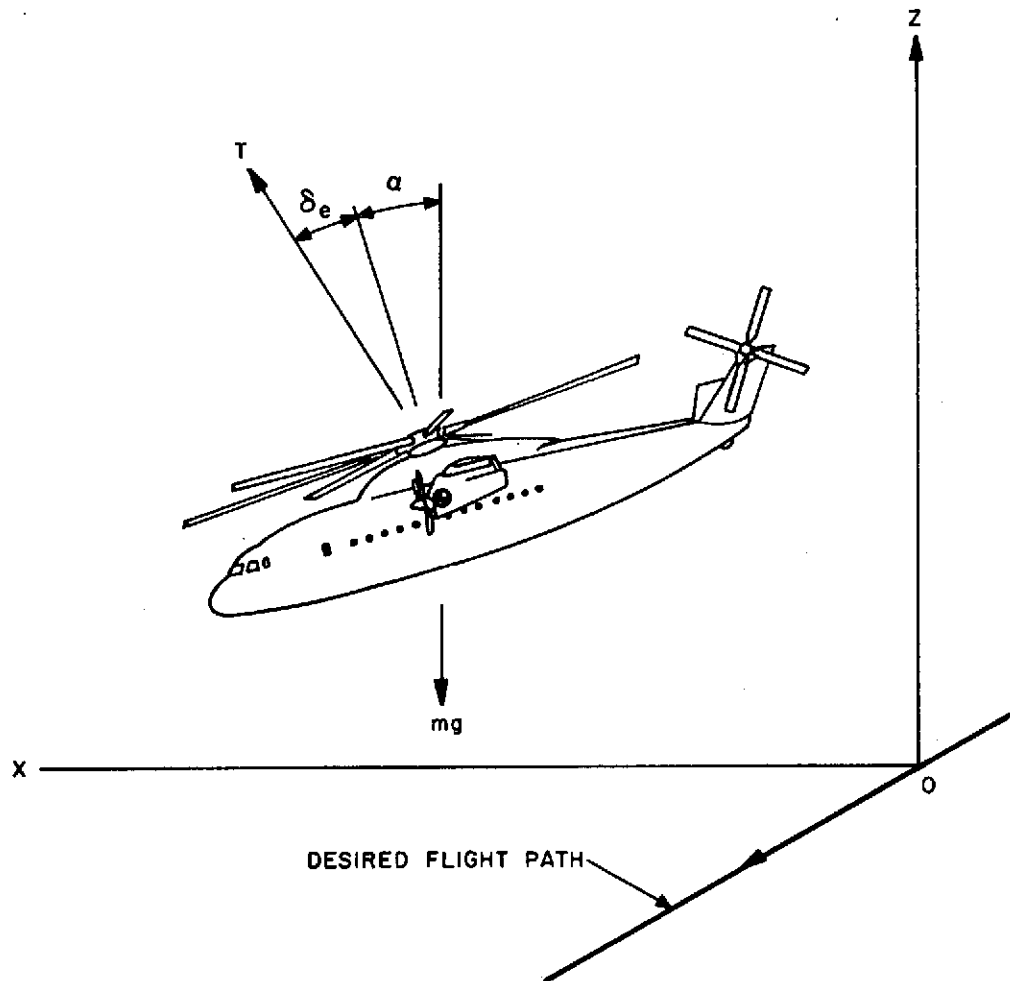
Figure 10. Nomenclature for Rotorcraft Analysis.

$$\ddot{z} = \frac{T_{\delta_o}}{m} \delta_o \qquad (4)$$

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where x, z = longitudinal and vertical translation perturbations

α = pitch angle perturbation

δ_e = angular displacement of thrust vector due to cyclic control

δ_o = collective control displacement

T_{δ_o} = thrust change per unit thrust control displacement

h_c = distance from rotor center to rotorcraft cg

m = aircraft mass

I_{YY} = pitching inertia of aircraft about cg

During low speed descent, longitudinal velocity of the rotorcraft is controlled by tilting the rotorcraft as a whole, and therefore its thrust vector. Equations (2) – (4) show that the response of the aircraft to cyclic or collective control displacements is a change of pitch attitude or vertical displacement increasing as the second power of time, and a change of horizontal displacement increasing as the fourth power of time. A pilot attempting to control a rotorcraft on a steep descent path requires a great deal of anticipation and control coordination; the task approaches the impossible under adverse conditions. While the use of attitude stabilization in current rotorcraft simplifies the pilot's control task by reducing the horizontal displacement response to an increase with the second power of time, a high degree of anticipation and control coordination by the pilot is still required; the presence of gusting winds, building-induced turbulence, and low visibility further complicate this task.

2.2.4 ECONOMY

A key factor in the feasibility of a commercial VTOL system is economy of operation. To be economically successful, service must be performed with a high degree of reliability regardless of weather or conventional traffic. Since a significant percentage of the VTOL service will involve traffic connecting with trunk and regional airlines, the system must have the capability of operating into and out of CTOL airports. Moreover, it must be able to schedule frequencies so as to meet connections with a high degree of reliability.

If the VTOL operation is subject to undue air traffic delays, not only will connections be missed, but Direct Operating Costs (DOC) will increase rapidly, as shown in Figure 11 (Ref. 6). For example, on a 200-mile flight, a 15-minute delay may result in nearly a 40 percent increase in DOC. Thus, even though the VTOL service carries strictly local traffic, the cost effect of landing/takeoff delays may cause economic disaster. The relative effect of delays on the short-haul DOC is much more severe than on the long-haul DOC.
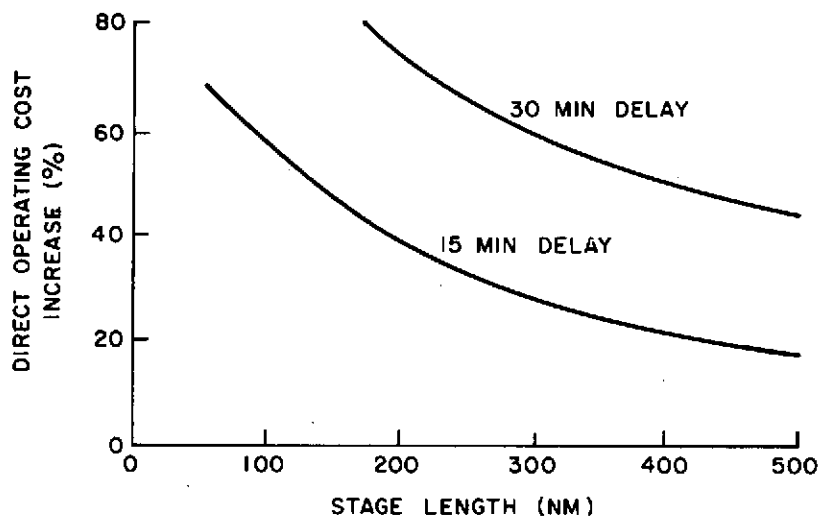
Figure 11. Effects of Delay on VTOL Direct Operating Cost.

Two obvious implications of the economic situation are: 1) the VTOL system must be capable of operating in adverse weather conditions to the same degree as conventional traffic; and 2) the VTOL aircraft must also be permitted to operate essentially independently of the CTOL traffic to avoid delays. Both requirements have a significant impact on the VTOL navigation and guidance requirements.

2.2.5 SAFETY

Unquestionably, safety is a necessity for the commercial VTOL system. Routes must be established which avoid obstructions, conventional traffic, noise sensitive areas, etc., and these must be followed with close tolerances in all weather. Consequently,

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the navigation system must provide extreme accuracy and operate reliably even at low altitudes in the urban environment. Moreover, to achieve independence from the conventional air traffic control (ATC) system, the VTOL should be able to provide its own separation from other air traffic, both CTOLs and other VTOLs.

2.3   IFR OPERATIONS

2.3.1   BACKGROUND

In recognition of the traveling public's insistence on schedule reliability, there is widespread agreement that IFR authorization is necessary to obtain a fuller measure of the inherent operational capabilities of modern helicopters (Refs. 7 - 10). In the past, most IFR operations have been conducted by military helicopters including single-engine types without civil IFR certification, by remote area operators, and by airline helicopters with limited IFR authorization. The helicopter was initially certificated only for VFR operations because, compared to a fixed-wing aircraft, it did not possess inherent stick-free or stick-force stability. Helicopters were utilized mostly in remote areas and for limited speed and range activities in which there was no "must go" dependence in that waiting out the weather was acceptable.

In earlier IFR certification attempts, electronic stabilization was not considered an alternative solution. The piston-powered Cessna helicopter obtained IFR certification by adding a system of bellows, springs and mechanical systems to incorporate the required stick forces. Newer twin-turbine helicopter transports with improvised stabilization systems achieved limited IFR certification by the FAA. For example, Los Angeles Airways had an IFR departure authorization to an on-top clearance above the fog. More recently, the FAA has issued IFR standards which give the option of electronic stabilization in lieu of stick force, thus permitting IFR certification for auto-pilot-equipped helicopters.

Some commercial operators have been operating helicopters under IFR conditions but with handicaps. Okanagan Helicopters Ltd. is an example of remote area operators. For approximately four years, Okanagan has been operating Sikorsky S-61 helicopters, under IFR conditions, to oil rigs up to 300 miles offshore. As an example, of the 144 hours flown in December 1971, all but five hours and thirty minutes were flown IFR. Okanagan uses Decca and radar, and have also done some work with the

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Global VLF Navigation System. The single autopilot system on the S-61 has been satisfactory. Okanagan's biggest problem in their IFR operations has been the alternate routing, where fixed-wing weather minimums are enforced.

Another offshore operator, Petroleum Helicopters, also uses the VLF navigation system satisfactorily in the Gulf of Mexico.

KLM North Sea Operations has obtained an IFR route certification for its helicopters with certain avionics and airways aids supplemented by onboard radar to locate and make approaches to petroleum platforms in the North Sea off Holland. Approximately 20 percent of all their flight time is IFR. Weather minimums are 150 feet with 1/2-mile visibility. Helicopter instrumentation includes VOR, ILS, ADF, Decca and airborne radar.

U.S. military forces have been performing IFR operations with rotorcraft as standard procedure. Most of the instrument operations are in the UH-1 Huey with no unusual instrumentation or radio groupings. The Army uses the lowest fixed-wing minimums and reduces the visibility minimum by one half. The Army also considers alternates as a major problem due in part to the limited range of helicopters. Automatic stabilization for IFR is not required.

2.3.2   NEW YORK AIRWAYS

New York Airways (NYA) provides a scheduled shuttle service between the three major New York metropolitan area airports (Newark, LaGuardia, Kennedy); downtown Manhattan (Wall Street); Morristown, N. J.; and, recently instituted, Teterboro, N. J. All present NYA operations are conducted with Sikorsky S-61 helicopters under VFR or special VFR flight rules, and all navigation is performed visually. Minimum weather requirements are shown in Table 5. Under existing operations, service to Morristown is occasionally halted by low ceilings due to a ridge west of Newark, even though weather on either side of the ridge is acceptable. With these SVFR minimums, NYA has been able to achieve a completion goal of about 92 percent (Ref. 11). However, IFR capability would enable them to raise this to about 98 percent in the relatively near future, and eventually to perhaps 99.6 percent. Considering that, in a peak summer month, New York Airways carries over 40,000 passengers, a 6 to 7.6 percent increase in meeting scheduled flight performance is a significant economic factor.

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Table 5. NYA SVFR Weather Minimums.

	Visibility (mi)	Ceiling (ft)
Enroute		
JFK-LGA	1	300
East River	1	400
Brooklyn	1	500
Terminal		
(Sliding Scale)	3	300
	2	400
	1	500

New York Airway's experience with the Decca navigation system provides a realistic example of IFR operation, by a commercial helicopter service. NYA began working on the development of an IFR capability more than two decades ago (Refs. 12, 13). Early investigations revealed that the Decca VLF hyperbolic navigator system, then in extensive use for marine navigation, was capable of establishing aircraft location without the use of line-of-sight VOR/DME signals. A Decca Chain was installed in the New York area in 1957 under a contract between New York Airways, the Decca Navigator Company and the Airways Modernization Board. The installation was utilized in the Boeing Vertol V-107 helicopters under visual flight conditions to monitor enroute flight tracks and the airborne system was appropriately called Flight Track Monitor System (FTMS). NYA commenced an intensive testing program of the equipment, logging over 40,000 flight hours. NYA received authority from the FAA to utilize the Decca FTMS to conduct full instrument operations both enroute and at the terminal area. With the complete implementation of this approval, NYA estimated that flight schedule cancellations for weather reasons would be reduced by about five times.

Complete segregation of helicopter instrument traffic from the CTOL traffic was the project goal in the early stages of the program. After a lengthy and careful study, however, it was conceded that a completely independent operation was not feasible in the New York area because of the need to co-mingle aircraft in the airspace surrounding each major airport facility. The adopted air traffic control plan provided

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for the maximum independence of VTOL instrument traffic through the use of procedural segregation (Refs. 14, 15). The helicopter routes, holding patterns, and altitudes are depicted visually in Figure 12. The routes provided one-mile separation on parallel courses to active ILS runways and allowed adjustments in routing to correspond with the particular runway in use. The only altitude assigned was 1100 feet, with the exception of a 2000-foot altitude along the Hudson River between Newark and LaGuardia. The basic airways were 1 nm wide, with a 1 nm buffer zone on each side. No accommodation was made by the existing CTOL traffic in establishing the VTOL route structure. IFR flights were not conducted to Manhattan, since a satisfactory missed approach procedure could not be specified. If holding was necessary, it was accomplished within the airway itself; however, there was seldom a need to hold since the helicopter could adjust its speed readily between 55 kt and 120 kt. The additional time required for the IFR routes did not exceed 10 to 15 minutes; however, such delays were substantial since under VFR most flights take only 8 – 12 minutes. Area navigation approaches using the FTMS were developed for Newark, LaGuardia and Kennedy Airports. Figure 13 shows typical approaches to LGA and Kennedy. Note the minimum descent altitudes of 400 feet, since these are "nonprecision" approaches (no vertical navigation information).

Although NYA was very satisfied with the accuracy and utility of the FTMS, scheduled IFR operations were conducted for less than six months, primarily because of the difficulty and cost of maintaining pilot IFR proficiency. Other contributing factors were the V-107's limited single-engine capability and the relatively high approach minimum descent altitude of 400 ft, which could not be reduced without vertical guidance.

As a result of the Decca experience, NYA feels there are two major barriers to commercial VTOL IFR operation in the New York City area:

- Crew training and proficiency.
- Existing CTOL traffic operations.

Crew proficiency is economically impossible to maintain by actual or simulated IFR flight operations. Actual IFR weather does not occur often enough; a third, qualified helicopter pilot is required in the cockpit for simulated IFR on scheduled flights; and the helicopter operating costs are too high for dedicated training flights. The need exists for a realistic simulator at a reasonable cost. To alleviate existing traffic operation,

- 27 -
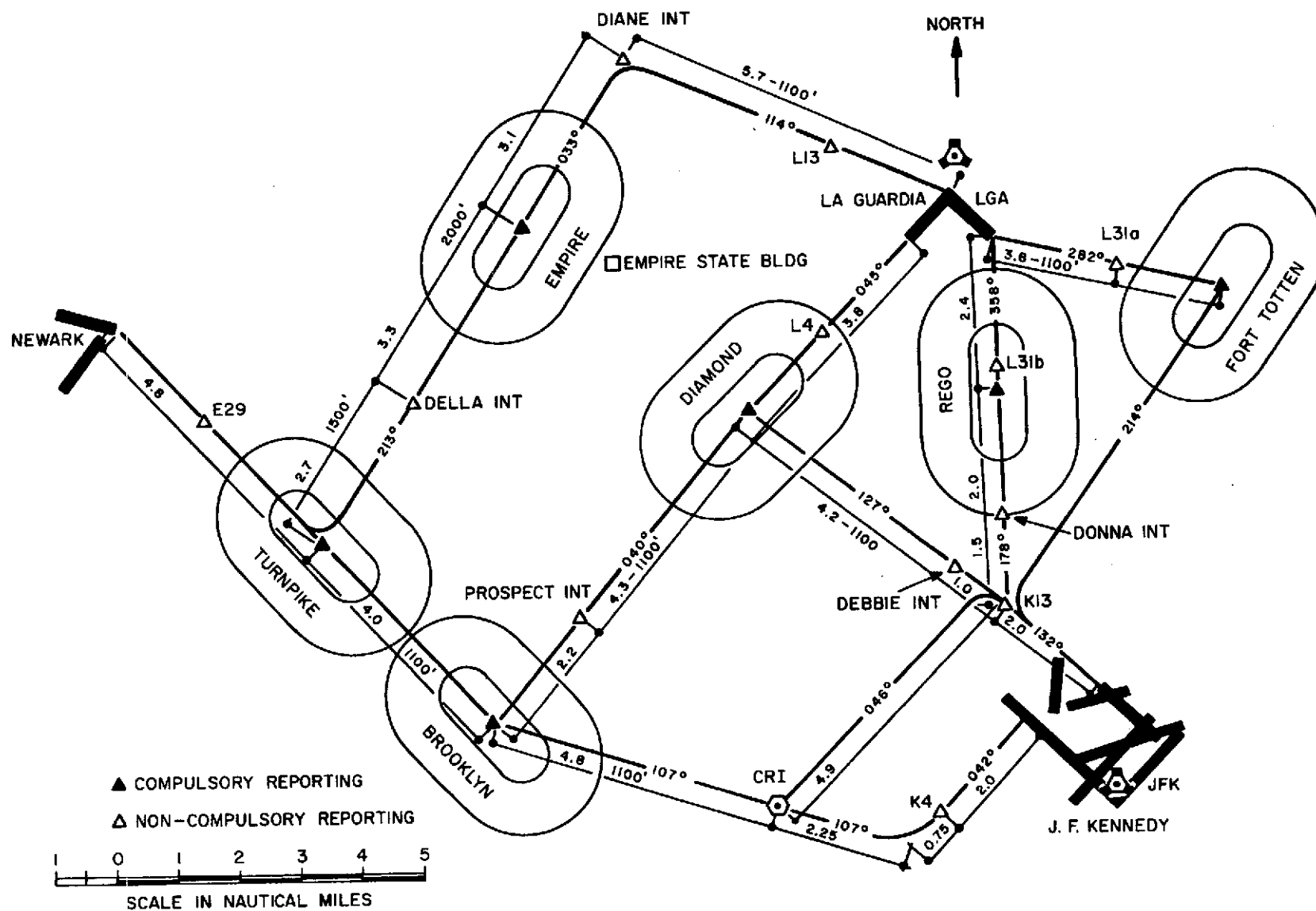
Figure 12. Helicopter IFR Routes – New York Airways – Flight Track Monitor System.

- 28 -
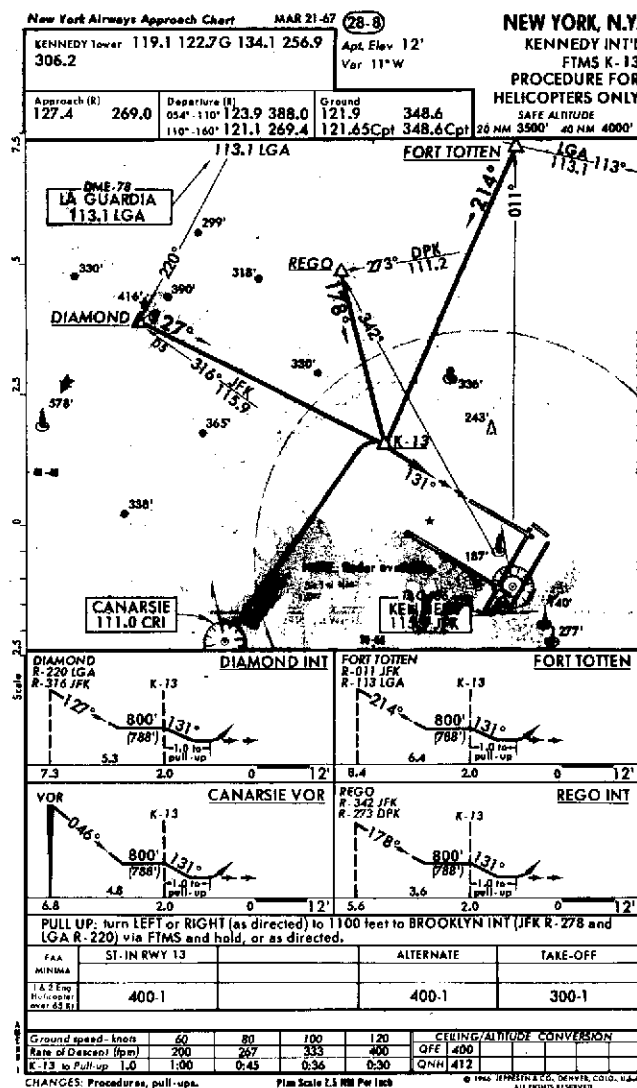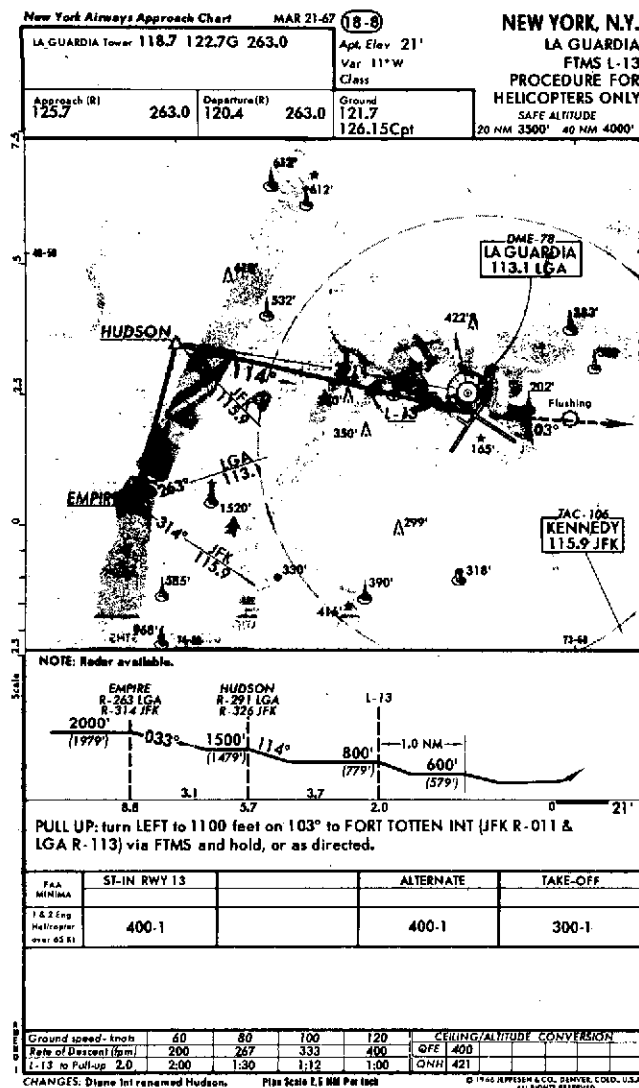
Figure 13. Typical FTMS Helicopter Approach Plates.

the New York Metroplex would have to be restructured to accommodate both CTOL and VTOL traffic equitably.

2.3.3 AREA NAVIGATION

Area navigation (RNAV) appears to be the answer to the IFR needs of commercial VTOL in the enroute and terminal areas, as well as for nonprecision approaches to low-density terminals which could not justify an expensive landing system. By providing the capability for direct point-to-point navigation, RNAV will permit discrete VTOL routings which are independent of existing traffic and which can avoid interference with existing control zones, towers, natural obstructions, etc.

While discrete enroute airspace structuring for VTOL operations may be somewhat complex in the high-density corridors and areas, it is nevertheless feasible if the helicopters are equipped to follow designated RNAV routings with a high degree of accuracy. This accuracy will be required not only in the lateral and longitudinal dimensions, but also in the vertical dimension (3-D RNAV) so that preestablished "overpasses" and "underpasses" relative to CTOL traffic may be followed. Extensive routing around CTOL traffic would be uneconomical, thus necessitating three-dimensional RNAV route structures. Four-dimensional RNAV routes, where time is specified as well as position, will undoubtedly be needed to achieve the one-operation-per-minute requirement for the high-density VTOL terminals.

The final approach may be carried out by reference to a ground-based landing system, or by reference solely to an RNAV system. Also, a "point in space" approach may be made using RNAV, and, if in visual contact with the surface, final approach and landing may be completed under Special VFR criteria. In the climbout and departure phases, the IFR helicopter can follow RNAV flight paths to avoid conflict with CTOL traffic, with the capability to apply speed controls readily as necessary to provide time separation from other traffic.

The capabilities of the VTOL coupled with RNAV make possible IFR operations virtually independent of CTOLs in high-density traffic areas, at high-density conventional airports, and to and from heliports in city centers and at outlying landing areas. A flight program to show the feasibility of IFR helicopter operations independent of CTOL traffic, but within the ATC system, was carried out in the Washington, D. C. area early in 1973 (Ref. 16). This "real world" demonstration used a Bell 212

- 30 -
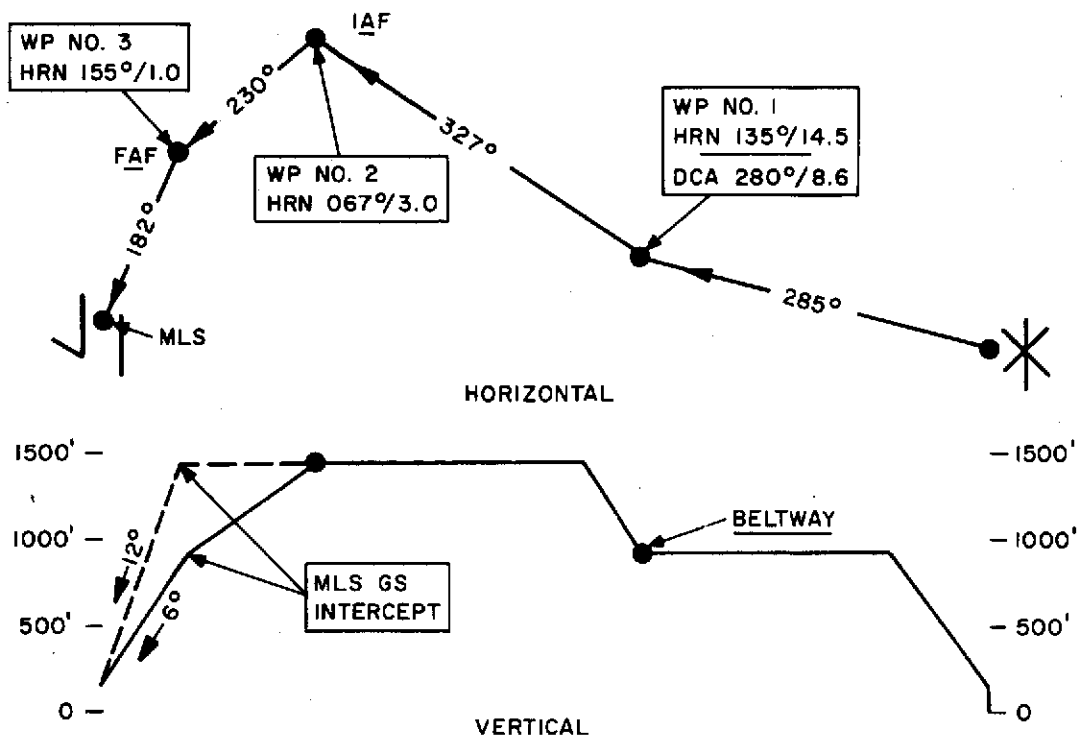
(a) National to Dulles
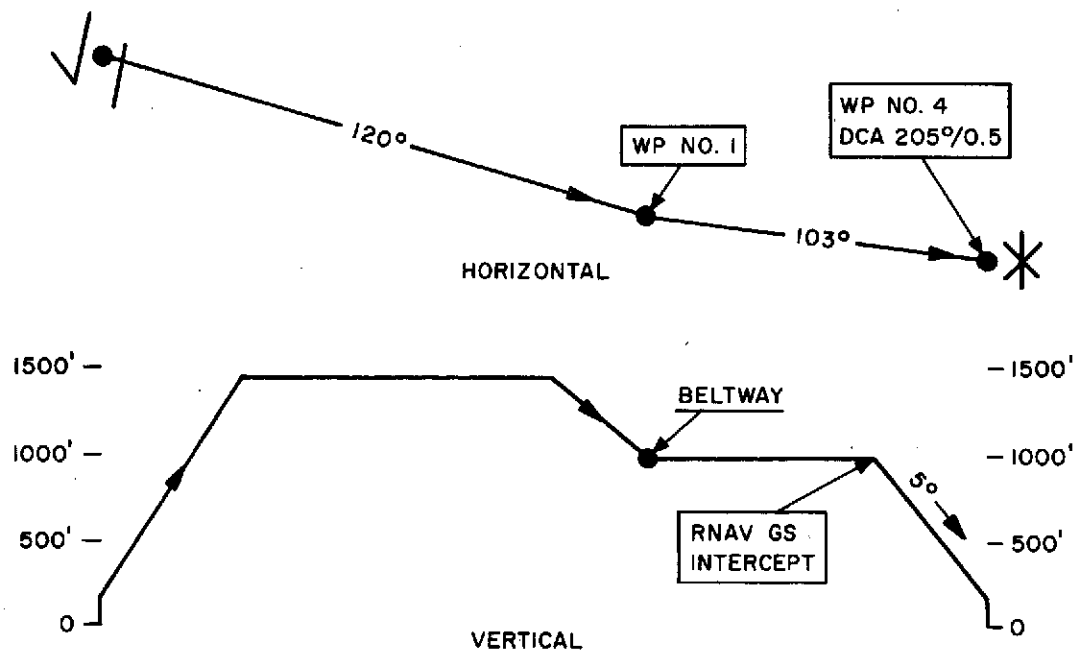
(b) Dulles to National

Figure 14. Flight Plans for 3D-RNAV/MLS Helicopter IFR Demonstration.

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helicopter equipped with a 3-D RNAV system and a scanning beam microwave landing system (MLS). The 3-D flight plans followed between Dulles (IAD) and Washington National (DCA) are shown in Figure 14. An MLS approach was made at IAD, and a 3-D RNAV approach executed at DCA. These demonstration flights showed convincingly the feasibility of the vehicle, the RNAV system, and the scanning beam MLS equipment.

2.3.4 IFR APPROACHES

In terminal area operations, the various advantages of the VTOL's flight characteristics (ability to slow down readily, variable approach and climb gradients, small landing area requirements) introduce many factors which favor IFR helicopter operation over CTOL. Because the VTOL is capable of slowing down to a hover, an IFR approach can be made to an arbitrary "point in space," displaced from the desired landing site; the VTOL can then air taxi VFR to the landing spot after breaking out beneath the weather.

In anticipation of the coming IFR helicopter era, the FAA recently established several regulations specifically relating to helicopter IFR operation (Ref. 17). One is a recognition of the "point in space" approach. At the same time, the VTOL's unique low-speed landing capability has been recognized and helicopters are permitted to reduce visibility minimums to one-half the published values for CTOL. However, no complete definition of VTOL precision approach categories has been established by the FAA. For the purpose of this investigation, a proposed set of consistent VTOL approach categories has been formulated using criteria such as "see to hover," "see to air taxi," etc. Table 6 compares these suggested VTOL precision approach categories with their CTOL equivalents. Comparable categories show the ceiling and/or visibility for VTOL to be about half that for CTOL. Using the proposed criteria, comparisons between CTOL and VTOL instrument operations are more realistic.

The lower speed and hover capability of VTOL aircraft make low IFR approaches safer than for CTOL aircraft. Since they minimize the necessity for the "missed approach" and its associated problems for both the pilot and the air traffic controller. However, every helicopter instrument approach requires a missed approach procedure similar to those of conventional aircraft, which must be executed if unable to land or proceed VFR upon

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Table 6. Proposed VTOL Precision Approach Categories and CTOL Equivalents.

	Category	Ceiling (ft)	RVR (ft)	Criteria
CTOL	I	200	2400	See to land – auto approach to 200 ft; visual transition and flare
	II	100	1200	See to land with lights – auto approach to 100 ft; autoflare; visual runway guidance on rollout
	IIIa	0	700	See to touchdown
	IIIb	0	150	See to taxi
	IIIc	0	0	No visual contact
VTOL	I	100	1200	See to hover
	II	50	600	See to hover with lights
	IIIa	0	150	See to air taxi
	IIIb	0	75	See to ground taxi
	IIIc	0	0	No visual contact

reaching the missed approach point (MAP). For automatic VTOL approaches all the way to touchdown, the missed approach point is actually the landing point. Nevertheless, the requirement still exists for a missed approach procedure, since it is often executed prior to reaching the MAP for reasons other than lack of visual contact. For example, traffic conflicts, loss of navigation aids, loss of communication, emergencies in the cockpit or at the heliport, etc. would all require the approach to be aborted. Although the missed approach procedure might be to hover in place, this is not desirable for fuel economy or where proximity to the ground or obstacles could be hazardous. Consequently, current regulations requiring a routing and holding fix in the event of a missed approach are not expected to change.

2.4   OPERATIONAL PROCEDURES

To achieve maximum efficiency of service, VTOLs must be able to operate essentially independently of CTOL aircraft. Such independent operation involves separate VTOL flight paths enroute, in terminal areas, and during landing/takeoff. Here again RNAV can play an important part in facilitating the use of discrete routings. During the takeoff and landing phases these routes will be dictated primarily by noise restrictions, obstacle clearance, and aircraft capabilities. Interaction with CTOL air traffic, existing route structures, and the VTOL aircraft capabilities will be major considerations during the enroute and terminal phases.

2.4.1   LOW-ALTITUDE ENROUTE AIRWAYS

The proposed VTOL enroute airway structure consists of a system of one-way RNAV routes connecting the major terminals (Fig. 15). For the pure helicopter, these Zulu airways would be established below the existing low-altitude Victor airway structure for CTOL traffic. However, for the longer stage lengths of the compound helicopter, the Zulu airways would share the low altitude airspace with CTOL traffic,

USE VFR HEMISPHERIC ALTITUDES

ONE-WAY HIGHWAYS IN SKY   ONE-WAY HIGHWAYS IN SKY

1000'-2500' AGL   1000'-2500' AGL

WDC   NYC   BOS

INDEPENDENT LOW ALTITUDE TERMINAL
ROUTE STRUCTURE CONNECTING V-PORTS
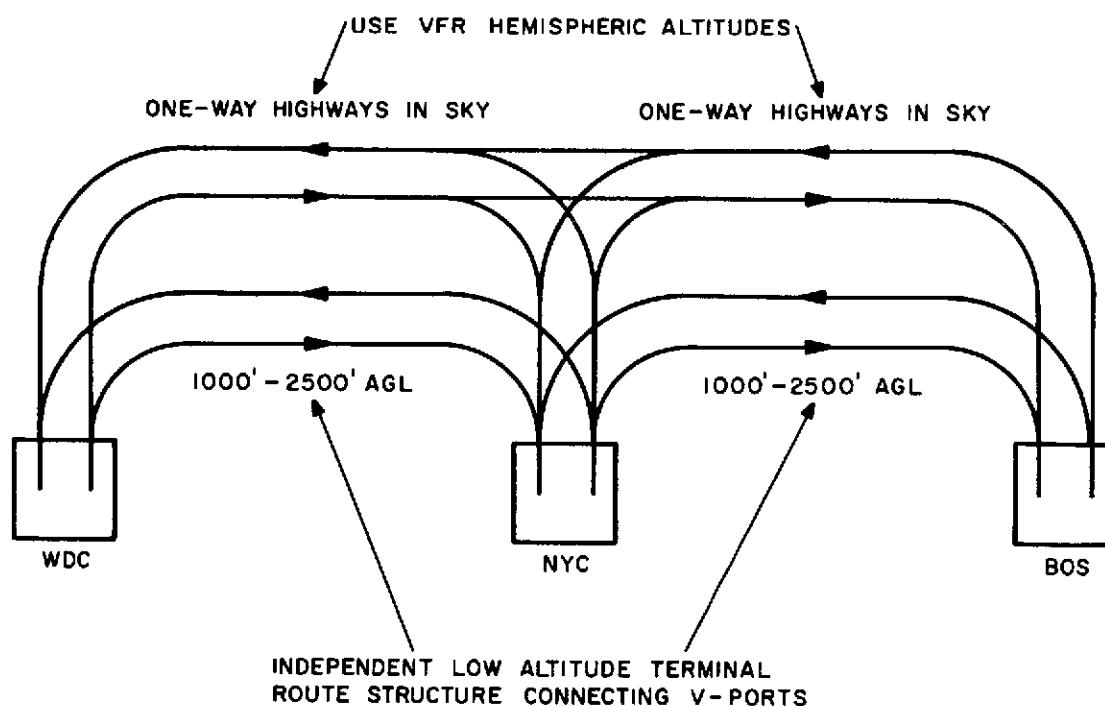
Figure 15. VTOL Airway Structure.

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since (by design) the compound helicopter performance is essentially the same as CTOL aircraft during cruise. The upper-level Zulu routes would utilize the standard VFR hemispheric altitudes, and would take advantage of relatively unused airspace resulting from limitations in the CTOL ATC communications/surveillance facilities. The high and low altitude Zulu routes would be joined with the destinations by means of Tango connectors.

For the low-altitude airways, the criteria for obstruction clearance enroute will be based on the results of an FAA flight evaluation program for VTOL (Ref. 18). These criteria call for a minimum obstruction clearance altitude (MOCA) of 500 ft above obstacles within $\pm$ 2 nm of centerline tapering to zero altitude clearance for obstacles $\pm$3 nm of centerline, as shown in Figure 16. Traffic clearance enroute will avoid the airport traffic area around an operational control tower as defined by current Federal Air Regulations (5 statute miles; 3000 ft AGL). An arbitrary clearance of 2 nm and 1500 ft above ground level (AGL) will be established around principal uncontrolled airports. Noise pollution is not expected to be a problem in the enroute phase; however, major urban areas would be avoided, and the routes could be shifted periodically to eliminate the integrated annoyance effect.

2.4.2   TERMINAL AREA ROUTES AND APPROACHES

A set of RNAV Tango transition routes will be defined to correct the Zulu airways and destination heliports. An arrival Tango will take the VTOL to a specified waypoint from which the approach commences.

In the absence of constraints, normal helicopter approaches are essentially parabolic with constant rate of descent and constant longitudinal deceleration. Future VTOL must be capable of landing in the same weather conditions as future CTOL airliners (Category II or III) but along steep, curving glide paths. Since CTOLs use most of the airspace downwind of major airports for approaches, VTOLs will often be left with airspace requiring crosswind approaches. For a heliport, a minimum of only two approach paths are needed to tolerate high wind conditions; crosswinds pose no problems, but the helicopter cannot accept downwind approaches because of the vortex ring state. Care must be taken in applying specific landing geometry configurations to a wide variety of city center heliports since they each have site-dependent features which constrain approach and departure paths.

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SECONDARY AREA | NM

2 NM

PRIMARY AREA

2 NM

SECONDARY AREA | NM

PLAN VIEW

SECONDARY
AREA

MINIMUM OBSTRUCTION
CLEARANCE ALTITUDE

SECONDARY
AREA

PRIMARY AREA

500 FT

◄─ | NM ─► ◄──── 2 NM ────► ◄──── 2 NM ────► ◄─ | NM ─►

CROSS SECTIONAL VIEW
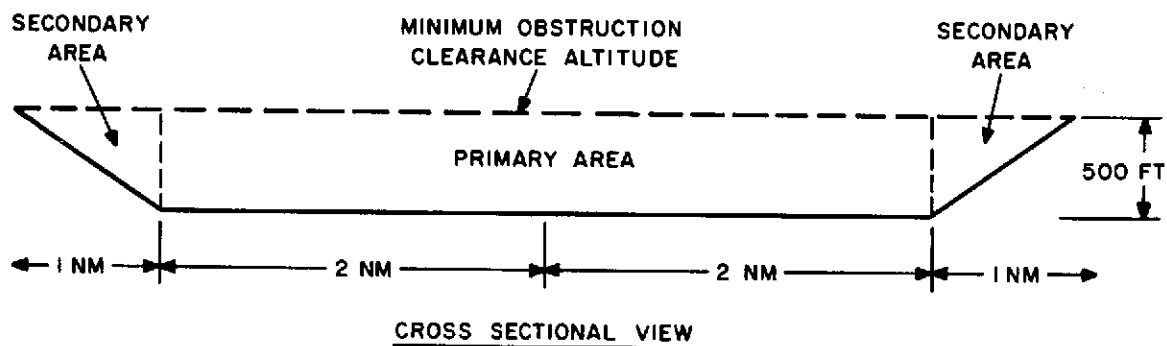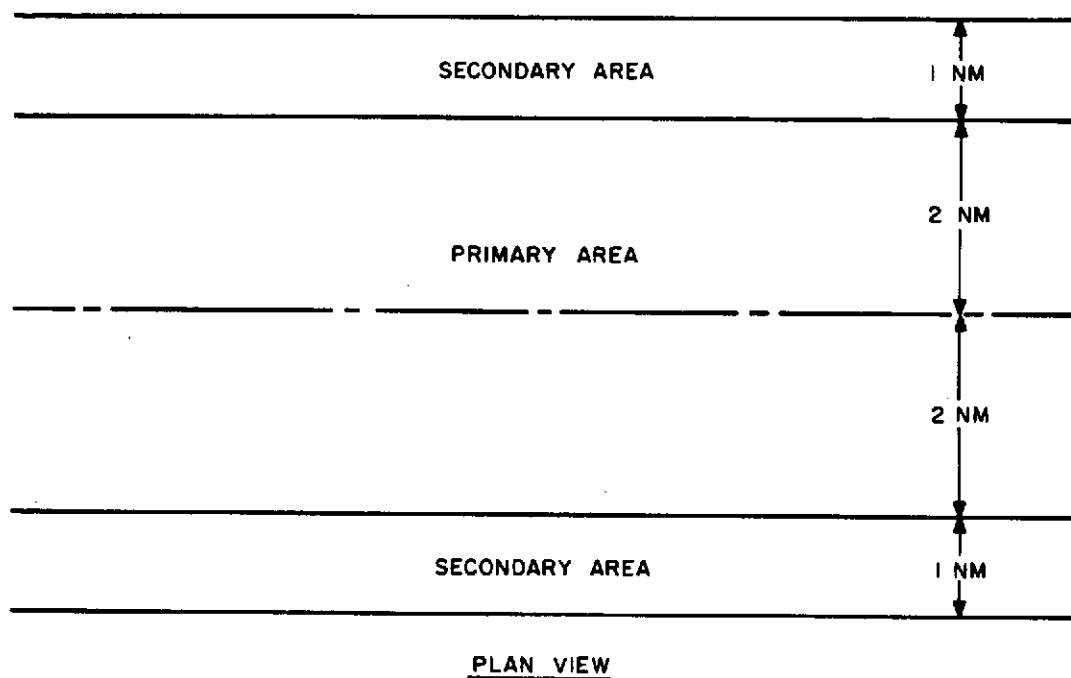
Figure 16. Proposed Helicopter Airway (Ref. 18).

Consideration has been given to the IFR handling of VTOL traffic at CTOL airports. At the present time, the ILS approach to the active runway blocks a wall of airspace that is typically 10 miles long and 1500 ft high. This creates a problem for VTOL traffic desiring to cross the active runway without interference to the CTOL

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traffic flow. It is proposed that the airspace directly over the runway be shared such that the CTOL traffic remains below 500 ft AGL over the runway, and VTOL traffic has free access to cross perpendicular to the CTOL traffic at 1000 ft AGL (Figure 17). Failure to allow IFR crossing of the CTOL runway in this way would necessitate an approach capability to both sides of each CTOL IFR approach course, followed by air taxi across active runways under CTOL ATC clearance.
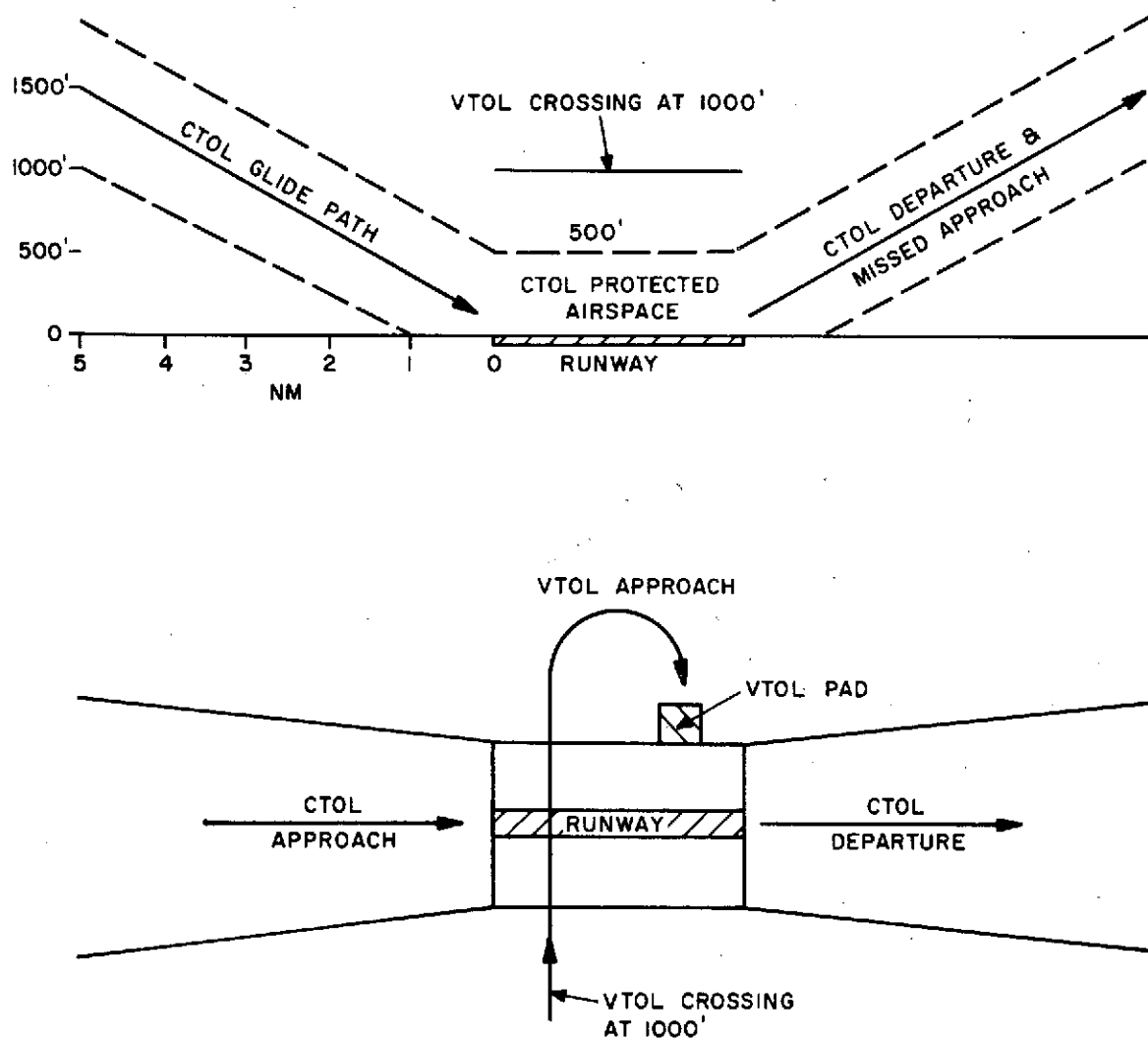
Figure 17. Suggested Noninterfering VTOL Approach to Conventional Airport.

After the 1000 ft crossing, descent will take 2 minutes at 500 ft/min; to expedite the approach, turn to the pad should begin as soon as possible. At standard rate (3 deg/sec) and 60 knots, this leads to a turning, descending approach with a turn radius of about 2000 ft, which fits conveniently into the typically available airspace. This procedure has the advantage of keeping the two traffic flows independent and without mutual interference. It also influences the characteristics of the VTOL approach procedure and the associated guidance requirements.

This spiral technique can be generalized to accommodate arrivals from all directions and could handle multiple helicopters in a "descent tube," as shown in Figure 18. The descent tube would be established in a vacant airspace sector of the
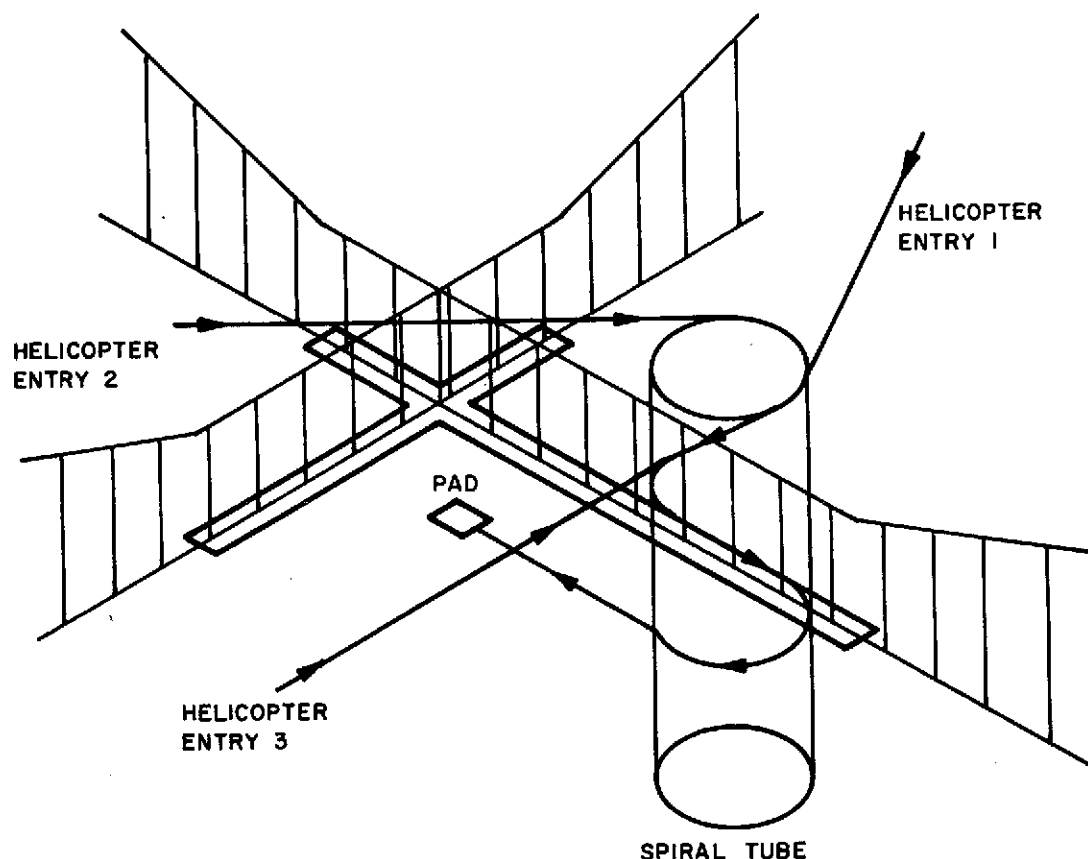
Figure 18. Spiral Descent Approach to CTOL Airport.

CTOL airport, with rotorcraft entries occurring above the CTOL approach/departure patterns. The spiral descent has most of the advantages of a vertical descent, but requires less power, maintains forward airspeed and controllability, and avoids the

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vortex ring state. The spiral is not restricted to CTOL airports, but can be applied to single or multiple pad V-ports as well, with provisions for a missed approach (Fig. 19).

2.4.3 TRAFFIC INFORMATION SYSTEM

A key element of the independent VTOL route system is the requirement for a reliable traffic information system. Since it will not be possible nor equitable to prohibit
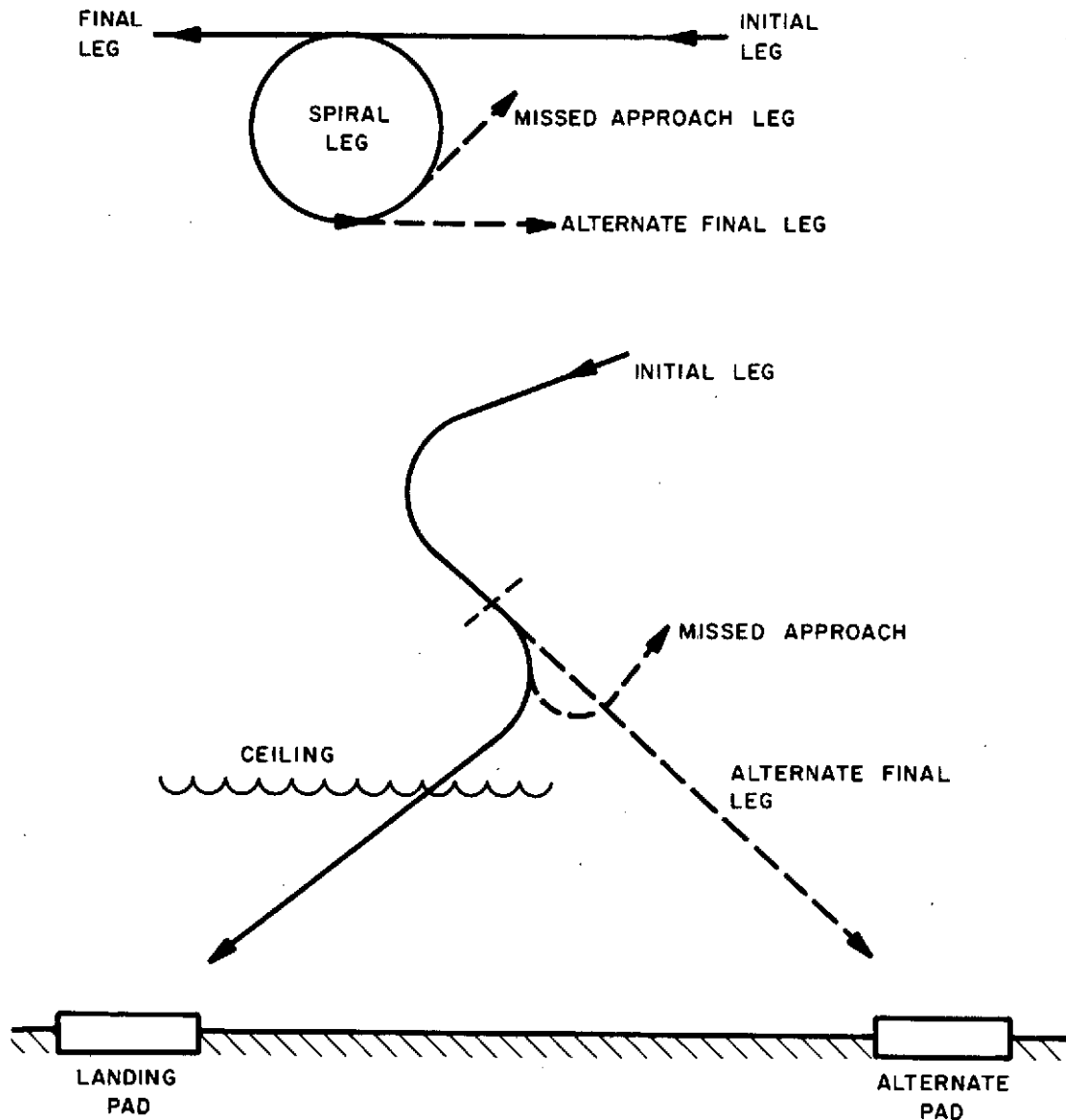
Figure 19. Spiral Descent Approach to Heliport.

non-VTOL aircraft from entering the Zulu/Tango airspace, the price of admission to the system will be the equipment to "see" other equipped traffic despite restrictions to visibility. Users of the low altitude structure will have to provide their own separation because they will be below ATC radar coverage a large percentage of the time. This requires some type of self-contained traffic information system or collision avoidance system (CAS) in order to operate IFR. Several possibilities being considered for such a system are shown in Table 7. To operate independent of ATC at higher altitudes will require dedicated airspace which again could not be justified unless other equally-equipped aircraft were also permitted to enter. Similarly, within a Terminal Control Area (TCA) dedicated Tango connector tubes could be established that do not require clearance from a controller, but do require CAS equipment on board. These tubes would take helicopters from cruise altitude to their low altitude structure independent of the conventional traffic.

Table 7. Possible Traffic Information Systems.

1. Synchro-dabs with ground broadcast of all traffic. (Has problem with coverage at low altitude)
2. Synchro-dabs with "listen" – CAS. (May need special interrogator or announcer for low altitude)
3. LORAN-C with random announcement by individual A/C
4. DME multilateration with random announcement by individual A/C
5. LORAN-C with time slot announcement by individual A/C
6. DME multilateration with time slot announcement by individual A/C
7. Transponder CAS
8. Time-frequency CAS

2.4.4   EXAMPLE VTOL OPERATIONS ANALYSIS FOR METROPOLITAN BOSTON

This section presents some results from an example analysis of VTOL operations in the metropolitan Boston area. It illustrates how the interrelated aspects of operations

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safety, economy, environment, VTOL/CTOL traffic, heliport location and community
noise requirements must be integrated and indicates the effect of the city-center environ-
ment on VTOL terminal operations.

In Reference 19, a steepest ascent procedure was used to determine fuel-
optimal takeoff and landing paths for an intra-urban VTOL vehicle. The object was to
minimize costs associated with fuel and time, subject to safety, traffic and noise
constraints. The terminal airspace was divided into noise-restricted and nonrestricted
volumes (Fig. 20) in order to constrain the VTOL from exceeding stated criteria. Noise-
restricted zones were determined by applying the following sound energy decay law
(Ref. 20) to each noise sensitive area (hospital, residential, etc.) surrounding the
heliport:
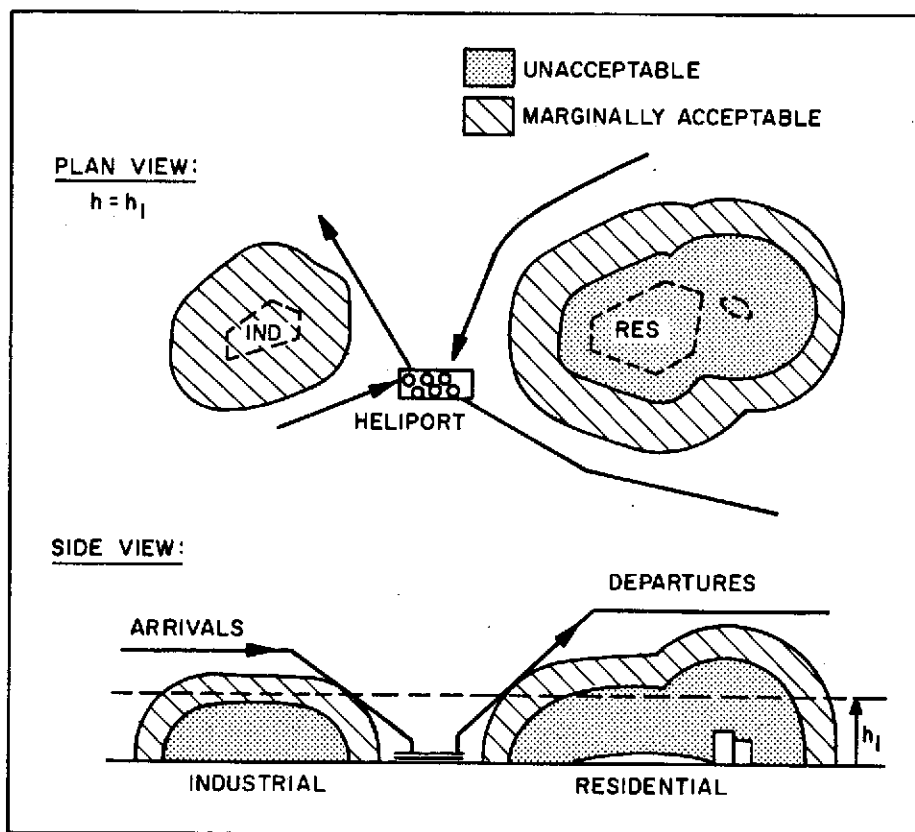
Figure 20. Community Acoustic Isolation Near Typical Heliport.

$$dB = dB_1 - 20 \log_{10}(d/d_1) \tag{5}$$

where dB_1 = known noise level at d_1 (aircraft noise rating PNdB)

dB = noise level at distance d (PNdB).

If the community response criteria is known, then this equation allows the calculation of the distances corresponding to the allowable noise levels for each area. As shown in Figure 20, the noise-contaminated airspace is characterized by varying degrees of sensitivity which correspond to acceptable, marginally acceptable, and unacceptable noise levels (Ref. 21). The degrees of sensitivity are established to account for uncertainties in the anticipated community response since reaction to noise varies widely from person to person. Suitable corrections may be included to account for attenuation characteristics, number of flight operations per hour, and time of day.

Obstacle clearance is provided by requiring aircraft to operate outside the restricted cylindrical volumes of airspace that result from assigning lateral and vertical clearances to each major obstacle in the terminal area. In the immediate vicinity of the vertiport where this requirement would be impractical, approach clearance surfaces are used to specify the minimum descent angle that an aircraft must maintain in order to clear surrounding obstacles during an approach to landing. Figure 21 indicates the obstacle clearance requirements for the final phase of an instrument approach to a potential heliport site servicing downtown Boston (Ref. 21). The figure indicates the minimum permissable descent angle for all approach azimuths; a 10° descent angle satisfies the clearance requirements in most instances.
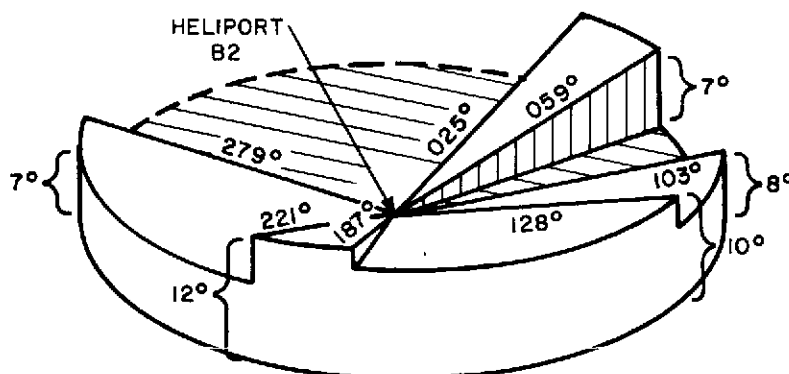
Figure 21. Restricted Airspace for VTOL Approaches to City-Center Heliport.

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A satisfactory model of the terminal airspace utilization may be realized by examining several altitude plans at 500-ft intervals up to 2000 ft. Figure 22 shows the airspace utilization chart at an altitude of 500 ft for metropolitan Boston (Ref. 22). It illustrates the influence of noise and obstacle constraints on VTOL operation at the proposed heliport site. The major constraint at low altitudes is clearly noise, and

OBSTACLE RESTRICTIONS AT 500 FT   NOISE ALLOWABLE AT 500 FT

NOISE RESTRICTED AT 500 FT   UNRESTRICTED AREA
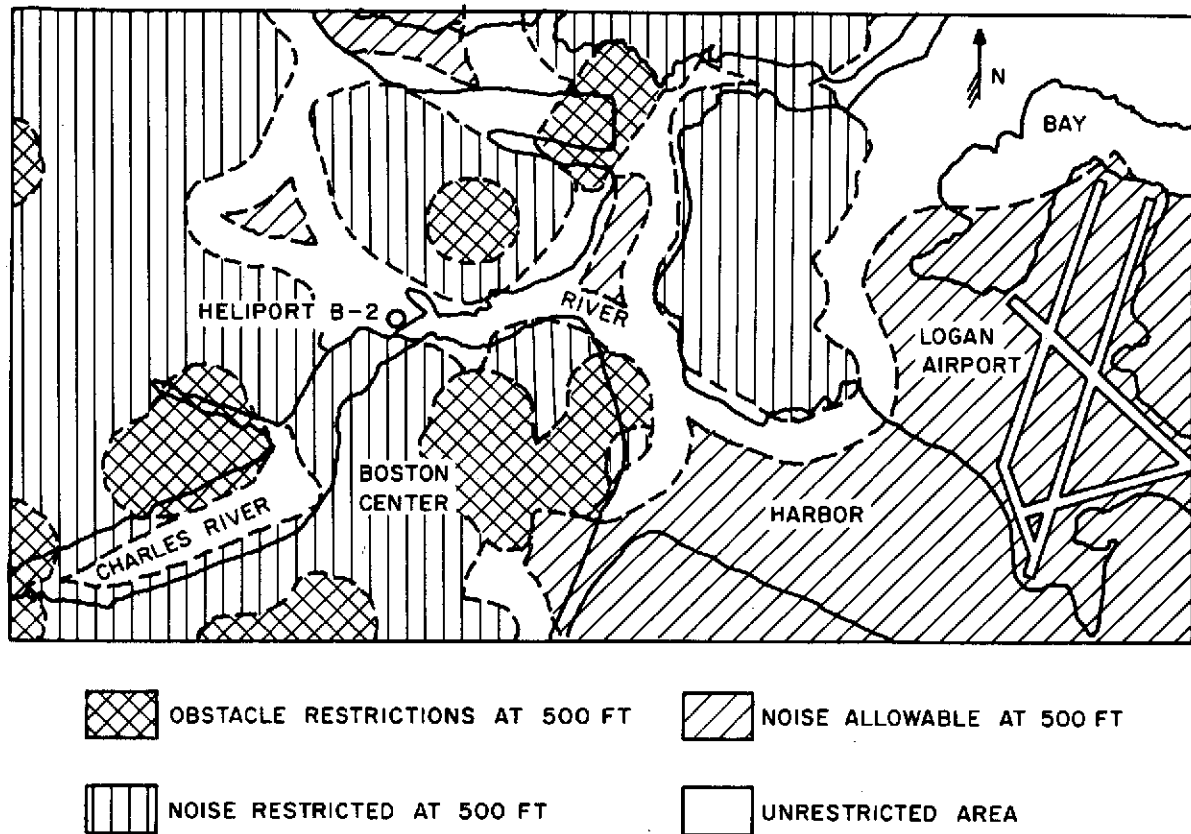
Figure 22. Boston Airspace Utilization at 500-ft MSL.

there is little variation in the noise-contaminated airspace between ground level and 500 ft. Air access is severely limited at all potential heliport sites and consequently operation in the marginal noise zones cannot be avoided at low altitudes.

Clearly, the tradeoff between proximity to the central business district and community response is of considerable importance in implementing VTOL operations. Since the advantages of VTOL aircraft accrue from operations near the city center, every effort should be made to reduce aircraft noise. It was found that at the higher

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altitudes, generally above 1000 feet, the noise restrictions diminish rapidly until at
2000 feet practically no noise-contaminated airspace remains.

The airspace utilization charts permit the synthesis of approach and departure
paths by routing the VTOL around obstacles and between the most critical noise zones in
the terminal area. In selecting the flight paths, a compromise is necessary between the
opposing requirements of steep glide slope angles for noise abatement purposes and shallow
glide slope angles for aircraft controllability and fuel consumption considerations. There-
fore, the minimum glide slope angles that allow operation out of the marginally acceptable
zones are specified, except where the noise constraint predominates (usually < 1000 feet).
Figure 23 shows the resulting approach paths to heliport B-2. Curvilinear paths with
steep and variable glide slope angles are essential to avoid obstructions and noise sensi-
tive zones in the metropolitan area. In almost all cases, a 15° final approach angle was
required in order to reduce the noise impact on the surrounding communities. Since the
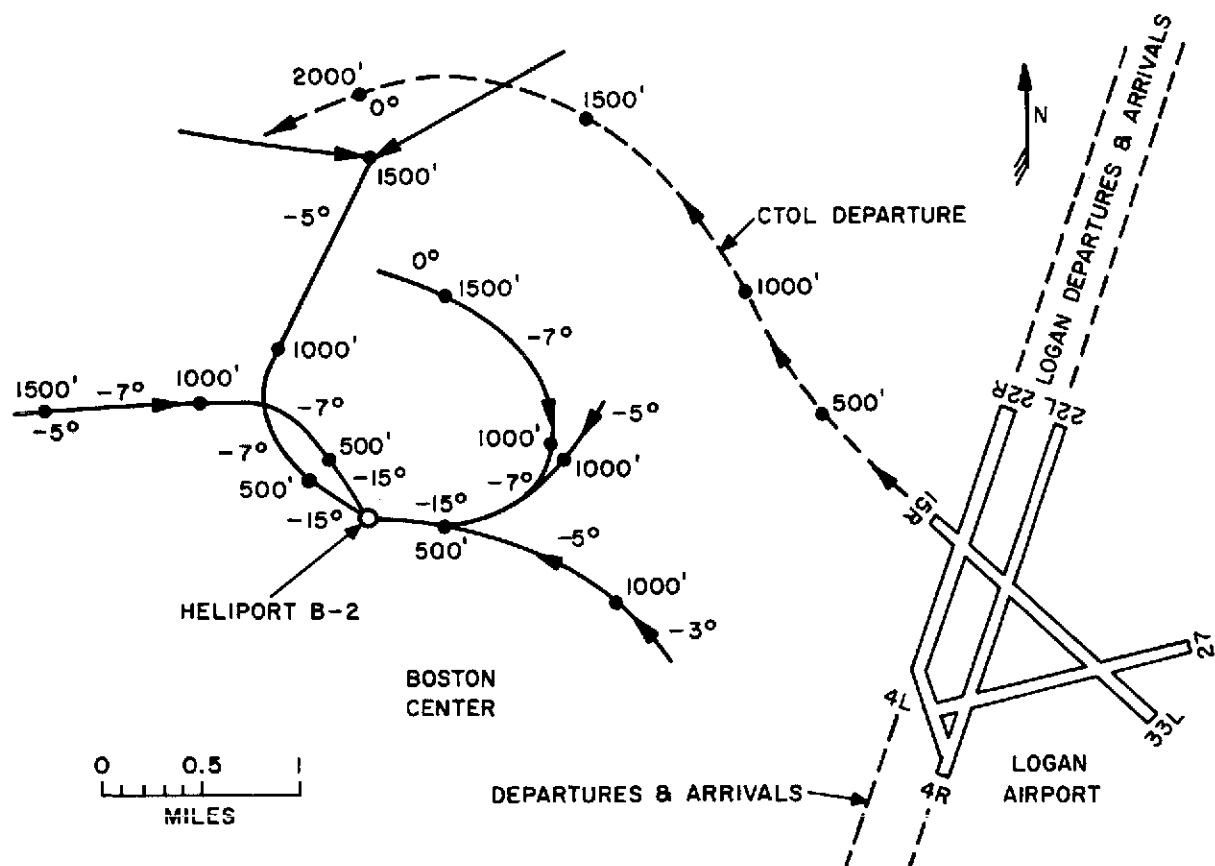
Figure 23. VTOL Curved Approach Paths to Heliport B-2 in Boston.

maximum angle required for obstacle clearances at this heliport is 12° (Fig. 21), the final descent angle is actually specified for noise abatement reasons. A comparison of Figures 22 and 23 shows that in order to avoid the noise sensitivity zones, narrow approach corridors must be established which only allow lateral deviations of about 300 feet about the nominal path. Finally, none of the sites examined have omnidirectional approach capability. The noise and obstacle constraints severely restrict air access near the city center.

2.5   COMMERCIAL VTOL NAVIGATION REQUIREMENTS

The previous development and analysis of VTOL commercial operations has indicated a number of requirements for the navigation and guidance system. The basic requirement is to provide VTOL operations over airways, approach paths, and landing facilities that are independent of, and non-conflicting with CTOL operations. This section discusses the avionics requirements in more detail.

2.5.1   INFORMATION REQUIREMENTS

The onboard and ground based systems must provide the following types of information to the pilot of a VTOL aircraft in all-weather commercial operations:

- Aircraft Status – basic information which affects the aircraft's ability to takeoff, cruise and land safely (fuel status, loading conditions, power plant performance, etc.).

- Systems Status – required to monitor and manage the operational status of all avionics and other subsystems (guidance, communications, control, etc.).

- Situation Information – required to make valid judgments regarding future actions (present track, speed, altitude, vertical velocity, time, aircraft position and any error in position).

- Command Information – required to efficiently control the aircraft's flight path (error in expected time of arrival, start of climb and descent points, steering commands, power changes).

- Special Navigation Procedures – needed to cope with a variety of special procedures involving computation, analysis and judgment (alternate routings, slant tracks, control time maneuvers).

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- Special Operational Procedures - required to comply with special noise abatement procedures during takeoff and climbout, and speed and noise restrictions during the approach and landing phase.

- Environmental Data - significant flight path variables are influenced by ambient temperature, wind direction and velocity, atmospheric pressure, density altitude, and natural hazards (ice, restrictions to visibility and turbulence).

- Hazard Avoidance - to safely manage the aircraft's flight path requires knowledge of the heliport situation, presence of turbulence, location of obstacles, and proximity to other aircraft.

- ATC-Related Control Information - requires information about radius of turn, rate of closure, proximity to other aircraft, intentions of aircraft approaching a conflict situation, terminal situation at expected time of arrival, and path stretching and speed control capabilities.

- Communications — Navigation/ATC Related - the ability to request, receive, revise, acknowledge, and evaluate clearance and instructions.

A variety of navigation systems which provide one or more of the above classes of information are in operation and/or under development. These systems are discussed in Section 3. A general listing of the required features for the VTOL navigation system is presented in Table 8. This table serves as a preliminary checklist for evaluating the existing and planned systems described in Section 3.

Table 8. Preliminary Navigation Requirements Checklist.

Non-Saturable	Time Independent
Minimize Nav. Frequency	Map Referenced
Line-of-Sight Independent	Common Output Format
Area Coverage	Growth Oriented
Real Time	Adaptive Flight Path Capability
All Weather	
Minimal Number of Ground Stations	Generate ATC Surveillance Data
Flexible to ATC Route Structure/Vector	Compatible with Information Needs
	Satisfy Accuracy Constraint

Many of the requirements in Table 8 are qualitative and/or relative in nature and are not amenable to the establishment of quantitative bounds. A brief discussion of each item in the table is presented below:

- **Non-Saturable**

  Certain navigation systems can accommodate only a limited number of users simultaneously, or the system accommodates users at a limited rate. These limits can constrain the navigation and guidance system. For example, a DME station saturates when interrogated by more than about 200 aircraft; receiver sensitivity is reduced when the interrogation rate is too high, thereby cutting off service to more distant users. Conventional ILS glide paths can handle only one aircraft on final approach at a time because of multipath errors created by reflection from the aircraft.

- **Minimize Nav. Frequency**

  Radio navigation systems have portions of the frequency spectrum dedicated to them. This load on the available spectrum is measured by the required bandwidth. VOR is a particularly heavy user because each ground station is on a different frequency. Omega is good because all stations around the world time-share a few common frequencies.

- **Line-of-Sight Independent**

  Very high frequency radio energy travels only in straight lines. Ground-based, high frequency systems are therefore range limited by the altitude of the user. Satellite systems avoid the problem by placing the station at very high altitude. At very low frequency the Earth and the ionosphere form a wave guide that propagates the energy around obstacles following Earth's curvature.

- **Area Coverage**

  Several factors affect the area coverage of a navigation system. Line-of-sight has already been considered. The power level of radio transmitters is also important and can be highly directive. Coverage may also be affected by the geometry of the transmitting stations. Hyperbolic systems offer no information to an aircraft which is on the extended baseline of a station pair.

- **Real Time**

  Certain navigation systems do not provide continuous position information. Omega, for example, only gives a position fix every 10 seconds. Satellite systems will probably give position fixes at a much slower rate. There is also a delay for signal processing and transmission between the time at which the position fix was taken and the time at which it is available. For satellites this delay will be several seconds. Other systems such as DME and Loran, require a delay for lock-on before navigation information is available.

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- **All Weather**

  Several radio navigation systems give degraded performance under certain weather conditions. Flight through rain or snow causes precipitation static that in turn causes loss of low frequency signals received with electrostatic antennas. The problem can be solved by using a loop antenna, but the direction to the station must be known to correct for the 180-degree phase shift caused by loop rotation. Snow on the ground distorts an ILS glide slope. Solar ionospheric disturbances can strongly affect radio transmission at certain frequencies.

- **Minimal Number of Ground Stations**

  The installation and maintenance cost of a navigation system is related to the number of ground stations, which ranges from none for inertial systems to several hundred for VOR navigation.

- **Flexible to ATC Route Structure/Vector**

  All area navigation systems provide this type of flexibility. The conventional ILS is an example of a system which does not, since there is only one path along which it can be used.

- **Time Independent**

  Some systems have markedly different accuracy depending upon the time of day. One primary reason is due to the change in the nature of the ionosphere in sunlight as opposed to shadow. Omega accuracy varies from roughly one mile in daylight to approximately two miles at night. Loran has a similar characteristic.

- **Map Referenced**

  Most systems could be used to give position in latitude and longitude map coordinates, but only at considerable expense in onboard computation. VOR/DME, for example, gives rho-theta coordinates relative to a VORTAC station. Automatic conversion to map coordinates requires storage of the latitude, longitude and altitude coordinates of the VORTAC stations and a coordinate transformation. The computation is slightly easier for hyperbolic systems because there is no altitude correction and there are fewer ground coordinates to be stored.

- **Common Output Format**

  ARINC specifications have favored output in the form of track relative to selected waypoints. As with the previous consideration, it is possible to do this with most systems, but it may be more difficult with some. The coordinates used for waypoint insertion will probably vary from system to system.

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- **Growth Oriented**

  VOR coverage growth is limited by bandwidth; continued channel splitting will be limited to preclude signal overlap. The microwave LGS is growth-oriented from the simplest configuration to the most advanced.

- **Adaptive Flight Path Capability**

  This refers to the difficulty involved in route changes during flight. The comments under "Map Referenced" and "Common Output Format" also apply here.

- **Generate ATC Surveillance Data**

  The repeatability and accuracy of position coordinates given by the system is the major factor that determines whether or not it could serve as the data base for surveillance. If the system can resolve two aircraft with an accuracy of under a mile it could probably qualify.

- **Compatible with Information Needs**

  Certain navaids provide only limited information and alone cannot satisfy all the requirements. Examples of this are marker beacons which only give a single position fix and conventional ILSs which only establish position along a line. These may not be compatible with curved approaches that are shifted in time to accommodate changing wind or environmental constraints.

- **Satisfy Accuracy Constraint**

  The position and/or velocity accuracy of each system is a primary consideration. It should be specified in terms of a 95 percent likelihood in appropriate units.

2.5.2   ENROUTE/TERMINAL REQUIREMENTS

The navigation system must provide accurate and continuous position and course guidance information to all interested users under all weather conditions. The VTOL navigation requirements are summarized below in terms of the operational functions (Ref. 23) in Table 9.

- **Route Guidance**

  Increased enroute traffic, multiple VTOL terminals, short stage lengths, and CTOL traffic suggest that navigation via fixed routes must be replaced by a more flexible area navigation system. The requirement for an RNAV system further suggests the necessity for a pictorial navigation/position display.

Table 9. Enroute/Terminal Navigation Requirements Summary.

Function	Mode	Enroute Coverage	Terminal Coverage	Capacity Required	Outputs	Accuracy Factors
Route Guidance	RNAV	Cruise Alt. NE Corridor	Low Alt. <25 Miles	Cooperative: High Self-contained: Low	Position Course Deviation Nav. Command	Operational Environment
Vertical Guidance	Terminal & Enroute	"	"	Cooperative: High Self-contained: Low	Position Course Deviation Altitude Command	Separation Standards
Autopilot Coupling	All Functions	"	"	---	System Monitor	Data Update Rate
Collision Avoidance	Cooperative System	"	"	Low	Hazard Location Command Man-euver Course Return	Safety Standards
Traffic Information	Cooperative System	"	"	Low	In-Trail Commands	

- Vertical Guidance

  In the current system, no guidance is provided in the vertical plane except for the ILS glide slope. With increased traffic loads, particularly in the terminal areas, and as airspace utilization becomes more critical, it will become necessary to provide precise vertical guidance during ascent and descent. The vertical guidance information could be either self-generated or established from external sources.

- Autopilot Coupling

  Any navigation system selected must be capable of operating with the vehicle's autopilot. Complete three-axis vehicle control with pre-programmed lateral and vertical maneuvering commands appears to be an essential VTOL requirement. Additional complexity results when the automatic flight control system must provide long duration vertical ascent and descent guidance and during hovering.

- Collision Avoidance

  In order to achieve independent operation, the system must be capable of providing the pilot with information to ensure safe operation of vehicles. More advanced systems should provide appropriate display information to indicate the form and direction of escape maneuvers. Appropriate consideration must be given to the variety of interacting vehicles and their differing speed and maneuverability characteristics. Resumption of normal navigation must be expeditiously accomplished following the traffic avoidance maneuver. Integration of the CAS function and the basic navigation function may be possible using a cooperative navigation system.

- Traffic Information

  A different aspect of the vehicle proximity guidance is the requirement to maintain separation of aircraft in trail either enroute or in the terminal area. The return to the aircraft of the responsibility for maintaining vehicle separation even under IFR conditions represents a departure from current procedures. This approach may be necessary for high traffic densities and for independent VTOL operations.

Reliable navigation coverage must exist for all operating areas of the VTOL system. Enroute navigation coverage should be continuously available for all altitudes from the minimum enroute altitude for the pure helicopter to the maximum cruising altitude of the compound helicopter throughout the Northeast Corridor. The minimum enroute altitude may be as low as 1000 feet AGL in some areas. Reliable navigation must exist despite terrain or obstacle shielding and despite precipitation or atmospheric effects.

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Terminal area coverage requirements are similar to the enroute requirements except that there is increased emphasis on lower altitude coverage in metropolitan areas. The terminal area extends approximately 25 miles from the landing site. Altitude coverage may be required below 1000 feet in many areas.

Any passive navigation system such as the VOR has unlimited capacity. Likewise, completely self-contained systems cannot be saturated. However, two-way navigation systems such as DME have finite limits as to the number of users. Any two-way system must be capable of supporting all airborne vehicles desiring to use the system.

Pilot display requirements include a direct readout of current position and course deviation. Such a system must permit the pilot to operate in an area navigation environment and to fly any preselected courses within the desired area. Integration of terrain, obstacles, hazardous weather conditions and conflicting aircraft into the navigation display is desirable.

As indicated in the table, several factors have an impact on the navigation system accuracy:

- Operational Environment

  The basic purpose of the navigation system is to allow the vehicle to travel from point to point conveniently and efficiently in all weather. Further, the navigation system must allow routine operations in conformance to an established schedule in order to make the VTOL operation commercially feasible.

- Separation Standards

  Current radar separation standards must be reexamined in light of the increased traffic demands and advancements in vehicle and avionics technology. All factors suggest the desirability of reducing the VTOL separations in order to increase system capacity; however, the feasibility will have to be demonstrated. Any reduction in separation standards implies a corresponding requirement of increased navigation system accuracy and an onboard proximity warning or conflict detection system.

- Data Update Rate

  The position accuracy is directly related to the navigation system data update rate, which becomes increasingly more important at higher speeds. Solutions to the problem involve tradeoffs between passive versus active navigation technologies. Passive navigation systems such as VOR or Omega provide position information at a fixed rate. Two-way navigation systems such as DME or TACAN

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have a finite limit to the number of simultaneous users and a finite update cycle time. However, except under conditions of saturation, the update cycle time is low and the user is under the impression of receiving continuous navigation information. The systems most affected by update rate are self-contained such as an inertial platform, which accumulates a position error over time until an external update signal is provided.

2.5.3 APPROACH/LANDING REQUIREMENTS

The VTOL avionics system must provide landing and takeoff guidance to acceptable weather minima at each of the designated landing sites. The approach, landing and takeoff requirements for VTOL are discussed below in terms of the necessary functions (Ref. 23) shown in Table 10.

- Variable Approach Paths

    In order to provide increased flexibility at the VTOL landing sites, multiple directions of approach should be available under the minimum weather conditions. To minimize equipment costs (airborne and ground), a single navigation system should provide the information for all of the multiple approaches.

    To further enhance the traffic flow, traffic sequencing, and integration with CTOL vehicles at the major terminals, multiple approach paths and a variable glide slope angle should be selectable.

- Takeoff Guidance

    The terminal guidance systems will also be required to provide takeoff/departure guidance. Variable course and ascent paths must be available to permit the vehicles to efficiently enter the enroute (or neighboring terminal) navigation system. Guidance in the vertical plane should be considered as essential for takeoff as for landing.

Table 10. Approach/Landing/Takeoff Requirements Summary.

Function	Mode	Coverage	Capacity Required	Display	Accuracy Factors
Variable Approach Paths	Automatic	Low Altitude <5 Miles	Moderate	Path Deviation Command Guidance	Separation Standards
Takeoff Guidance	Automatic	Low Altitude <5 Miles	Moderate	Path Deviation Command Guidance	Traffic Density

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Obstacle clearance and avoidance will become a more active function with the advent of VTOL operations. As flights into less prepared sites and enroute operations at low altitudes increase, an automatic and positive means of obstacle and terrain avoidance is required. Potentially hazardous conditions must be displayed to the pilot in a manner so that he can safely react and correct the situation.

Geographic coverage must be available within the vicinity of each landing site. Range of coverage should extend beyond the point of interception of the final approach course. Altitude coverage should exist above the final approach interception altitude and continue down to the surface. Precipitation, terrain, and obstacle shielding effects should be minimized.

The capacity of the navigation system must be sufficient to handle all potential users. Peak VTOL operations of up to 60 per hour at each VTOL port are contemplated, and at any one time each landing/takeoff system must service six to ten users per site. Thus, all-weather capacity at each V-port must equal or exceed current CTOL IFR maximums and also provide for future growth.

An integrated display takeoff/landing/enroute navigation course information seems appropriate for VTOL operations. Two-dimensional course deviation information and flight path progress information should be provided for landing, takeoff and missed approach guidance.

Even though CTOL vehicles will not be using the VTOL landing sites there will be many joint use airports. Consequently, it's very desirable that the VTOL and CTOL landing/takeoff systems be compatible, and eliminate the need for VTOL aircraft to carry two landing systems, or for the CTOL airports to install two landing systems. The same basic equipment should provide the appropriate flight path guidance which best meets the performance characteristics of each vehicle.

Two related accuracy factors are separation standards and traffic density. Currently, under positive terminal radar control, all IFR operations require three miles longitudinal separation and one mile lateral separation (parallel runways). Reduction of these separation standards will require a corresponding increase in landing/takeoff guidance accuracy. Directly related to the separation standard problem is the amount

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of traffic and its performance characteristics. High traffic densities are the incentive to reduced separation standards. Variation of approach and departure speeds tend to increase separation requirements.

2.5.4 QUANTITATIVE NAVIGATION REQUIREMENTS SUMMARY

Many of the requirements defined in the previous discussions have been presented qualitatively. Quantitative requirements for certain parameters in each of the various phases of operation are summarized in Table 11.

The requirements in Table 11 are presented to be representative of the majority of anticipated commercial VTOL operations. However, it must be emphasized that each specific operation will require detailed evaluations to establish its own precise navigation requirements. In a few situations, these may be considerably more restrictive than the guidelines presented herein. But, if the general requirements were to accommodate every foreseeable alternative, they would be far too restrictive for the majority of users, and consequently much too expensive as well.

2.5.4.1 RANGE REQUIREMENTS

The range requirements are based on the premise that appropriate navigation information should be available throughout each particular phase of operation. The takeoff and landing operations are considered to be complete within a 5 nm radius of the heliport, which is the same radius as a conventional airport control zone. The terminal area was defined by a radius of 25 nm for purposes of this study. Complete navigation information should be available throughout the range of cruise operation.

2.5.4.2 COVERAGE REQUIREMENTS — AZIMUTH AND ELEVATION

The coverage requirements are based on the premise stated above; i.e., that navigation information should be available throughout the entire phase of operation. The coverage requirement for elevation in the landing phase does not exceed 20° because there has been no general need established for steeper approaches. The 20° applies to the sloped portion of the approach only and assumes that any final vertical segment, spiral tube, hover or air taxi, takes place within the $0-20^\circ$ coverage. (Note that the apex of the angle would not be at the touchdown point in these cases.)

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Table 11. Quantitative Navigation Requirements Summary.

Parameter	Takeoff and Landing	Terminal Area	Cruise
1. Range Requirements	5 nm	25 nm	complete
2. Coverage Requirements Elevation Azimuth	0 – 20° ±90°	500 – 10,000 ft All	1500 – 30,000 ft All
3. Requirements for Operation in Proximity of Obstacles	to within 500 ft	0.5 nm minimum separation	2 nm minimum separation
4. Accuracy Requirements: Range Velocity Angular	25 ft 2 kt 0.05°	500 ft 5 kt	2000 ft 10 kt
5. Multiple Aircraft Requirements	1 landing/min 1 nm longi- tudinal spacing	500 peak airborne count	----
6. Multiple Pad Requirements	400 – 800 ft spacing	----	----
7. Inertial Smoothing Requirements	2 kt INS for velocity control	Depends on navaid	
8. Reliability/Redundancy Requirements	Cat. V – II – Dual autopilot or autopilot plus independent monitor Cat. V – III – Triple redundancy		
9. Update Rate Requirements	1 sec	4 sec	10 sec
10. Data Link Requirements	8000 bits/sec	8000 bits/sec	8000 bits/sec
11. Ground/Air System Tradeoff	Need Both		
12. Requirements for Signal Continuity and Fidelity, including Proximity of Obstacles	No Multipath Use ICAO ILS standards	Need study of urban RF interference	----
13. Inertial/Radio-Inertial Requirements	2 kt INS for velocity control	Lower quality INS satisfactory with radio update	

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The azimuth coverage has been limited to $\pm 90^{\circ}$ by the fact that actual approach paths to proposed sites do not arrive from all directions; constraints imposed by noise, traffic and obstructions limit the possible approach directions, hence a 360°-azimuth coverage requirement in the landing phase is too restrictive. Experience with ILS and MLS has shown that it is very difficult to achieve large azimuth coverage, avoid multipath, and meet accuracy requirements simultaneously. (The former FAA requirement for all-azimuth localizer coverage was reduced to 35° for this reason.) RTCA Special Committee 117 called for $\pm 60^{\circ}$ for Cat III MLS to accommodate CTOL curved approaches to closely spaced parallel runways. The requirement for $\pm 90^{\circ}$ is considered necessary to accommodate Cat III approaches to multiple landing pads.

Coverage in the terminal area should include all altitudes between 500 ft and 10,000 ft which are the normal extremes of terminal area operations. Coverage enroute needs to extend down to 1000 ft above ground level, where the feasibility of VTOL airways, has been demonstrated. Cruise coverage should extend to the highest altitude which might be used. The choice of 30,000 ft is above the ceiling of the rotorcraft studied here, but high enough to accommodate future advanced VTOL vehicles. However, high altitude coverage is not normally a difficult requirement for enroute navigation systems.

2.5.4.3 REQUIREMENTS FOR OPERATION IN PROXIMITY OF OBSTACLES

Helicopter requirements for separation from obstacles in the terminal and landing areas have been established by the FAA TERPS Manual (Ref. 17). The required clearance is specified by defining plane surfaces below the approach path through which no obstacles are permitted to penetrate, as illustrated in Figure 24. In the primary area, the surfaces are level in a direction perpendicular to the approach course and slope up from the heliport or missed approach point along the approach course. In the secondary area, the surfaces also slope up in a direction perpendicular to the approach course. The boundaries of the areas taper outward from the heliport as shown. For normal VTOL operations to occur in close proximity to buildings, steep and curved approaches will be necessary to meet the TERPS requirements. Consequently, obstacles will be expected near the boundaries established in the TERPS manual. The width of the primary area for a precision approach is 500 ft at the point
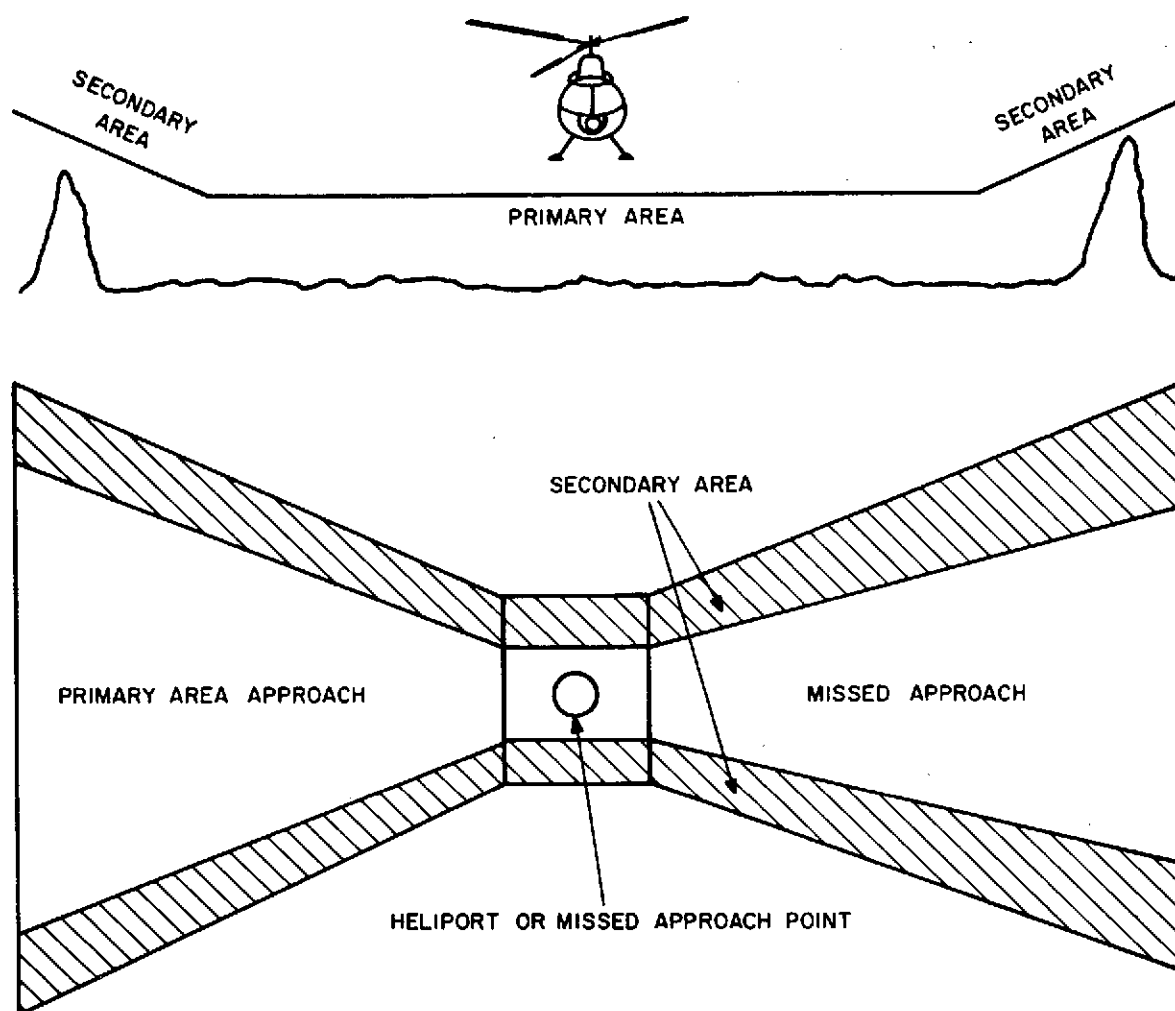
Figure 24. Clearance From Obstacles.

where the glideslope intersects the ground and tapers to a 1 nm width at a range of about 3 nm. The entries shown in Table 11 are intended to give a rough indication of the requirements specified in detail by the TERPS manual. The cruise separation was established in Section 2.4.1.

2.5.4.4 ACCURACY REQUIREMENTS

The horizontal accuracy requirements were established by using the separations described above. The landing guidance position error of 25 ft (2σ) is approximately the

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same as the goal for CTOL CAT III lateral touchdown dispersion (Ref.24). The 2 kt velocity requirement for landing is based on Reference 25, while the 10 kt cruise requirement is consistent with the FAA procedure for reporting airspeed to the nearest 10 knots and also the fact that the surveillance radar systems only estimate ground speed to 10 knots. A 5-knot velocity requirement in the terminal area was chosen as an intermediate value between cruise and landing specifications. The landing guidance angular accuracy requirement of 0.05° is slightly higher than the ICAO standard for CAT II ILS. The angular accuracy requirements for terminal and cruise are range dependent, and should be accurate enough to provide the linear accuracy given in the table. Vertical accuracy is partially covered by specification of the glide slope requirement. Absolute altitude should be known to one part in one hundred which is available from state of the art radar altimeters. Near touchdown the vertical speed should be known to 0.2 ft/sec. A typical touchdown descent rate is about 2 ft/sec and 10 percent accuracy should be adequate to prevent a hard landing.

2.5.4.5 MULTIPLE AIRCRAFT REQUIREMENTS

The landing guidance system must be able to handle aircraft at a rate of one per minute with a nominal longitudinal spacing of one nm, based on a nominal final approach speed of 60 knots. As with CTOLs, the minimum separation may ultimately be limited by the presence of wake vortices from the preceding aircraft which causes the spacing to depend on aircraft size. The lack of existing information on the magnitude of the wake vortex problem for rotorcraft creates uncertainty in the spacing requirement. The terminal area peak airborne count of 500 aircraft includes CTOL traffic. Since the mean time each aircraft spends in the terminal area is under 20 minutes, an average of over 25 aircraft will enter and exit each minute to maintain the airborne count at 500.

2.5.4.6 MULTIPLE PAD REQUIREMENTS

Based on the pad sizes given in Table 1 the spacing between pads is established at 400 to 800 feet between centers, which allows for a between-pad clearance equal to one pad diameter. Simultaneous approaches to individual pads would have to be time synchronized; independent approaches would guarantee only 400-800 feet separations.

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2.5.4.7 INERTIAL SMOOTHING REQUIREMENTS

Horizontal velocity accuracy of about 2 knots is needed for display and/or control during approach and landing (Ref. 23), based on experience with inertial velocity control systems developed by the MIT Draper Laboratory. Physically, this corresponds to the uncertainty which can be tolerated in hover just prior to touchdown to avoid a dangerous landing situation. Velocity aiding is also required by Omega and LORAN navigators in order to provide the long averaging times necessary for them to achieve their quoted accuracies.

The optimum combination of inertial velocity information with external position data produces a hybrid navigator which provides both position and velocity information of better quality than is available from either component system by itself. The requirement for two knot velocity accuracy is at the output of the hybrid. Consequently, the accuracy of the input velocity information can be of lower accuracy when a hybrid combination is used.

2.5.4.8 RELIABILITY/REDUNDANCY REQUIREMENTS (CAT II, CAT III)

The requirements defined in Table 11 for CAT II and CAT III landings are the same as those developed for CTOL aircraft. The proposed VTOL precision approach categories in Table 6 were established so that the CTOL requirements could be applied to VTOL.

2.5.4.9 UPDATE RATE REQUIREMENTS

The update requirements for cruise and the terminal area are the same as the surveillance information rate used by the NAS and ARTS radar systems respectively. There is ample experimental evidence that these rates are adequate for either surveillance or pilotage. It should be emphasized that these rates apply only to position information, and it is assumed that the helicopter has a velocity control system. To elaborate this point, Figure 25 shows that position information feeds the guidance logic through the outer loop while velocity information feeds the velocity control system through the next inner loop. The innermost attitude loops are part of the attitude stabilization system. In general, the bandwidth of the inner loops is wider than the outer loops, which means that the response time of the inner loops is faster than that

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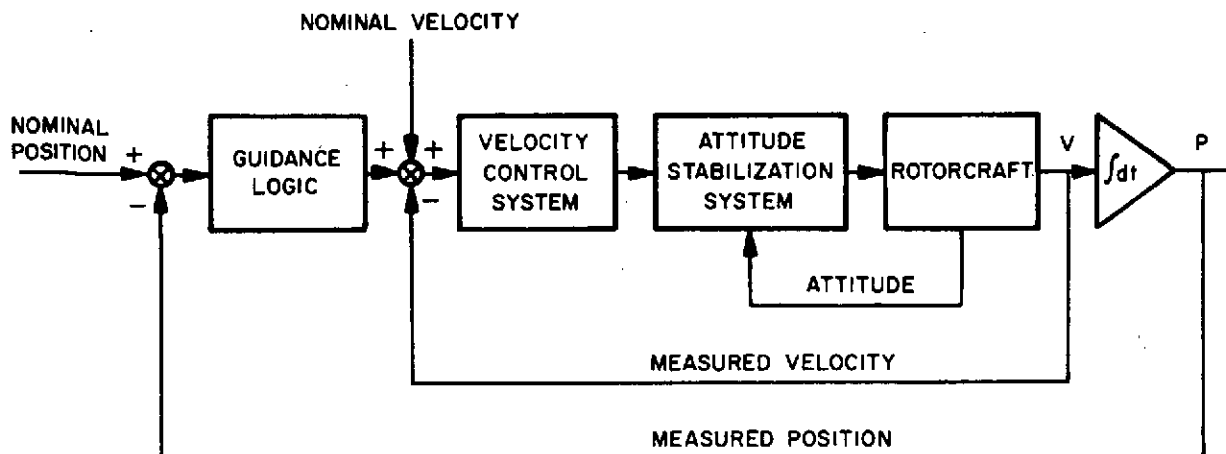
Figure 25. Helicopter Guidance and Control System.

of the outer loops. For larger helicopters the closed loop response of the attitude sta-
bilization system is limited to below 4 Hz. (Raising the loop gain above that corre-
sponding to 4 Hz causes coupling with the rotor dynamics.) The actual bandwidth is
about 1 Hz (6 rad/sec) in roll and slightly lower in pitch. Consequently, the attitude
stabilization system cannot respond faster than about 1/6 second at best, and the re-
quirement on velocity data rate does not need to exceed this value. It need not be
this fast when the onboard navigation system provides continuous airspeed, Doppler
or inertial velocity information.

The closed-loop bandwidth of the velocity control system is normally below
1 rad/sec, which means that it cannot respond to commands faster than about 1 sec.
Consequently, there is no requirement to update the position more often. Although
position updates are provided once each second, knowledge of the vehicle's position
does not lag by one second since the velocity information is used to dead-reckon
between measurements. For example, the worst position error deterioration that can
occur in one second, with velocity information of 2-knot accuracy, is about 3 feet.
For comparison, the data rate required for an unstabilized helicopter without the
velocity loop closed is 5 scans/sec for helicopter use of the MLS (Ref. 26).

2.5.4.10 DATA LINK REQUIREMENTS

The data link requirement is based on providing sufficient information for a ,

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traffic situation display in the cockpit. A complete traffic picture every four seconds can be handled by an 8 kilobit/sec transmission rate (Ref. 27). This data rate can be accommodated in a 25 kHz VHF channel. Information which could be contained in the message includes aircraft coordinates, altitude, identification, ground speed from ground tracking data, and sequencing and spacing commands. Map information with approach and departure routes plus alphanumeric text for altimeter setting, heliport conditions, etc. can also be included.

2.5.4.11 GROUND/AIR SYSTEM TRADEOFF

Self-contained airborne navigation systems such as inertial, Doppler and air data provide velocity information, whereas ground radio systems such as MLS, multi-lateration, Loran, Omega, and VOR/DME provide position information. Both position and velocity information of the required accuracy are necessary for the VTOL navigator. Position can be inferred from velocity measurements by integration, but the errors build up with time. For example, the two knot accuracy requirement on velocity integrates into a position error equal to the landing accuracy requirement (25 feet) in less than 10 seconds. On the other hand, it is possible to estimate velocity from position by differentiation; but this process introduces high frequency errors. To obtain a velocity update with two knot accuracy every 1/4 second by differencing two position measurements requires an accuracy of better than one foot. Consequently, it would appear that both ground and air systems are desired; the information from both can be combined optimally to form a hybrid system. The basic argument for a hybrid navigator is the simultaneous need for horizontal velocity information of two knot accuracy along with position accuracy of 25 feet. To obtain both position and velocity from a ground system imposes a burdensome accuracy requirement and, furthermore, signal loss from a ground system providing both would leave the helicopter in a compromising control situation.

2.5.4.12 REQUIREMENTS FOR SIGNAL CONTINUITY AND FIDELITY, INCLUDING PROXIMITY OF OBSTACLES

For takeoff and landing guidance, the system should meet the standards established by ICAO for the applicable CAT II or CAT III landing category. This essentially requires that there be no multipath problems. The enroute requirements depend

on the specific navigation system and are discussed in the appropriate sections of Section 3. Some of the candidate low frequency systems require study of the effect of urban RF interference. Specifically, 60 and 400 Hz interference may be a problem with Omega. Flight near power lines might cause signal loss of both Loran and Omega.

2.5.4.13 INERTIAL/RADIO-INERTIAL REQUIREMENTS

The requirement for an inertial hybrid is based on the need for velocity information with an accuracy of about 2 knots for control during the approach and landing. The accuracy requirement can be met by a low cost inertial package. Choice of inertial over air data or Doppler is based on cost and reliability: Attitude information is already needed for IFR flight and a computer is necessary to provide the area navigation computations; the only additional cost is the accelerometers. Airspeed and heading information could be satisfactory enroute but the information is poor at low airspeeds near the ground. Inertial hybrid navigators should be updated at intervals less than one tenth the Schuler period (< 8 min) because the error buildup during this interval is very small in comparison to the long-term drift normally used as a figure of merit. As explained in References 25 and 28, the inertial system can have long-term drift much greater than 2 knots and still provide 2 knot velocity information when position updates are available.

SECTION 3

NAVIGATION SYSTEMS TECHNOLOGY

This section describes each of the leading navigation system candidates, and compares their principal advantages/disadvantages for commercial VTOL operations. Existing and planned radio navaids (VOR, DME, Omega, etc.) are discussed first, followed by dead-reckoning (INS, Doppler), ground surveillance, area navigation (RNAV), hybrid, traffic information, and collision avoidance systems.

3.1   RADIO NAVIGATION

Radio navigation systems require communication between the aircraft and one or more surface stations. Because of this dependency, these systems have been slow in implementation and have remained in use long after the advancing state of the art has made them technologically obsolete. Improvements in a system can only be made if they are compatible with the existing equipment. Table 12 shows the major systems that have been developed over the years that either are in actual use by a substantial number of aircraft or have been seriously proposed for VTOL operations.

3.1.1   DIRECTION FINDING

Direction finding (Ref. 24) represents the earliest use of radio for navigational purposes. With the proper receiving equipment, the direction to any transmitter can be found. The main drawback of direction finding is that elaborate receiving equipment must be used to obtain the best accuracy.

Direction finders for aircraft navigation fall into two classes: ground-based and airborne. Ground-based direction finders take bearings on airborne transmitters and the pilot is then advised of his bearing from the ground station. Such stations can afford the necessary complex equipment, but the operation is cumbersome, time-consuming, and requires an airborne transmitter and communication link.

Airborne direction finders, which take bearings on ground transmitters, can afford only the simplest of systems and must therefore tolerate relatively large errors. However, even large bearing errors will not prevent an aircraft from homing to the ground station, although not by the most direct route. Position of an aircraft is well established when a direction finder indicates station passage. Primarily because of

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Table 12. Radio Navigation Systems.

System	Frequency	Remarks
Direction Finding	Many	Earliest radio navigation system; still in great use as a backup system due to its great flexibility.
Nondirectional Beacons	200 to 1700 kHz	In worldwide use with airborne LF/MF direction finders.
Marker Beacons	75 MHz	Used as distance markers in instrument-landing systems; previously used as check points along the airways.
VHF Omnidirectional Range (VOR)	108 to 118 MHz	International standard. Undergoing accuracy improvements and likely to remain in service for several decades.
Distance-Measuring Equipment (DME)	960 to 1215 MHz	International standard. Often colocated with VOR to form a single-site area-coverage system.
TACAN	960 to 1215 MHz	Military short range omnibearing and distance measuring system.
VORTAC		Colocation of VOR and TACAN to provide rho-theta navigation.
Decca	70 to 130 kHz	Continuous-wave hyperbolic system; used extensively in Europe by ships and fishing fleets; some use by aircraft, but Not an accepted standard.
Loran-A	2 MHz	Long-range aid developed in World War II; used by transoceanic aircraft; U.S. chains being phased out in favor of Loran-C.
Loran-C	100 kHz	Partial successor to Loran-A; longer range and improved accuracy obtained by cycle-matching techniques.
Loran-D	100 kHz	Short-range tactical system compatible with Loran-C.
Omega	10 to 14 kHz	Hyperbolic system with longer range and less accuracy than Loran-C; worldwide coverage when all 8 stations completed.

Table 12. Radio Navigation Systems (Cont.)

System	Frequency	Remarks
VLF	10 to 20 kHz	Hyperbolic systems which use both Omega signals and carrier waves of military VLF communication facilities.
Differential Omega	10 to 14 kHz	Proposed Omega system with improved accuracy for terminal area and landing navigation provided by local corrections.
Instrument Landing System (ILS)	108.1 to 111.9 MHz (Localizer) 329.3 to 335.0 MHz (Glide Slope)	International standard. Provides precision vertical and horizontal guidance along a linear approach path. Includes marker beacons.
Microwave Scanning Beam Landing Guidance System (LGS)	C-Band & K_u-Band	Proposed successor to ILS. Will provide curvilinear approach paths and wider coverage than ILS.
Flarescan	K_u-Band	Family of advanced landing systems with extended azimuth and elevation coverage; airborne selectable glide slope and sensitivity.
Tactical Landing Approach Radar (TALAR)	15.5 GHz	Microwave ILS using simple time-sharing transmitter and single receiver; portable ground station.
Simplified Aircraft ILS (SAILS)	9080 to 9160 MHz	Airborne radar tracks beacon near desired touchdown point; approach path and glide slope selected by pilot.
Remote Area Terminal System (RATS)	UHF	Airborne interrogator-computer tracks slant range and bearing to ground transponder; altitude, azimuth and barometric glide slope selectable by pilot.
Multilateration	Many	Multiple precision ranging measurements between aircraft and surveyed ground stations.

the low cost of nondirectional beacons (see Section 3.1.2), direction finders are an excellent backup aid to more precise systems; they have been valuable for helicopter IFR over water approaches to ships, oil rigs, etc. (e.g. Refs. 7, 29).

3.1.2   NONDIRECTIONAL BEACONS

The widespread use of low- and medium-frequency airborne direction finders by IFR aircraft prompted the installation of special ground stations whose sole functions are to act as omnidirectional transmitters (Ref. 24). These beacons (also known as compass locators) operate in the 200 to 1600 kHz bands, with output power ranging from 20 watts up to several kilowatts. Modern designs are entirely solid state.

In addition to the bearing information given to direction finders some distance away, such beacons have another useful property; namely, a sharp reduction in signal strength as the aircraft flies directly over the beacon, provides a specifically defined fix. The accuracy of the fix produced by this "cone of silence" is somewhat dependent on the airborne antenna; it is improved if the airborne-antenna pattern contains a null in the downward direction.

All nondirectional beacons suffer from skywave contamination, groundwave bends, and interference from thunderstorms or other stations. They have retained considerable popularity because they are inexpensive, omnidirectional, and place responsibility for accuracy entirely on the airborne receiver.

3.1.3   MARKER BEACONS

To provide better fixes along the airways, the development of marker beacons was begun in the 1930s (Ref.24). Although the marker beacon has been practically phased out as an enroute aid by the implementation of area-coverage fixing systems, it remains an essential element of the conventional instrument landing system. All marker beacons operate at 75 MHz and radiate a narrow pattern upward from the ground, with little horizontal strength, so that interference between beacons is negligible.

The transmitter is crystal-controlled, delivers up to 100 watts, and is tone modulated, with its Morse code identity indicated by gaps in the tone. The airborne receiver is a crystal-controlled superheterodyne, with its output providing an audio and/or visual indication. Complete transistorization is common; most marker receivers

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are completely contained in their indicator-lamp housings, with a total weight of about a pound.

The accuracy of the marker beacon depends on the altitude of the aircraft and on the sensitivity of the receiver. However, it was the first aircraft navigation aid to operate reliably — with no anomalies due to weather, the atmosphere or propagation, and with a minimum of ground and airborne equipment.

3.1.4   VHF OMNIDIRECTIONAL RANGE (VOR)

The VOR system was developed during the 1930s and 1940s to replace the low- and medium-frequency radio navigation system. When distance-measuring equipment (DME) is added to VOR, a rho-theta area-coverage grid system is formed. This is the standard International Civil Aviation Organization (ICAO) short-range navigation system; each VOR frequency is paired with a DME frequency, with the airborne channel selector being common to both systems. The United States VORTAC system is a VOR/DME system, which uses the DME function of the military TACAN system for distance measurement.

The VOR operates in the 108-118 MHz band with channels spaced 100 kHz apart, although the channel spacing will soon be reduced to 50 kHz. The ground station provides bearing information by transmitting two signals: 1) a directional signal that is rotated in azimuth at a rate of 30 revolutions per second, and 2) a 30 Hz omnidirectional signal. The airborne equipment comprises a horizontally-polarized antenna and a crystal-controlled superheterodyne receiver. This receiver detects the 30 Hz amplitude modulation produced by the rotating pattern and compares it with the 30 Hz frequency-modulated reference. The phase difference between these two signals is a direct measure of the aircraft bearing from the ground station.

The airborne equipment has two common types of display: one uses a servo-motor phase comparator to display the bearing directly; the bearing may be remoted by selsyns to an autopilot. Another display uses a vertical left-right needle to show angular deviation from a manually selected desired bearing. Most VOR radios also receive the 108 to 112 MHz instrument-landing-system localizer signals. Typical receivers weigh from 5 to 20 pounds, exclusive of antenna.

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The major VOR error source is site error at the ground station; this causes a bias in bearing which has a systemwide standard deviation of 1.3 degrees. Instrument accuracy of better than 1 degree is typical of airline quality receivers. Overall system accuracy at the aircraft may show an error of 4° and still be acceptable for flight. Doppler VOR can reduce site errors to the order of a half degree at a typical cost of $100,000 per transmitter. The combination of Doppler and precision VOR (to reduce receiver errors) could probably improve total system accuracy to the order of 0.25^o; however, widespread implementation of precision VOR is unlikely since airborne sets must be modified, and the ability of a pilot to maintain a course is on the order of 1°.

3.1.5   DISTANCE-MEASURING EQUIPMENT, TACAN, AND VORTAC

Distance-measuring equipment (DME) is the international standard pulse-ranging system for aircraft navigation. TACAN (Tactical Air Navigation) is a military omnibearing and distance measurement system using the same pulses and frequencies for the distance measurement function as the standard DME system. VORTAC is the coloca-tion of VOR and TACAN ground equipment to provide rho-theta navigation to both civil and military aircraft.

The airborne equipment includes an interrogator which transmits pairs of pulses on one of 126 frequencies in the 960 to 1215 MHz band. Paired pulses are used to reduce interference from other users. The ground beacon (transponder) receives these pulses and, after a 50-μsec delay, retransmits them on a frequency 63 MHz below or above the airborne transmitting frequency. The airborne receiver compares the elapsed time between transmission and reception, subtracts the 50-μsec delay, and displays the result on a meter calibrated in nautical miles.

The peak power of the transponder is in the range of 1 to 20 kilowatts. Each beacon is designed to handle at least 50 aircraft simultaneously, with 100 being a more typical number. Thus, up to 126 separate beacons are possible in any line-of-sight geographical area, with each handling 100 or more aircraft. Since each beacon's duty cycle is still only 2 percent under these conditions, sufficient capability exists to expand the system to handle much heavier traffic.

Typical airborne equipments range from 10 lb for the simplest sets to about 30 lb for the more accurate long-range sets. All circuits are typically solid state, with

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the exception of the pulsed transmitter-amplifier chain. The peak pulse power varies among airborne transmitters from 50 watts to 2 kilowatts. Displays range from calibrated voltmeters to servo-driven digital number wheels. Accuracy is limited by the type of readout, stability of beacon delay, accuracy of pulse rise times, etc. The ICAO requires an overall system accuracy of 0.5 mile or 3 percent, whichever is greater.

For reasonable distances from the VORTAC station, the major position uncertainty is due to the VOR bearing error. For this reason Dual-DME has been suggested as a more accurate utilization of the VORTAC system. One problem with this approach is that a DME beacon saturates when many more than 100 aircraft interrogate it for distance information. Also, for terminal operations at low altitude, two DME stations may not be within line-of-sight. Finally, the Dual-DME position is ambiguous, and must be resolved by dead reckoning, a third DME, a VOR bearing or other position fix.

3.1.6 DECCA

Decca is a hyperbolic navigation system developed by the British during World War II. It is extensively used by shipping in northwestern Europe, and by offshore helicopter services in the North Sea. As described in Section 2, Decca was formerly used for IFR helicopter operations by New York Airways. Decca is unique in that most chains have been privately owned; it is not an internationally standardized system.

A Decca navigation measures the differential arrival times of signals transmitted from two or more synchronized ground stations. Most Decca chains comprise a master station and three slave stations around 40 miles apart. Each station transmits a synchronized continuous-wave frequency (70-130 kHz) that bears a fixed relationship to the frequencies of the other stations (Fig. 26). Phase comparison therefore produces a family of hyperbolic lines of position where the phases are equal. The spaces between these isophase lines are called lanes. The receiver multiplies the incoming frequencies before phase comparison, resulting in a lane width on the order of 250 yards along the baseline. The intersection of two lines of position provides a fix.

Because of the low frequency, Decca is not limited by line-of-sight transmission and is therefore satisfactory for operations behind buildings and natural obstructions. However, Decca is range limited by skywave contamination to distances of about 200 nautical miles. Position accuracy (2σ) varies from below 100 yards when between

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	MASTER	84.280 KHZ	(6f)
——————	PURPLE	70.233 KHZ	(5f)
—— ——	RED	112.373 KHZ	(8f)
— — — —	GREEN	126.420 KHZ	(9f)
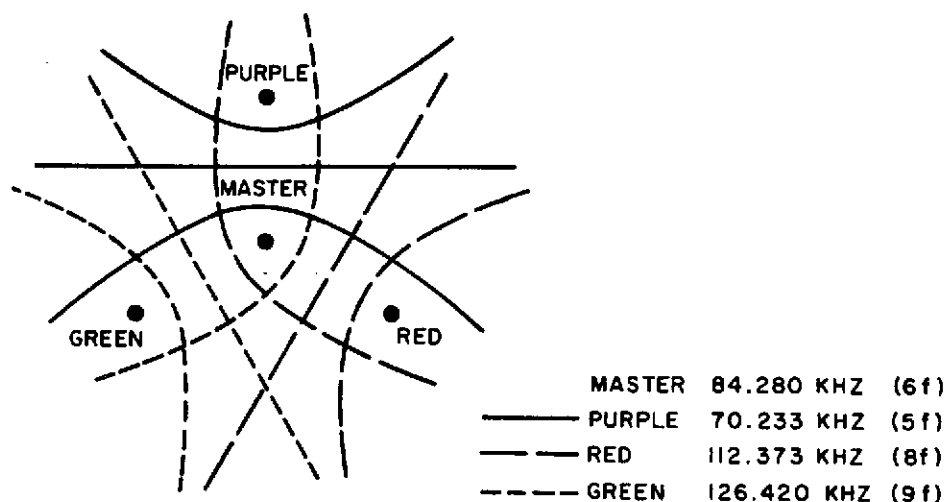
Figure 26. Typical Decca Chain.

stations on a summer day (where the geometry is good and there is no sky wave), to
several nautical miles when 200 miles away from the master station during a winter
night (where geometry is poor and sky-wave contamination is present). Although Decca
is a very attractive system from a technical viewpoint, its private ownership by a foreign
company makes its adoption unlikely for widespread use in the United States.

3.1.7 LORAN-A

Loran-A is a hyperbolic navigation system which uses pulses rather than con-
tinuous waves to avoid sky-wave contamination. A Loran chain normally comprises a
master and two slaves about 200 miles distant; it is usually installed along a coastline
to serve vehicles on or over the ocean. The United States is currently planning to
decommission all Loran-A chains in favor of Loran-C.

The master station transmits pulses on a carrier frequency from 1750-1950 kHz.
These pulses are received by each slave and rebroadcast after a fixed delay. The re-
ceiver measures the differential delay between reception of the master pulse and a
slave pulse; this time difference defines a hyperbolic line of position, with the master
and slave as foci. The intersection of two such lines, one from each slave, provides a
position fix. The typical readout is by oscilloscope observation of the time difference,
followed by manual translation to a chart on which the hyperbolic lines are preprinted.

The range of reception of Loran-A signals varies from about 500 miles at equa-
toral latitudes to about 800 miles in the arctic. The accuracy of a line of position

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depends on the geometry. Along the base line between stations, it is on the order of 1000 ft; at extreme range and at right angles to the base line, it is on the order of half a mile. The accuracy of a fix further depends on the intersection angle of the hyperbolic lines.

3.1.8   LORAN-C

Loran-C operates in the 90-110 kHz frequency band, has a longer range than Loran-A, and achieves an order of magnitude improvement in accuracy by using phase information in addition to counting pulses. The master and slave stations are separated by 600 to 800 miles. A system of 40-50 stations would be required to give world-wide coverage with Loran-C.

The transmitter operates at a fixed frequency of 100 kHz. Each pulse is designed to build up and decay slowly to keep 99 percent of the radiated energy within the assigned frequency band. Skywave contamination becomes significant about 30 μsec or 3 cycles after the beginning of the pulse so only the first three cycles are generally used for navigation. The receiver must have a very high effective selectivity because the first three cycles may be contaminated by atmospheric noise and other interference. Selectivity is obtained by tracking the received signal with a servo loop that has a long characteristic response time. For use in aircraft the receiver must have velocity information to keep the servo loop locked onto the signal.

Modern Loran-C receivers using integrated circuits feature automatic search, a weight of 25 lb, and a power consumption of 200 watts. Readout from the receiver itself is in time differences, requiring the navigator to transfer these to the corresponding hyperbolic lines on a chart. Digital computers are available which (at the price of doubling the size, weight, and cost) provide readout in latitude and longitude, together with left-right steering information and distance along track.

Atmospheric noise at the receiver is the major source of error in the Loran-C system. The accuracy depends on the signal-to-noise ratio which varies widely with range, and on the response time of the servo tracking loop. For averaging times of 100 seconds at medium range, an error of 300 feet is typical. The instantaneous accuracy could change by a factor of three in either direction depending upon actual range.

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3.1.9 LORAN-D

This tactical military system is intended for short-range service at low altitudes, where line-of-sight systems do not provide adequate coverage. It is based on, and is compatible with Loran-C. The major differences are the following:

- The base line between master and slaves is reduced.

- The radiated power is substantially less, due to smaller transmitters and lower antenna masts.

- Partly to compensate for the lower power, more pulses are radiated in each group; they are sampled at their peaks, rather than on the leading edge.

Airborne equipment is otherwise identical to that of Loran-C.

3.1.10 OMEGA

Omega is a very low frequency (VLF) hyperbolic navigation system capable of covering the entire globe with only eight ground stations. Although Omega was developed primarily for marine applications, the system has many desirable features for aircraft navigation. Four Omega stations, covering most of the western hemisphere, are in operation at North Dakota, Trinidad, Norway, and Hawaii. By 1976, additional stations are to become operational in Japan, Argentina, Tasmania and Reunion Island. The Trinidad station is to be replaced by a new facility in Liberia.

The VLF Omega signals, in the range of 10 to 14 kHz, do not penetrate the ionosphere and thus travel for exceptionally long distances. Eventually all Omega stations will use three basic frequencies: 10.2 kHz, 11.3 kHz, and 13.6 kHz. The number of frequencies is intended to reduce the ambiguity problem. In a hyperbolic system using phase comparison at 10.2 kHz, isophase lines, or lanes, are formed about every 8 nm. A two-frequency receiver, using also the 13.6 kHz lines of position, can provide lanes 24 miles apart by using the beat between 10.2 and 13.6 kHz (3.4 kHz). A three-frequency receiver improves this ambiguity to 72 miles, using the beat between 10.2 and 11.33 kHz (1.13 kHz).

The phase of the VLF signals is remarkably stable, but diurnal variation in the velocity of propagation requires compensation. The primary Omega system errors are due to inaccuracies in the signals measured by the aircraft. An extensive list and description of the Omega error sources, the resulting error magnitudes, and their general

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time-varying character has been compiled by Scott (Ref. 30). Propagation variations are a function of specific path, time of day, and time of year. Sky-wave correction models which can reduce the RMS error magnitude to less than one nm, can be applied automatically, using a small computer at the receiver.

Another major source of error is broad-band atmospheric noise at the receiver. As is the case with Loran-C, the long integration times needed to cope with poor signal-to-noise ratios make implementation difficult in fast aircraft. An inertial sensor may be employed to provide short-term corrections, or this may be provided by inputs from the aircraft's heading and Doppler navigator or airspeed.

After an equivalent amount of development, airborne Omega hardware is expected to be about the same order of size, weight, and cost as a Loran-C receiver.

3.1.11 DIFFERENTIAL OMEGA

This is a proposed technique for reducing the affect of Omega propagation errors. Ground stations at known geographic locations would measure the Omega propagation error and broadcast a correction to local aircraft, in the same manner as local barometric pressure is provided for altimeter corrections. The error due to propagation variation would be reduced to the difference in the error at the aircraft and at the reporting station, which is on the order of a half mile at a distance of 200 miles. However, an additional error might exist if the Omega correction was not current, particularly around sunrise or sunset. This correction could improve the absolute Omega accuracy from about 10,000 feet to approximately 1000 feet.

3.1.12 INSTRUMENT LANDING SYSTEM (ILS)

The Instrument Landing System (ILS) consists of a glide slope beam, a localizer beam, monitor beacons and approach lights to guide an aircraft during final approach to a particular runway. The glide slope provides UHF vertical steering signals, while the localizer provides VHF lateral steering signals; the intersection of the two beams is the straight-line glide path. Two or three marker beacons provide checks of position at approximately 4.5 miles from the runway, at the 200-ft altitude (CTOL Category I) decision height, and at the 100-ft altitude (CTOL Category II) decision height.

The glide slope antenna establishes a radiation pattern in space from which the airborne receiver derives a signal proportional to the vertical displacement from

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the glide path. This signal drives a crosspointer needle or flight director in the aircraft. The glide path is typically sloped at 3° and intercepts the runway approximately 1000 ft beyond the threshold. The localizer signal is proportional to lateral displacement from the vertical plane through the runway center line. This signal drives the left-right crosspointer needle or flight director.

The ILS has been used for 2-1/2 decades and is standardized by the ICAO. Its major limitations are caused by beam bends due to reflections from buildings, terrain, airborne aircraft, taxiing aircraft, and ground vehicles; and due to nearby radio-noise sources. The near-field character of the glide slope renders it unsuitable for landing.

3.1.13 MICROWAVE LANDING SYSTEM (MLS)

Microwave landing systems are less susceptible to spurious reflections and, apparently, are destined to replace the current VHF ILS. Prototypes have been under development and test, but the final data signal format and performance parameters are still being resolved. The scanning beam landing guidance system (LGS) proposed by the RTCA (Ref. 26) is a possible contender for the international standard which is scheduled to be chosen by ICAO in 1975.

The RTCA requirements stipulate that the guidance system should not impose limitations on any of the aircraft using it. Recognition was given to the increased size and speed of wide-body jets and supersonic aircraft, the expected growing role of V/STOL aircraft, and the rapidly increasing population of general aviation aircraft. The airborne unit obtains precision azimuth, elevation, and range data referenced to the runway, which are suitable for display to the pilot or for input to the flight control system. Provision is made for future implementation of highly automated aircraft approach and landing with maximum system integrity.

The horizontal and vertical signal coverages for several postulated LGS configurations are shown in Figure 27. These configurations, defined in Table 13, provide for various performance capabilities, categories of weather minimums, and aircraft approach profiles. The simplest system provides limited straight approach paths, while higher capability systems provide for multiple curved approach courses and curved glide paths. Although the upper coverage angle selected is 15 degrees, the capability of accommodating higher approach angles exists for possible future requirements.

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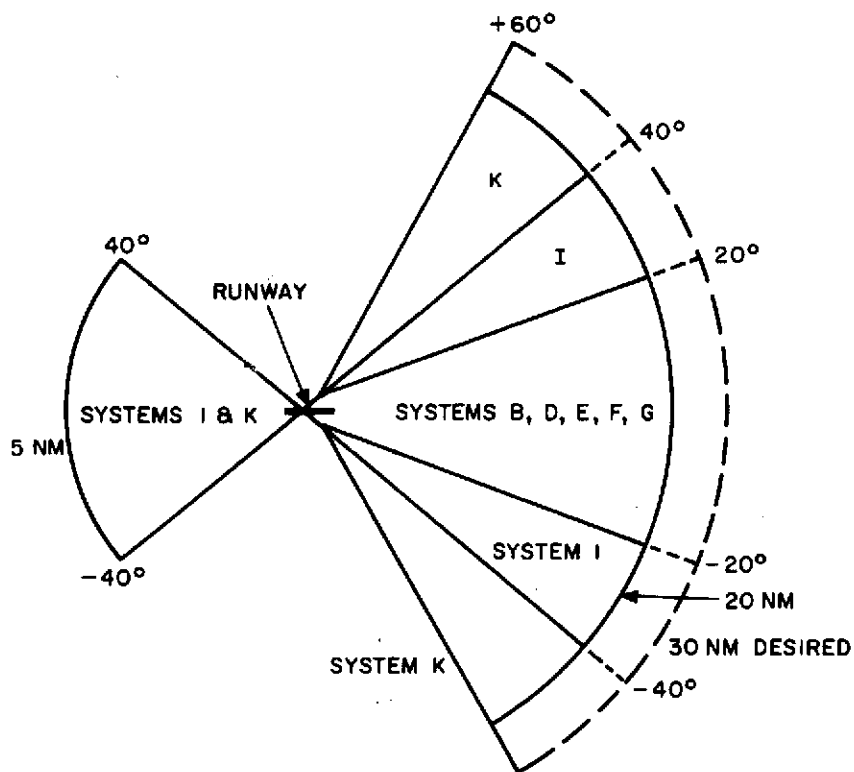
PLAN VIEW
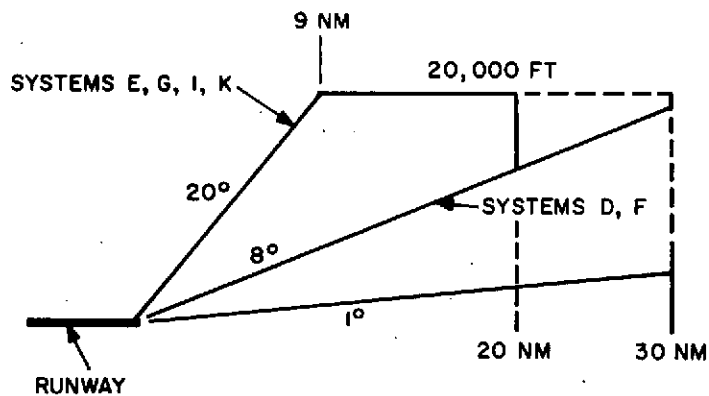
ELEVATION

Figure 27. MLS Signal Coverage.

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Table 13. Microwave Landing System Configuration Data.

Configuration	B	D	E	F	G	I	K
Guidance Coverage							
Azimuth	Straight	Straight	Straight	Straight	Straight	Curved	Curved
Elevation	No	Straight	Select	Straight	Select	Curved	Curved
Range	Basic DME	Basic DME	Basic DME	Basic DME	Precise DME	Precise DME	Precise DME
Missed Approach	No	No	No	No	No	Yes	Yes
Facility Performance* (CTOL Categories)	CAT I	CAT I	CAT I	CAT II	CAT II	CAT III	CAT III
Minimum Guidance Altitude (AGL)	150 ft	150 ft	150 ft	50 ft	50 ft	0	0
Coverage							
Elevation	NA	8°	20°	8°	20°	20°	20°
Azimuth	± 20°	± 20°	± 20°	± 20°	± 20°	± 40°	± 60°
Missed Approach	—	—	—	—	—	± 40°	± 40°
Accuracy* (noise)							
Elevation (2σ)	NA	7 ft	7 ft	1.4 ft	1.4 ft	1.4 ft	1.4 ft
Azimuth (2σ)	26 ft	26 ft	26 ft	11 ft	11 ft	9 ft	9 ft
Range (σ)	300 ft	300 ft	100 ft	100 ft	20 ft	20 ft	20 ft
Data Rate (Max)	2.5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	10 Hz	10 Hz
Runway Length	7000 ft			12,000 ft		14,000 ft	

*Accuracy refers to the decision height for CAT I and II Configurations and to the runway threshold for Configurations I and K.

Horizontal coverage is required to a range of 20 nautical miles with a desired range of 30 nautical miles.

Angular position of an aircraft is measured by reference to ground-generated fan beams that scan across the coverage sector in both azimuth and elevation. An airborne unit extracts the modulated angle data that corresponds to the central angle of the line-of-sight from the ground antenna to the aircraft. Range measurements are made by airborne interrogation of a ground transponder. The signal format provides for transmitting auxiliary data to an aircraft, including runway identity, equipment status, weather data, siting constants, and other data. The airborne unit computes position data or flight path deviation data suitable for inputs to the flight control system and/or display to the pilot.

Several industry teams within the United States are pursuing diverse technical approaches in the FAA compeition for the technique which the United States will submit to ICAO for the international standard (Refs. 31, 32). Moreover, a number of overseas programs also exhibit a variety of approaches (Ref. 33). Australia is developing an all C-band system called Interscan, which uses an electronically-scanned planar-beam antenna. It provides a separate DME in C-band which is independent of the azimuth and elevation subsystems. K_u band was ruled out because of its vulnerability to heavy rainfall. France is developing a ground-derived transponder system with an L-band discrete address uplink, which combines operation of an MLS with an air traffic control data link. The airborne interrogation is subjected to angular measurement by ground sensors to determine position. The French viewpoint is that the operation of an MLS in high density traffic areas cannot be efficient without an air traffic control data link, both of which their system provides. Expanded versions could service multiple runways or helicopter landing pads. The British have developed an air-derived system which uses Doppler scanning, while the West Germans have a system which uses the existing DME airborne equipment in the aircraft. The ground station of the latter system measures azimuth and elevation with special antenna arrays and retransmits the data back to the aircraft along with the normal DME reply pulses. The system is compatible with standard DME or TACAN airborne equipment, and has the unusual advantage of providing navigation for enroute, approach and landing.

In addition to those systems proposed for future adoption, several existing microwave systems have been developed for special applications.

Florescan is a family of microwave landing systems (Ref. 34) which use a narrow K_u-band beam that sweeps through extended azimuth and elevation angles with a varying pulse spacing to convey angular information. Shorscan and A-Scan are portable versions of this complete system employing small scanning antennas stationed on the ground. The aircraft receiver provides selectable glide angle and glide sensitivity, and may include a DME module for direct readout of range and range rate. Azimuth coverage of the system is $\pm 15^o$ with elevation coverage up to 25°.

TALAR is a microwave ILS which has potential application to VTOL operations because of its simplicity and flexibility (Ref. 35). The system comprises a single time-sharing transmitter generating localizer and glide slope beams to a single receiver in the aircraft. The output of the receiver operates conventional ILS instruments including flight director and auto-approach couplers.

The Landing Aid System (LAS) operates in the C-band with four amplitude-modulated beams, two each for glide slope and localizer guidance (Ref. 36). Fly-up, fly-down commands are generated by beam modulation. Both glide slope and localizer information are transmitted from a single unit. Onboard the aircraft, the small LAS horn antenna receives the microwave signal, which the airborne electronics unit converts to standard VHF/UHF ILS frequency and format. These signals are then sent to the existing VHF/UHF receivers and displays. LAS has an 18 nm minimum range with 30° azimuth coverage and 6° elevation coverage. The glide slope coverage is adjustable from 2.5^o to 7°. The airborne equipment weighs 18 lb and consumes 15 watts of power.

3.1.14 SIMPLIFIED AIRCRAFT INSTRUMENT LANDING SYSTEM (SAILS)

The SAILS system (Ref. 37) employs a small, lightweight, helicopter-borne radar which tracks a beacon located at or near the desired touchdown point. The resultant position information is used to drive conventional cross pointer indicators as well as to generate range and range rate. Provision is made to offset the touchdown point up to 2 miles horizontally and 1000 ft vertically from the beacon position. The approach path, glide slope, and offsets are all selected by the pilot; all measurements and computations are performed in the aircraft. SAILS is particularly adapted to steep

descent approaches since the glide slope is not determined by a ground-based beam configuration, but rather is selected by the pilot. This affords a capability of inter-mixed descent angles to the same terminal point, and provides the possibility of a variable descent angle programmed according to aircraft type.

The airborne equipment weight, exclusive of computer servo unit, displays and controls, is about 25 lb and the ground unit weighs 15 lb. The latter requires no special installation or alignment, hence is adapted to operation in remote areas. Since SAILS is essentially an angular system, the accuracy is a function of geometry, but improves as the touchdown point is approached. In fair weather the range is about 40 miles, whereas in very heavy rainfall it diminishes to about 10 miles.

3.1.15 REMOTE AREA TERMINAL SYSTEM (RATS)

RATS is a simple CW ranging and communication system operating within the UHF communications band (Ref. 38). An interrogator-computer in the aircraft continuously tracks a transponder on the ground, developing an accurate, continuous measure of slant range and bearing to the beacon. The computer determines height above the touchdown point from the manually inserted barometric pressure for that location. The height above touchdown is then compared with the measured slant range to derive a vertical angle to the beacon. The pilot selects the descent angle, and the angular deviation off that path is displayed on the glide slope meter in conventional form. Like SAILS, RATS provides 360-degree azimuth glide slope information, allowing the pilot the flexibility of choosing almost any direction and approach angle to the beacon.

3.1.16 MULTILATERATION

This is a proposed navigation technique which uses range measurements from three or more ground stations to determine position. The multilateration system proposed by Weiss (Ref. 39) uses a network of ground stations synchronized by atomic clocks. The ground stations transmit pulses in the GHz range, and position is determined by measuring the difference in time-of-arrival of the pulses from several stations. The aircraft must be within line-of-sight to at least three ground stations to obtain a position fix.

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An alternate approach, which appears capable of providing high-precision velocity and position signals, along with near-hemispheric coverage, is being developed and evaluated by LaRC. The concept uses a cooperative FM/CW Doppler multilateration technique. A system design and analysis is being performed, and signal distribution, modulation and data processing techniques, and minimum time-delay-variation transponder designs will be examined. An experimental system will then be built and flight tested to evaluate different modulation formats, multiplexing techniques, station configurations, and data processing techniques.

The development of a dedicated multilateration system for rotorcraft terminal navigation is a controversial subject, both technically and politically. The advantages and disadvantages of the multilateration system are summarized below.

Advantages

- The use of ground computation and a data link to the aircraft provides landing guidance with a minimum of airborne equipment.

- Lateral guidance can be provided over the area of a heliport and serve several landing pads simultaneously.

Disadvantages

- The accuracy of vertical guidance suffers drastically from geometric dilution. For any station pair, the accuracy of a measurement is proportional to the sine of half the angle between the lines-of-sight to the two stations; the most accurate measurement is obtained on the baseline between the two stations. The sensitive direction for any measurement lies in the plane determined by the helicopter and the two stations. Outside the station cluster on a 15° glide path, the vertical accuracy is poor because the angle between the lines-of-sight is small. Near touchdown the measurements are insensitive to vertical position because the aircraft and all the stations lie approximately in a single horizontal plane.

- Multilateration systems were considered as the ILS replacement by the RTCA (Ref. 26) and rejected. The primary reason was the difficulty of solving the multipath problem. Difficult sites were expected to require special preparation and antenna tailoring in addition to very complicated multipath rejection schemes.

- Complex coordinate conversion and computation is required for multiple approach paths or non-standard baselines. Station coordinates must be transmitted to the aircraft if the computations are to be performed on board.

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- The location of multiple ground facilities at precise locations would be difficult to accomplish in many applications such as in city centers, on high buildings, or over water.

- For operational utility, it is essential that a landing system be universally adopted by all users. The major impediment to the acceptance of a universal system is not so much technical as it is political; i.e., worldwide agreement on a single system. For example, the final decision by ICAO on an MLS standard will come in 1976 from proposals now being submitted by participating countries. The U.S. entry, which has evolved starting with the formation of RTCA SC-117 in 1967, is committed to the use of a microwave scanning beam. Efforts to promote the use of a special-purpose system can be counter-productive. There is a real danger that such efforts could ultimately block the overall goal of achieving a universal system.

3.2   GROUND-BASED RADAR

Ground-based radar is primarily a surveillance system as opposed to a navigation system, and unlike the radio navaids, radar does not require special equipment onboard the aircraft. However, radar vectoring from the ground is frequently used for navigation in terminal areas, and surveillance radar approaches are available at major airports.

3.2.1   PRIMARY RADAR

Primary radar comprises a powerful transmitter and a directional antenna that "illuminates" a given target, and a sensitive receiver that detects energy reflected by the target. By measuring the elapsed time between transmission and reception, the distance to the target is determined, whereas the direction of the target is obtained by means of the antenna-beam directivity. A cathode-ray-tube displays the target as a bright spot, whose distance and azimuth are proportional to the aircraft; true position with respect to the antenna. By using a transparent overlay map, the target's position with respect to known geographical features may be observed.

The outstanding advantage of primary radar is its ability to detect a non-cooperating target. For best results, the target must be located in an environment that has much less reflectivity than the target itself; otherwise, the target is obscured by reflections from its surroundings (clutter). Radar is particularly effective in distinguishing aircraft against a background of sky. A device for improving target detection is the moving-target indicator, which discriminates against fixed clutter (due to

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terrain, buildings, mountains, etc.) and responds only to targets that have more than a certain radial velocity with respect to the radar site.

Since primary radar involves transmission over a round-trip distance, its range is proportional to the fourth root of transmitter power. High transmitter power — on the order of hundreds of kilowatts — is therefore necessary for all but the shortest ranges and largest targets.

3.2.2 AIR TRAFFIC CONTROL RADAR BEACON SYSTEM (ATCRBS)

Where targets are cooperative, secondary radar can be used. In the ATCRBS, the target carries an amplifying device or transponder, thereby greatly reducing power requirements at the radar transmitter. Moreover, transmission and reception can then be at different frequencies, thus eliminating clutter, and can use various modulation schemes for target identification.

The present air traffic control system uses secondary radar as its primary source of aircraft position, identity and altitude information. A ground interrogator transmits a pair of time-coded pulses at 1030 MHz from a highly directional antenna, to elicit a coded reply from each airborne transponder. The reply is radiated nondirectionally at 1090 MHz (up to 16 bits). It is received by the ground station (interrogator-receiver), processed, and transmitted to the controller's display. The transponder in the aircraft consists of a receiver/transmitter and a coder/decoder. Any detected pulse pair that has the correct spacing will cause the transponder to reply with one of the 4096 possible reply codes containing the appropriate data (i.e., identity or altitude).

The principal error in the ATCRBS range accuracy is the variation in the transponder reply delay; the total range error is within 1/16 nautical mile. The limiting factor in resolving targets involves the detection and separation of overlapped replies, which limits range resolution to about 400 ft. The standard deviation for azimuth accuracy is 0.25 degree for terminal radars with a scan rate of 20 rpm. The azimuth resolution is dependent upon the antenna beamwidth, receiver sensitivity, power outputs, and system processing technique. The beamwidth of 4 degrees allows resolution of two targets separated by about 5 degrees.

The major problem with ATCRBS is overinterrogation. All interrogators operate on the same frequency and all transponders reply on a common frequency. As a result,

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all transponders in a given reception area (which may be hundreds of miles in diameter) reply to all interrogations picked up by their receivers. In a high-density terminal area, there may be as many as 60 radar interrogators, each querying a specific airplane but receiving replies from every transponder within line-of-sight. The result is a high level of interference, both at the transponders and at the interrogator receivers on the ground, causing lost or garbled replies.

3.2.3   DISCRETE ADDRESS BEACON SYSTEM (DABS)

In 1969, the Department of Transportation Air Traffic Control Advisory Committee (Ref. 40) foresaw the need for discretely-addressable airborne transponders for improved quality and reliability of surveillance data. Additionally, they recognized the opportunity of incorporating a digital data-link for the transfer of data communications and control information between the aircraft and the ground. From these recommendations emerged the Discrete Address Beacon System (DABS).

DABS is essentially a considerably advanced ATCRBS; the primary difference is that the airborne transponder will be programmed to recognize its own specially-assigned (discrete) call number. It will reply only when the querying pulses contain that special signal, ignoring the interrogations beamed to other aircraft. Its reply train will include a "signature," so that controllers will know that the proper transponder has responded.

Being developed as part of the ATCRBS improvement program is a new type of antenna called Electronic Scan or E-Scan. This is a stationary circular array of a large number of columns of dipole antennas, that, by means of electronic phasing and switching can form a beam pointing in any given direction. For updating azimuth information, E-Scan could eliminate the need for waiting until the rotating antenna completes a sweep. From computer-stored information that provided the last known azimuth of any tracked airplane, the E-Scan could be properly pointed toward the area of an aircraft target for instant updating.

Since DABS addresses individual aircraft, it offers an additional potential for data communications and control purposes by means of the data link to be incorporated in the system. DABS will have data communications capacity beyond that required for identity/altitude queries; this capacity will be adequate for most simple

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control instructions that would permit quicker corrective action than voice transmission. In this sense, DABS offers a new dimension of utility as a ground-based collision-avoidance aid to a concept known as Intermittent Positive Control. Similarly, the data link could also be used to update the onboard navigation system.

Two interesting DABS modifications have recently been proposed. "Synchro-DABS" would use tracking information on the ground to time individual interrogations such that aircraft replys would always start at universally synchronized time slots. Consequently, by listening to other transponder replys, an aircraft could easily measure the range to all others in the vicinity. "Astro-DABS" would cause the ground interrogation to go via satellite and thereby increase the coverage.

The details of DABS are still being established but the potential exists for using it as a form of accurate navigation and surveillance. The data link capability means that ground and air derived information can be easily exchanged. The accuracy goal of DABS is 200 feet.

3.3   DEAD-RECKONING SYSTEMS

Dead-reckoning navigation systems extrapolate a "known" position to a future time by measuring velocity and direction of flight. The simplest dead-reckoning system uses the airspeed indicator, magnetic compass and a wind estimate. Doppler radar and inertial navigation are much more accurate forms of dead-reckoning navigation.

Dead-reckoning can be characterized as the basis of all navigation, with position-fixing constituting a method of updating it. Actually, dead-reckoning and position-fixing complement one another, each providing an independent means of checking the accuracy of the other. Where position-fixing is intermittent, with relatively long intervals between fixes, dead-reckoning is appropriately considered the primary method. If fixes are available continuously or at very short intervals, the primary method might then be either dead-reckoning, position-fixing or an integrated output from both.

3.3.1   DOPPLER RADAR

A Doppler radar navigator is a self-contained dead-reckoning system that obtains the desired navigation information through measurement of aircraft velocity

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and direction by means of a Doppler radar, and directional sensor, respectively. A computer combines these data, and integrates the velocity into two components of distance traveled from the point of departure. The present position information is compared with destination coordinates to provide quantities such as bearing to destination, distance to destination, track-angle error, and cross-course deviation. These can be fed to suitable displays and the autopilot.

The Doppler navigator has the following advantages over other methods of navigation:

- Continuous velocity and position with respect to the ground.
- Completely self-contained. (No ground stations required.)
- Average-velocity information, the quantity used for navigational position determination, is extremely accurate.
- All-weather operation.
- Navigation is possible over oceans and over underdeveloped areas.
- International agreements are not required, since ground equipment is not needed.
- Doppler radars (unlike mapping radars) are amenable to high-reliability all-solid-state design because of their low radiated power.
- No preflight alignment or warmup needed.

The disadvantages of the Doppler navigator are:

- Dependent for azimuth information on an external directional sensor (e.g. gyromagnetic compass, heading-attitude platform, or astrocompass).
- Internal or external vertical reference information is required for conversion of velocity information into earth coordinates.
- Position information degrades linearly with time.
- Instantaneous velocity information is not as accurate as the average velocity.

The total position error of a Doppler navigation system is determined by the errors of the three major components of the system: the Doppler radar, the heading reference, and the computer. The error contributed by the heading reference has a major effect on the overall system error; a 1° error in heading represents a 1.75 percent cross-track position error. The computer that combines the Doppler-radar velocity

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information with the heading information and integrates the velocity into elapsed distance also contributes an error to the position determination. When analog computation is used, this error may be appreciable. The principal uncertainties in the Doppler radar data are due to a scale factor error in the groundspeed reading, a bias in the antenna boresight alignment relative to the aircraft, and the effects of over-water errors. A typical error budget for a high-performance Doppler radar is shown in Table 14 (Ref. 41). Based on current accuracy characteristics of the three components, a total Doppler navigation system position error of less than 0.25 percent (1σ) of distance traveled is within the present state of the art. In view of the relatively low

Table 14. Typical Error Budget of High Performance Doppler Radar.

Error	Type	Value	Correlation Time
Fluctuation (After 10 nm)	Random	0.073 %	0.25 - 1 sec
Beam Direction (Antenna and Radome)	Bias & Random	0.065 %	1 sec - ∞
Sea Bias (Residual After Lobe-Switching)	Bias	0.035 %	∞
Altitude Hole (Residual After Lobe-Switching & Modulation Wobbling)	Bias & Random	0.02 %	1 sec - ∞
Readout (Data Conversion)	Bias	0.02 %	∞
Installation and Calibration	Bias	0.03 %	∞
Frequency Tracker	Bias	0.1 kt	∞
Total Ground Speed Error	0.11 % + 0.1 kt (1σ)		
Total Drift Angle Error	6 arc-min (1σ)		

weight of modern solid-state Doppler navigators and the capability for measuring negative speed, their use in VTOL aircraft will steadily increase, particularly for offshore and remote area operations. Vertical velocity and absolute altitude will be extracted in future systems. A typical Doppler radar of the future will have a total weight of less than 10 lb and probably will cost less than $10,000.

3.3.2   INERTIAL NAVIGATION SYSTEM (INS)

An inertial navigation system (INS) is a completely self-contained dead-reckoning device. Once the initial position is known by the navigation computer, accelerometers mounted on an inertial platform determine the movement of the aircraft from this position. The inertial platform is usually kept level with respect to the local surface of the earth by suspension in a set of supporting gimbals. The gimbal angles are changed to compensate for the rotational movement of the aircraft over the surface of the rotating earth. Any angular motions of the platform are detected by gyroscopes, which generate torquing signals to a servo system to keep the platform locally level.

Compared with other methods of navigation, an INS has the following advantages:

- Indications of position and velocity are instantaneous and continuous.

- Completely self-contained since it is based on measurements of acceleration made within the vehicle itself.

- Navigation information is obtainable at all latitudes, in all weather, and without the need for ground stations.

- Navigation information is substantially independent of vehicle maneuvers (in contrast to, for example, Loran and Doppler systems).

- Position, groundspeed, azimuth, and vertical outputs are provided; it is the most accurate means of measuring azimuth and vertical on a moving vehicle.

The disadvantages of the inertial system are:

- Position-and-velocity information degrades with time, whether the vehicle is moving or stationary.

- Equipment is expensive and relatively difficult to maintain and service.

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- Initial alignment is necessary. Alignment is simple on a stationary vehicle at moderate latitudes, but it degrades at latitudes greater than 75° and on moving vehicles.

When the inertial system is turned on, it must be aligned so that the computer knows the initial position and groundspeed of the aircraft, and so that the stable platform has the correct initial orientation relative to the earth. The platform is typically aligned in such a way that its accelerometer input axes are horizontal, often with one of them pointed north. As the aircraft maneuvers the accelerometers measure changes in velocity, and the computer records the motion. The navigation errors which result from using inertial systems are due to the following primary sources:

- Initial misalignment of the inertial platform.
- Initial heading and position error of the aircraft.
- Gyro torquing motor scale factor and bias.
- Gyro drift.
- Accelerometer bias and scale factor error.
- Gyro and accelerometer misalignment on the platform.
- Velocity quantizer error.
- Random noise.

The most severe limit on position measurement is the knowledge of the Earth's gravity field in the region of operation, since accelerometers cannot distinguish between kinematic acceleration and gravity. Angular errors in the measurement of inertial space are primarily limited by the precession of the equinoxes and the migration of the earth's pole; these errors are 5×10^{-5} deg/hr, equivalent to 100 ft. Measurements of azimuth and vertical are typically limited by the angular returnability of the shock mounts and by the flexure of the vehicle; these typically range from 2 minutes of arc to 0.5°.

Three inertial navigation systems currently in use in commercial aircraft are the Litton LTN-51, the Delco Electronics Carousel IV, and the Collins INS-61B. Typical systems weigh 50 to 75 lb (excluding cables), of which 20 lb is for the platform. The steady-state power consumption is approximately 200 watts. Overall system accuracy without update is on the order of one nautical mile per hour.

For use in a hybrid navigation system in which the INS outputs are periodically updated, the accuracy of the INS may be relaxed. The severity of the requirements for the inertial system varies with the quality and rate of the update information. For the landing phase, for example, a 2 to 3 knot inertial system is required for updates on the order of every 2 seconds. The initial costs of an INS of this quality are normally in the range of $75K to $150K, with high maintenance and upkeep costs and undesirably short lifetime. Current systems are gimballed platforms, leading to a highly complex system. NASA Ames Research Center, as a part of the STOL operating systems program (Ref. 42), will be flight testing a strapdown INS which uses six floated rate-integrating gyros and six accelerometers, with a digital computer to mathematically replace the platform gimbals. Ground tests of this system have indicated excellent performance, and it is expected that flight tests will verify these data. However, the cost will still be nearly an order of magnitude higher than a VTOL operator could afford.

New gyro technology is being developed which will provide sensors suitable for strapdown system application at small fractions of the cost of the conventional floated rate-integrating gyro. Examples are the ring-laser gyro, the electrostatically-suspended gyro, the magneto-hydrodynamic gyro, and the two-degree-of-freedom, tuned-gimbal gyro. Of these, the latter appears to have the best capability for the 1980's time period, based on current sensor development and accuracies. LaRC is attempting to further the development of an INS for VTOL applications, based on this technology. Research studies are examining candidate mechanizations of such a system using various degrees of redundancy to provide fail-operative or two-fail-operative capability. They will also examine error models, effects of vibration associated with some classes of VTOL aircraft, alignment and initialization requirements and procedures, self-test and failure analyses capability, and error propagation.

3.4   HYBRID NAVIGATION SYSTEMS

A low cost navigation system capable of all-weather operations with a high degree of accuracy and reliability can be achieved through optimum integration of equipment, subsystems and computer mechanizations. A hybrid aircraft navigation and guidance system employing a Kalman optimum estimation filter is capable of providing the necessary high accuracy performance using low cost subsystems. A Kalman filter implemented in the computer can provide optimum estimates of the subsystem and

equipment error quantities. These estimates can be used to "reset" the navigation and guidance system outputs as well as the outputs of component instruments such as gyros and accelerometers in the INS.

3.4.1   HYBRID SYSTEM OPERATION

A hybrid navigator combines redundant navigation information from two or more subsystems together in such a way that the resulting estimate of position and velocity is of improved accuracy over that which would be obtained by the use of one of the navigation systems alone. For the optimal case, a Kalman filter is used to make estimates on the basis of assumed error models for the navigation subsystems. An example is shown in Figure 28 where an inertial navigator is combined with a position fixing device such as Omega or DME. The INS is considered to be the primary source of required navigation and guidance information (i.e., aircraft position, velocity, attitude and heading). The fix can be thought of as a measurement of the present error in the inertial navigator. The filter processes the measurement to update its optimum estimate of the inertial error. These optimum error estimates are then added to the inertial navigator output to obtain the optimum position and velocity estimate. The form of the filter is determined by the error model assumed for each component navigation system.

The indicated INS position information in Figure 28 is comprised of true aircraft position plus an error, δP. The external position reference provides an independent indication of the aircraft's true position subject to an error, δP_r. Subtracting the reference position information from the INS-indicated position results in the error difference $\delta P - \delta P_r$ which is an input to the Kalman filter. Viewed in this manner, the error difference information constitutes the "measurement" with δP and δV being the signals to be estimated, and with δP_r and δV_r being the noises in the measurements. Therefore, the Kalman filter considered here is modeled not on actual quantities (P, V) but on error quantities (δP, δV). In order for the Kalman filter to be effective, knowledge of the statistical properties of each data source is required; this is generally obtained from system and component testing and from theoretical considerations.

Processing of the measurement information by the Kalman filter results in optimum estimates (in the sense of satisfying a minimum variance criterion) of the error states, denoted in Figure 28 by the "caret" quantities. As mentioned earlier,
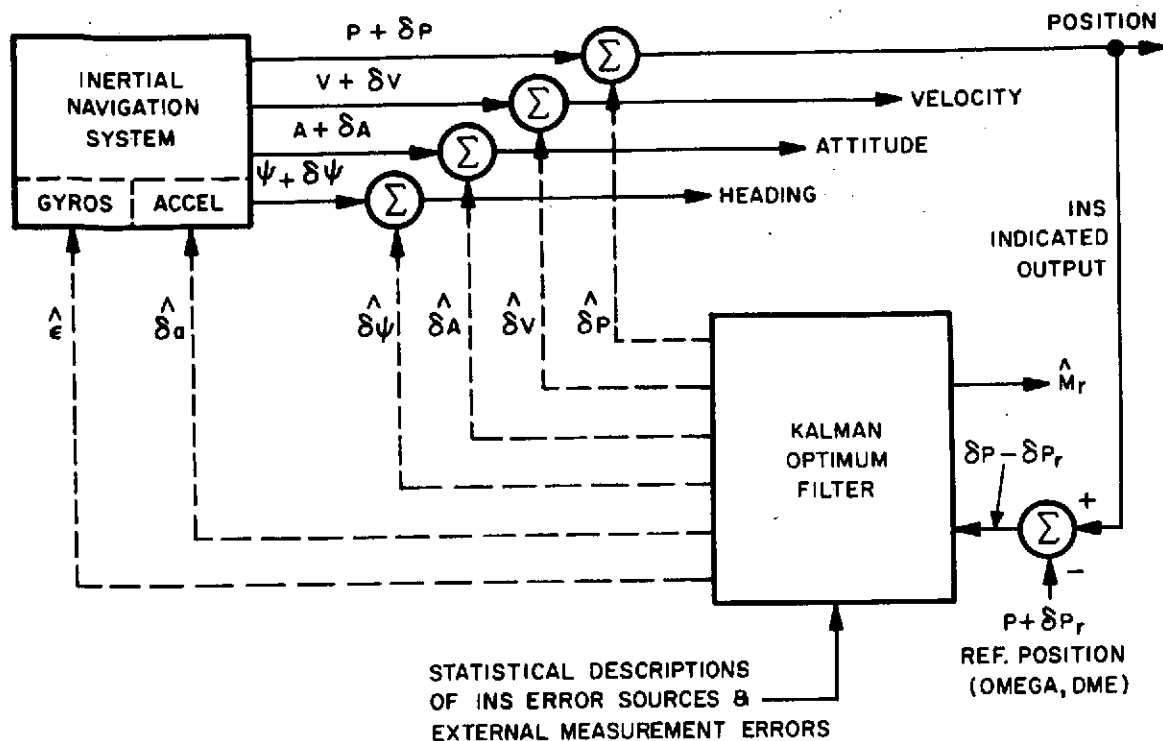
Figure 28. Block Diagram of Kalman Filter for Hybrid Navigation and Guidance System.

equipment errors can be estimated as well as the subsystem output errors. The filter output M_r denotes an estimate of a measurement error in the reference information source (Omega or DME). The final step of the process is to perform the update; i.e., to correct for errors in the subsystem outputs and component errors. This can be done in a closed-loop manner, by a mechanical or electrical reset of the equipment, or by an open-loop reset, in which the individual subsystems and components are not physically corrected but rather externally compensated in the computer. In either case, the result is an optimum hybrid system using inputs from all available navigation subsystems and equipments, and providing a continuous display of the best possible navigation and guidance information.

3.4.2   HYBRID NAVIGATOR ADVANTAGES

In the more general case, navigation information from any or all of the navigational aids discussed in previous sections may be combined to obtain the best estimate of the aircraft's position and velocity. Another significant advantage of a hybrid

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system is increased reliability. The hybrid navigator will use all the available information; if data from one navigation system is lost for some reason, the output will still be the best estimate based on the remaining inputs. The filter in Figure 28 may not necessarily be the Kalman optimum, but perhaps a simpler scheme which provides near-optimum performance. Indeed, excessive computer requirements may well dictate that sub-optimal schemes be used, although the future availability of low-cost, large-scale integrated circuits will probably minimize this consideration.

To summarize, the major advantages of the Kalman filtering approach to hybrid navigation systems are:

- Optimum integration of subsystems provides more accurate navigation and guidance information than is available from any individual subsystem.

- The optimum filter provides the most efficient use of all available navigation information. All navigation subsystems can be modeled in the Kalman filter with a statistical description of each subsystem.

- The measurement time for any one source of information is independent of all others; therefore, optimum filtering does not depend on the availability of any one source of navigation information.

- Redundant navigation information permits accurate backup modes to be automatically available in case of a subsystem failure. An optimally integrated navigation system can provide calibration of the subsystems and their components. In the event of a subsystem failure or the unavailability of reference information, the remaining subsystems can continue to function with greater accuracy than they originally were capable of providing.

- The hybrid system provides a means of subsystem accuracy checkout and failure detection, since a statistical description of the navigation subsystem error models is available. By placing confidence limits on the accuracy of the navigation information indicated by the various subsystems, an accuracy checkout scheme is provided. If the expected limits are grossly exceeded, a subsystem failure may be indicated.

3.4.3   LIMITATIONS OF THE HYBRID NAVIGATOR

The use of Kalman filtering for hybrid navigation has a great many theoretical advantages; however, the implementation of such a system has several practical limitations. Sensitivity to inaccurate error models and statistics, and the inherent computational

burden are among the most important of these. Certain aspects of the limitations are discussed below:

Error Models and Statistics

Implementation of the Kalman filter equations presumes exact knowledge of the linear state dynamics of the navigation system and measurement errors, and the statistics of the random processes involved. Since exact a priori information is impossible, some form of sensitivity analysis is necessary to verify system performance. Moreover, many systems, by virtue of nonlinear dynamics or measurements, do not immediately lend themselves to application of the Kalman filter. Some techniques which have been used to overcome the difficulty of nonlinear behavior include linearization about a nominal trajectory, inclusion of the nonlinear behavior in the filter implementation but basing the error covariance calculations on linear approximations, and iterative procedures which attempt to reduce the effect of the nonlinearity. In each case the validity of the resulting error calculations, and the accuracy and stability of the resulting filter must be established by exhaustive simulation techniques.

Suboptimal Filtering

Since the filter equations must be solved on a computer of finite size, it is nearly always necessary to approximate the system or its statistics or to otherwise simplify the filter implementation. Again, it is necessary to verify that the modified estimator will not experience a significant loss of accuracy. The largest computer burden of the Kalman filter is imposed by the requirement to compute the error covariance matrix as a prelude to determining the filter gains. Therefore, the covariance calculation problem is often circumvented by determining filter gains in an approximate or altogether different manner. For example, typical gain histories are observed during the design of the filter and may be approximated in the actual system by simple functions of time — constants, staircases, exponentials, etc.

Computer Accuracy and Speed

The implementation of a hybrid inertial navigator employing a Kalman filter must also consider the finite word length and speed of the navigation computer. In many applications the use of fixed-point arithmetic compounds the accuracy problem.

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Errors are also introduced by numerical algorithms used to approximate mathematical operations.

In many practical uses of the Kalman filter in hybrid systems the filter gains decrease as the number of independent measurements grows. Consequently, the filter tends to reject or discount the most recent measurements in favor of those obtained earlier in the estimation procedure. Since the error covariance and filter gain calculations do not normally take into account estimation errors introduced by computer roundoff and numerical algorithms, these effects can cause accuracy to deteriorate.

Another difficulty is sometimes encountered when the external measurements are very accurate, whereas initial estimates of the state contain large errors. In this situation the error covariance decreases very rapidly as the first few measurements are incorporated. The finite accuracy of the computer may permit the calculated error covariance matrix to lose its positive definite characteristics, thereby introducing the possibility of divergent estimation errors.

Often measurements are available more frequently than the computer is capable of processing them. For example, Doppler radar indications of velocity can be obtained several times per second. Rather than reject many of the measurements, the information may be processed by a separate algorithm which is capable of very rapid operation and then passed on to the Kalman filter in a modified form. Here the effects of distortion of information in the measurement due to averaging must also be evaluated.

3.5   AREA NAVIGATION (RNAV) SYSTEMS

Although the VORTAC system provides nearly complete coverage of U.S. airspace, available routes are limited by the requirement to fly from station to station. This has several disadvantages: the indirect routes are longer, much of the airspace is wasted, the danger of collision is increased near the station where numerous airways converge and coverage limitations may not permit navigation to certain locations. The use of area navigation (RNAV) equipment can alleviate these problems by permitting direct point-to-point navigation. RNAV devices have been under development for many years, but only within the past half-decade has serious testing demonstrated the feasibility of area navigation. Since then, considerable progress has been made not only in the equipment itself, but in the development of standards

and procedures for the implementation of RNAV in the National Airspace System. In fact, a joint industry-government task force has recently proposed to use RNAV as the basis for the air traffic system in the 1980s (Ref. 45).

RNAV does not refer strictly to the use of VORTAC; any system which can present position (and usually, velocity) information relative to arbitrary coordinates is actually an area navigation system. Systems such as INS, Omega and Doppler which provide direct routings are inherently RNAV devices. These systems are discussed separately, and the remainder of this section will consider the VORTAC-based RNAV equipment.

Most available RNAV systems use the information from a single VORTAC station for navigation. The RNAV routes are specified by waypoints, which are defined by their bearing and distance from a given VORTAC station. These waypoints are treated as conveniently-located 'phantom' VORTAC stations, and then used for navigation in the normal fashion. There are two forms of output. The more common output is range and bearing to a waypoint which has been established by a radial and distance from a given VORTAC station. The second form of output is a linear display which shows the aircraft position relative to some map coordinates.

No significant error is expected for the RNAV computations other than what exists for the VORTAC equipment itself. In the less expensive systems there might be some computational error added; however, more sophisticated hybrid RNAV systems would have reduced total error because of optimum filtering with air data, inertial or other measurements. The typical accuracy desired from RNAV is 2 nm enroute, 1 nm in the terminal area and 1/2 nm on approach. To achieve this accuracy throughout the country would require the installation of additional VORTAC stations. Competing systems, such as Omega and Loran-C, offer RNAV capability with greater coverage and the opportunity for improved accuracy.

3.6   COLLISION AVOIDANCE SYSTEMS

In order to provide independent commercial VTOL operations, it is necessary to ensure VTOL-VTOL and VTOL-CTOL separation. The conventional ATC system uses the ATCRBS to provide ground controllers with the traffic information necessary to vector aircraft clear of one another. Because VTOL commercial operations should be independent, and moreover, may take place outside the ATCRBS coverage area,

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alternate sources of traffic information are necessary. A likely candidate for this information is an airborne Collision Avoidance System (CAS). Both FAA and ICAO are of the opinion that any acceptable universal airborne CAS must supplement, be compatible with and be integrated into the ATC system. The existence of a universal airborne CAS would provide additional protection to VTOL aircraft from equipped VFR traffic operating near low altitude VTOL routes below ATCRBS or DABS coverage.

Three CAS systems are now undergoing FAA evaluations: EROS, AVOIDS and SECANT. EROS ia a time-frequency system; AVOIDS and SECANT are transponder systems. Each is described in greater detail below.

3.6.1 EROS

EROS is a cooperative system in which aircraft use a common time base to exchange flight data (Ref. 46). Uniform time is achieved by clocks in each aircraft which are repeatedly synchronized by radio transmission to maintain an accuracy of two-tenths of a millionth of a second. The use of precise relative time permits reserving a definite time period (message slot) for each aircraft to transmit while all other aircraft listen. Each aircraft transmits two pulses during its message slot. Receiving aircraft detect the delay between the start of another aircraft's message slot and the time at which the first pulse is received, and determine the range by dividing the velocity of propagation by the apparent propagation time. Range rate is determined by measuring the Doppler shift of the incoming signal. Thus, it is possible to obtain range (R) and range rate ($\dot{R}$) from the same signal and to determine the approximate time to closest approach (Tau) by the quotient ($R/\dot{R}$).

The altitude of the transmitting aircraft is derived from the second pulse, which is delayed in time from the first pulse as a function of altitude. Fine synchronization provides coherent time and frequency resolution sufficient to permit one-way range measurement to an accuracy of 200 ft, altitude comparison to an accuracy of 50 ft, and Doppler to an accuracy of better than ± 60 knots range rate. Altitude screening is used to eliminate targets which are not a threat by reason of widely differing altitudes. The receiving aircraft checks the received altitude information against its present altitude and any altitudes it will pass through in 60 seconds if it is in a climb or dive. Since collisions could occur between aircraft approaching each other below

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the limits of Doppler detection, the system warns of aircraft flying at coaltitude and within 1.5 miles, regardless of range rate.

3.6.2 SECANT

SECANT (Separation and Control of Aircraft using Non-synchronous Techniques) is a cooperative, transponding CAS designed to be compatible with the dense air traffic anticipated for the 1980s and beyond. Operating at L-band, SECANT performs the collision avoidance function by transmitting probes and receiving replies from all aircraft within hazard range (Ref. 47). Each reply pulse group contains a data list of the responder's digital message which gives his identity and altitude. Range and range rate are determined from the time of arrival of the reply. The frequency stability required for the SECANT system, one part in 10^6, is readily achieved at low cost. Various discriminants are used to eliminate the undesired signals or "fruit": different frequencies and probe spacings are allocated as a function of aircraft altitude; the fields above and below the aircraft are probed separately in 500-foot layers; and thresholds are established, based on the range required for the collision avoidance function, which discriminate against signals coming from aircraft too far away to be involved. Through such discrimination techniques, SECANT reliably eliminates undesired signals, minimizes false alarms and provides early warning time on potential threats.

3.6.3 AVOIDS

AVOIDS (Avionic Observation of Intruder Danger Systems) is an L-band pulse beacon ranging system which operates on a cooperative basis with other equipped aircraft (Ref. 48). The protected volume around each aircraft is shaped by signal processing and is independent of aircraft attitude and antenna patterns. The AVOIDS approach is to minimize the number of responses by having only those aircraft that represent possible threats respond. This is done by pulse coding and the use of altitude discrimination. The interrogation rate is minimized until a preliminary analysis indicates that a threat possibility exists. A correlation technique then sifts the potential threat from the total signals received.

During the interrogation mode, pulse-coded RF energy is radiated omnidirectionally; the rate is random to prevent synchronization and varies between two and ten

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interrogations per second, depending upon the severity of existing threats. The interrogation pulses convey information relative to the altitude of the interrogating aircraft. Other aircraft receiving this information compare the interrogator's altitude with their own altitude. A single pulse response is generated by an intruder, if the comparison indicates that it is within the particular altitude band being surveyed. These responses are received by the interrogator and stored, depending upon the distance from the intruder to the interrogator. A correlation technique is used to detect the presence of an intruder. The system sequentially interrogates four equal altitude bands 3200 ft above and below the protected aircraft; this reduces the probability of signal overlap of response pulses, allows the system to concentrate its interrogations within those altitude bands which contain potential threats, provides course altitude information, and allows the threat evaluator to sequentially consider each altitude band.

3.6.4   SYNCHRO-DABS

Another potential candidate for the CAS function is a modified version of DABS, called Synchro-DABS. Synchro-DABS would introduce synchronization of the airborne equipment so that airborne systems could be made to transmit time synchronized responses which would be used in the same way that the EROS synchronized signals are used.

3.7   TRAFFIC SITUATION DISPLAY

The traffic situation display (TSD) is a concept for expanding the CAS function to provide air traffic control, and yet leave the separation responsibility in the cockpit. TSD's are being studied both at LaRC (Ref.49) and at MIT (Ref. 27). The common equipment is an airborne display which depicts other traffic relative to the equipped aircraft. The identity, altitude and speed of each target are indicated with alphanumeric tags alongside the targets. The display can be fed by data link from a ground data acquisition system or by air-derived information. Although these studies have been directed toward CTOL operations in the terminal area, the concept is ideal for the independent VTOL operations.

The TSD concept (Fig. 29) utilizes a computer which generates flight paths with traffic sequencing and separation, a ground-aircraft data link, and a cockpit display showing actual and computer-desired aircraft positions overlayed on a terminal-
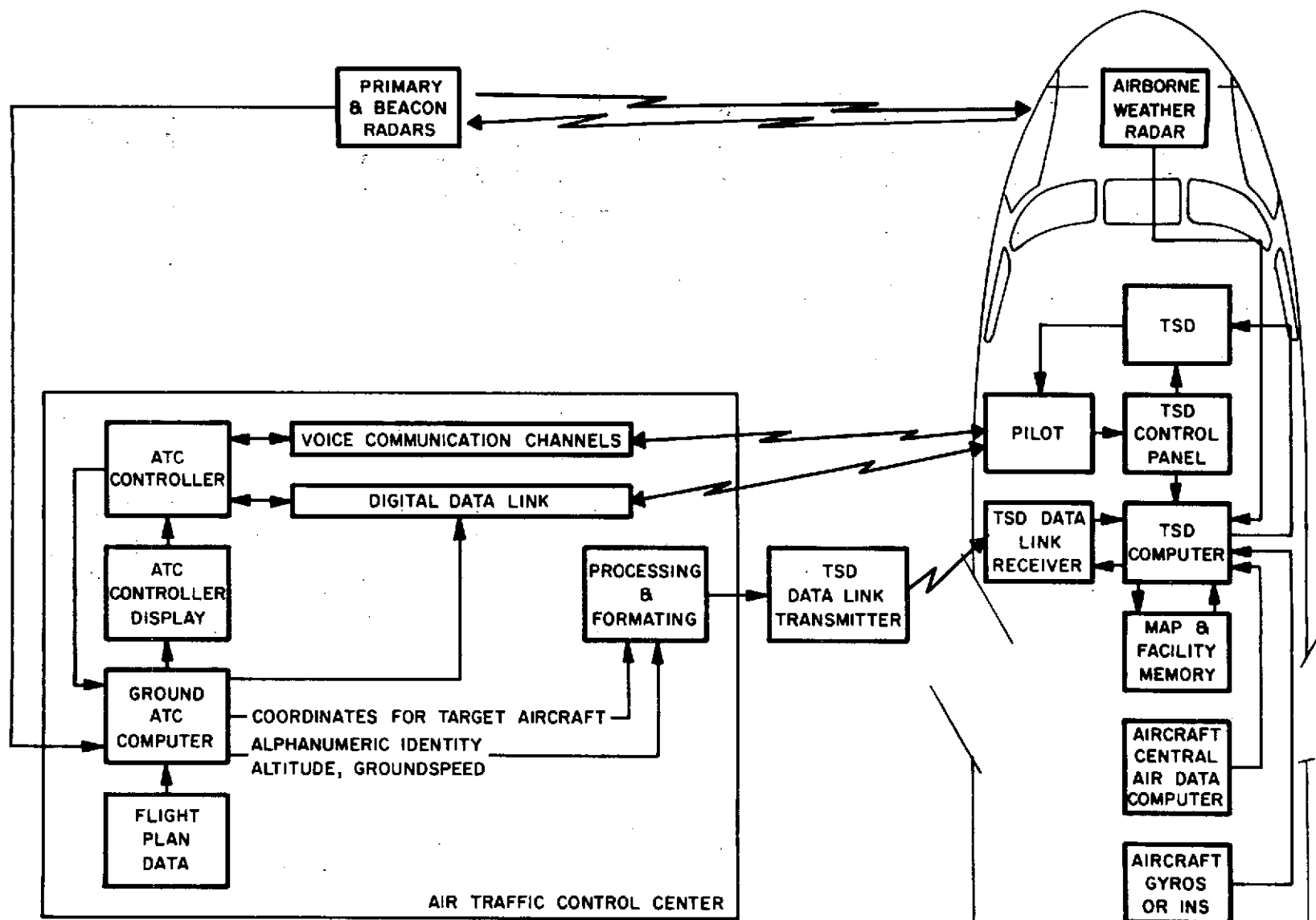
Figure 29. Traffic Situation Display Concept.

area video map. The controller is not an active participant in the system under nominal conditions; rather, he functions in a parallel mode to operate and monitor the ground computer system and ensure that the computer-generated flight paths sent to and executed by the pilots are providing sufficient separation and efficient sequencing. If a malfunction occurs, the controller serves as a backup using the radio voice link and the radar beacon system. During failure of some portion of the ground system, a set of emergency instructions previously loaded by the ground system as part of its normal set of display instructions is presented to the pilot for execution until backup ground procedures and equipment become available.

Implementation of this concept also requires that accurate aircraft locations and altitudes be fed to the computer. These inputs can be obtained from the existing ATCRBS, from the upcoming DABS, from aircraft-derived navigation information sent to the ground over a data link, or from an airborne CAS. Ground-determined and on-board-determined aircraft positions are compared for failure detection and then mixed in the computer for a best estimate.

A small onboard computer processes the information and displays aircraft traffic and map features near the aircraft position. The onboard computer also formats the computer-desired position of the aircraft and all desired flight-director information required to execute the path. Major advantages of this system are increased system capacity as a result of accurate execution of computer-generated flight paths and reduced time dispersion at touchdown, and increased pilot awareness of the local traffic situation and upcoming events. This display of computer-determined information will enable the pilot to execute a flight path accurately, and give him increased flexibility in compensating for system uncertainties.

3.8   COMPARISON OF NAVIGATION SYSTEMS

Table 15 presents an approximate comparison of the major differences in cost, accuracy, coverage and utilization of many of the navigation system avionics discussed in this section. The approximate cost of the equipment excludes land, building and installation expenses. The accuracies cited are typical for normal operating conditions. Utilization presents an estimate of the number of systems in operation.

Table 15. Comparison of Navigation/Surveillance Systems.

System	Cost[a]	Accuracy	Coverage[b]	Utilization[c]
Direction Finding	5,000/7,000	Variable	200 nm	100,000/2,000
Marker Beacons	1,500/3,000	300 ft	---	70,000/600
VOR	4,000/30,000	1.5 deg	LOS, 200 nm	150,000/2,000
DME, TACAN	5,000/50,000	200 ft to 3 %	LOS, 200 nm	40,000/2,000
Decca	6,000/2,000,000	300 ft; 2nm	200 nm	10,000/25
Loran-A	6,000/2,000,000	1,500 ft	600 nm	10,000/25
Loran-C	50,000/5,000,000	100-900 ft	1,200 nm	1,000/8
Omega + VLF	25,000/10,000,000	1 nm day; 2 nm night; 1,000 ft with differential Omega	Worldwide with 8 ground stations	Operational circa 1975
ILS	10,000/200,000	0.1 deg	LOS, 20 nm; ± 35° azimuth	20,000/500
Microwave LGS	10,000/200,000	25 ft range; .3 milliradian & elevation	LOS, 30 nm; ± 90° azimuth	Under development
Primary Radar	—/400,000	1,000 ft range; 1° azimuth	LOS, 200 nm	—/300
ATCRBS	6,000/30,000	400 ft range; .25° azimuth; 100 ft altitude	LOS, 200 nm	5,000/300
DABS	---	200-600 ft	LOS	Planning stage
Doppler	1,500/—	2-3 kt	Unlimited	5,000/—
Inertial	70,000/—	1 kt	Unlimited	5,000/—
RNAV	4,000/— (plus VOR & DME)	2 nm enroute 1 nm terminal; 1/2 nm approach	LOS, 200 nm	100/—

[a]Cost in dollars of: airborne equipment/ground equipment

[b]LOS - Line-of-Sight

[c]Number of airborne sets/number of ground stations or chains

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Figure 30 provides a comparison of the approximate accuracy of various navigation systems as function of range from the ground station. The systems which depend on angle measurement (such as MLS, VOR and radar) have position errors that increase
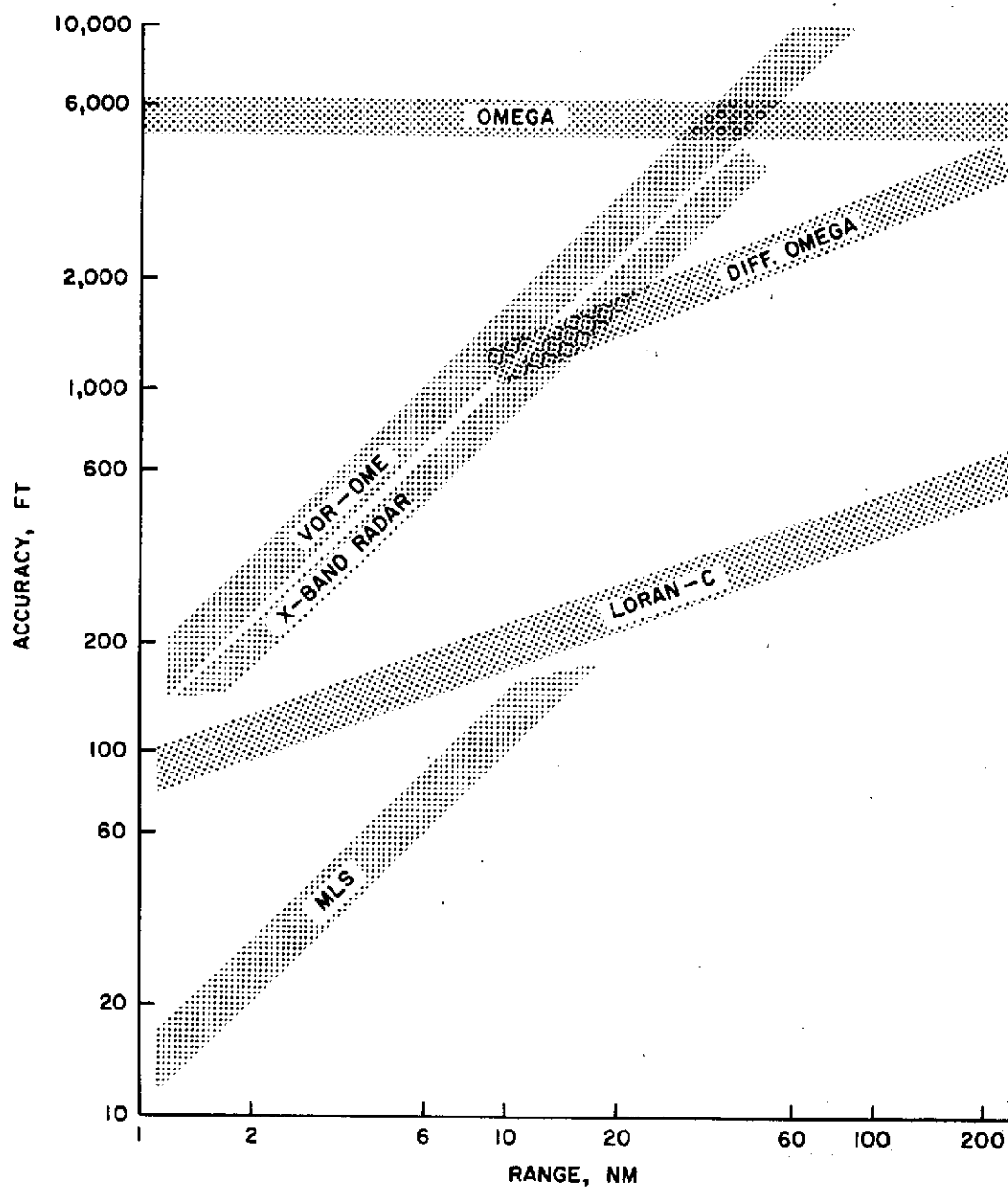
Figure 30. Approximate Navigation Accuracy vs. Range.

linearly with range. LORAN-C position accuracy decreases with range because of poorer geometry and signal-to-noise ratio. The range for a hyperbolic system is inter- preted roughly as the displacement from the baseline between station pairs. Differen- tial OMEGA has degraded accuracy with range from the station determining the differential correction. Although several of the relationships are crudely defined, the figure is helpful for making gross comparisons between systems.

Figure 31 indicates how the accuracy of the navigation or surveillance system affects the allowable separation between aircraft. The plot assumes that aircraft must be separated by a distance 5 to 10 times the uncertainty in measured position. By relating the accuracy to specific navigation systems indicated along the horizontal axis, it is possible to see in a comparative sense the potential spacing allowed by each system.
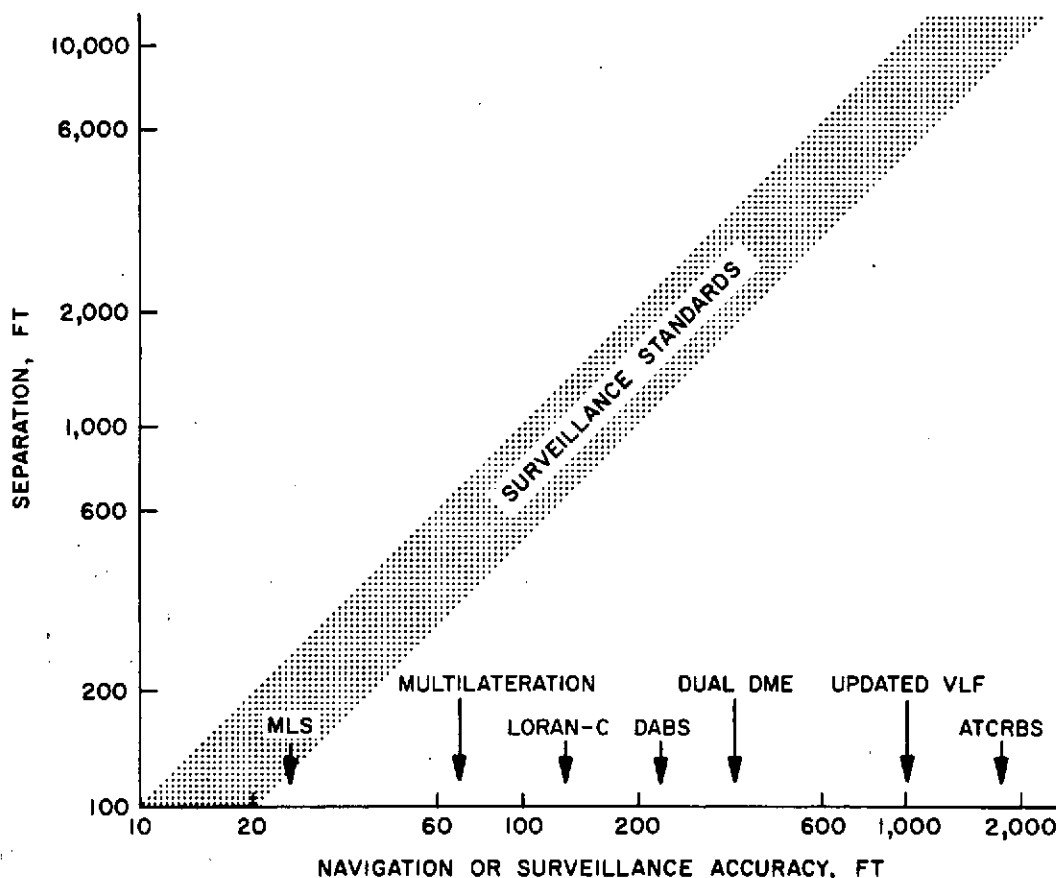
Figure 31. Separation Standards vs. Navigation or Surveillance Accuracy.

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Figure 32 shows the approximate navigation accuracy required to achieve specified visibility minimums. The approximate relationship was determined by using the established minimums for existing approach navigation systems. The normal CTOL and the newly-defined VTOL approach categories are indicated at various points along the visibility axis. Several specific navigation systems are indicated along the accuracy axis. The figure permits approximate prediction of the approach categories the various systems can achieve.
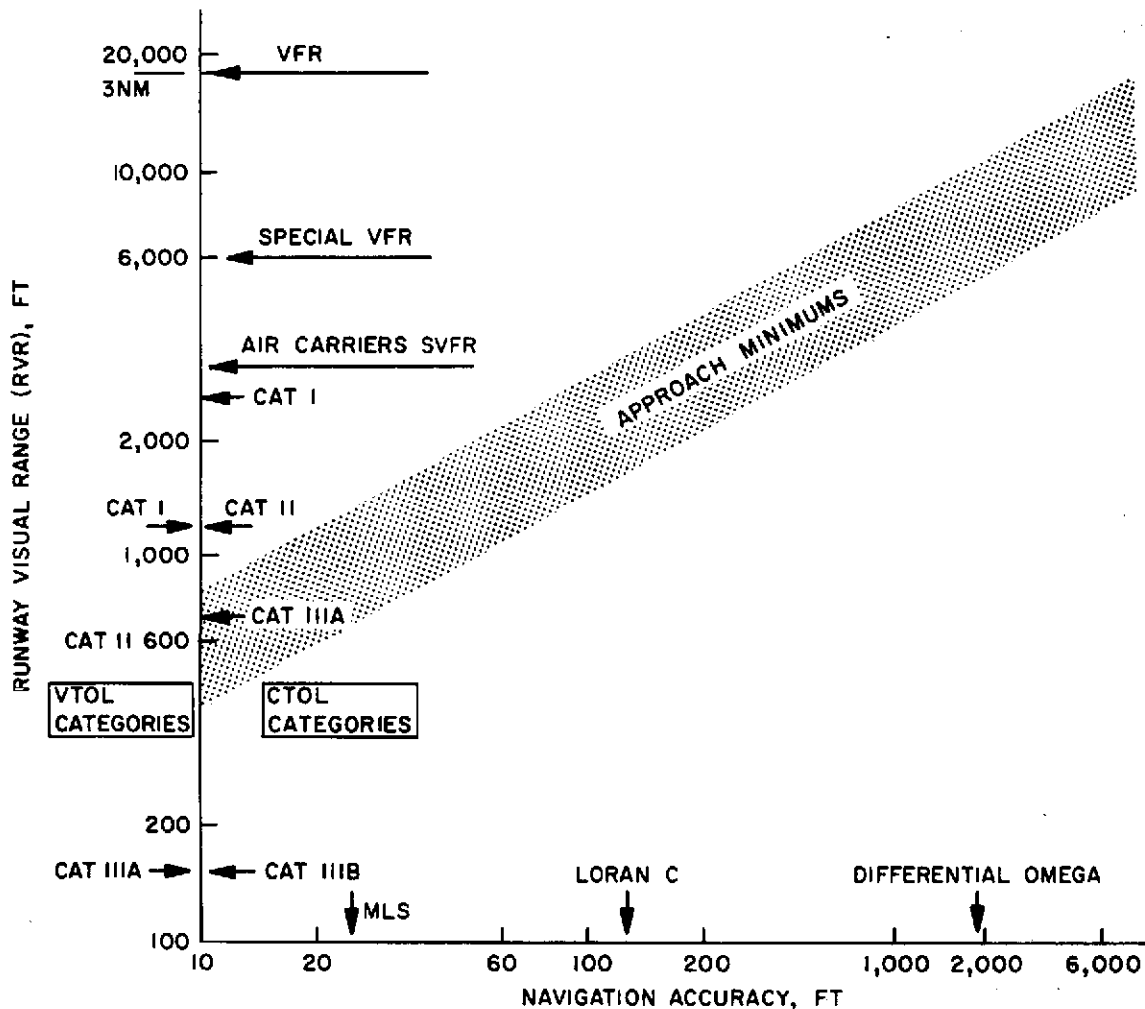
Figure 32. Visibility Minimums (RVR) vs. Horizontal Navigation Accuracy.

Figure 33 shows how the minimum ceiling and minimum visibility are usually paired. This allows the RVR minimums shown on the other plots to be translated into equivalent minimum ceilings for those who prefer to think in terms of ceiling rather

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than visibility minima. Moreover, low ceilings and low visibility tend to occur to-
gether in nature in about the way they are shown in the figure. The VTOL and CTOL
approach categories are indicated along the curve. This figure illustrates how much
worse the weather must be to require a particular approach capability for VTOL as
opposed to CTOL.
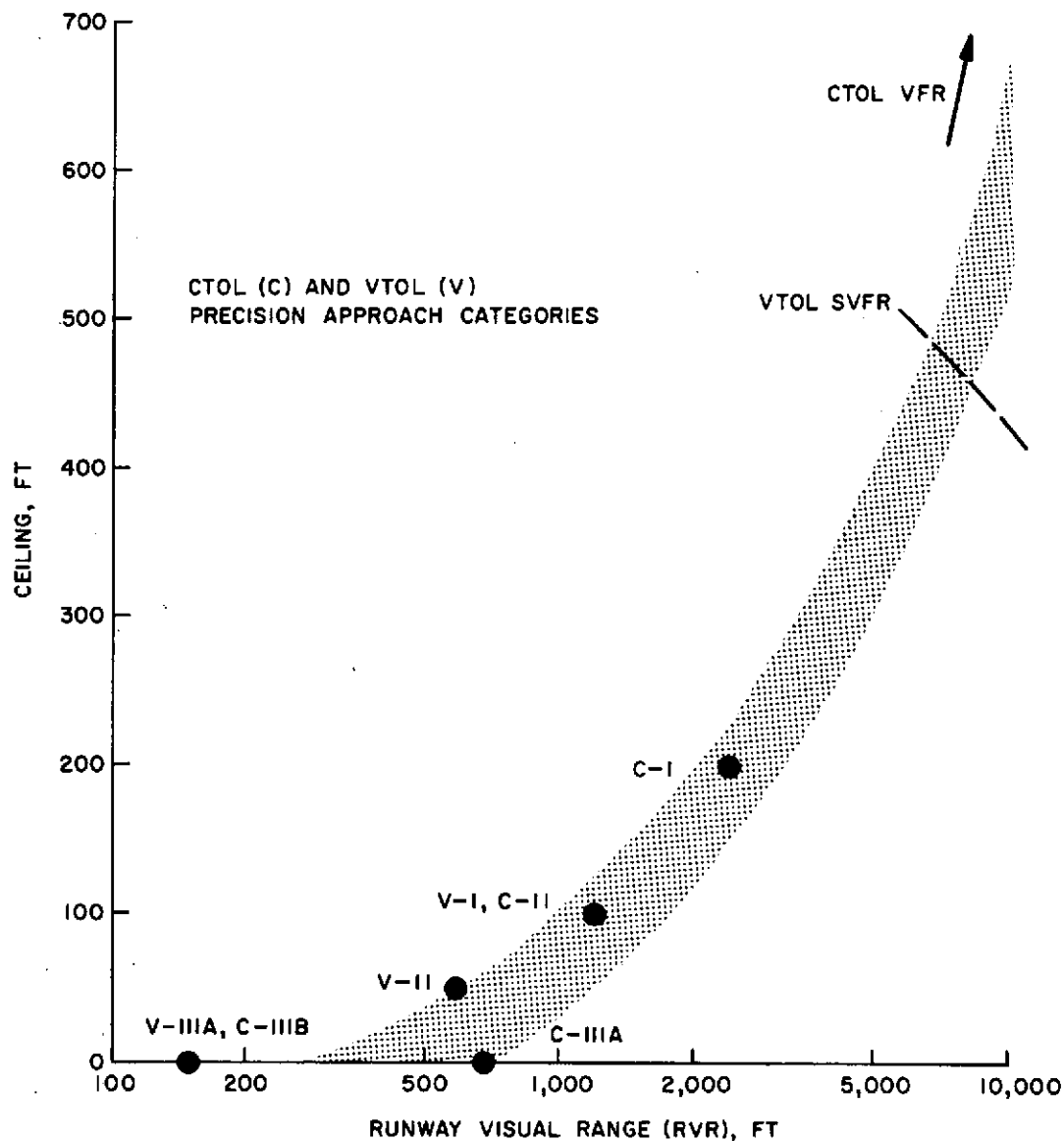
Figure 33. Typical Minimum Ceiling vs. Runway Visual Range (RVR).

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Figure 34 shows the percentage of the year when the weather is below a particular RVR for Boston, London and a point 500 feet above ground at Boston (which might represent an elevated V-port). The various approach categories are shown on the RVR axis. The important observation is that the percentage of the time for which very low approach capability is required is itself extremely small. Operations to an elevated V-port which projects up into low clouds does increase the percentage of time a given approach capability is required. For operators trying to avoid the expense of a low approach capability, it may not be attractive to elevate the landing site. Another important observation is that the percentage of time that IFR operation is required is very small. This means that it is very difficult for pilots to maintain their proficiency for normal IFR operation, to say nothing of Category I, II or III operations. As desirable as it may be to have all-weather capability at the V-port, it may not be economically feasible for the commercial operator to maintain either the equipment or the required pilot proficiency.
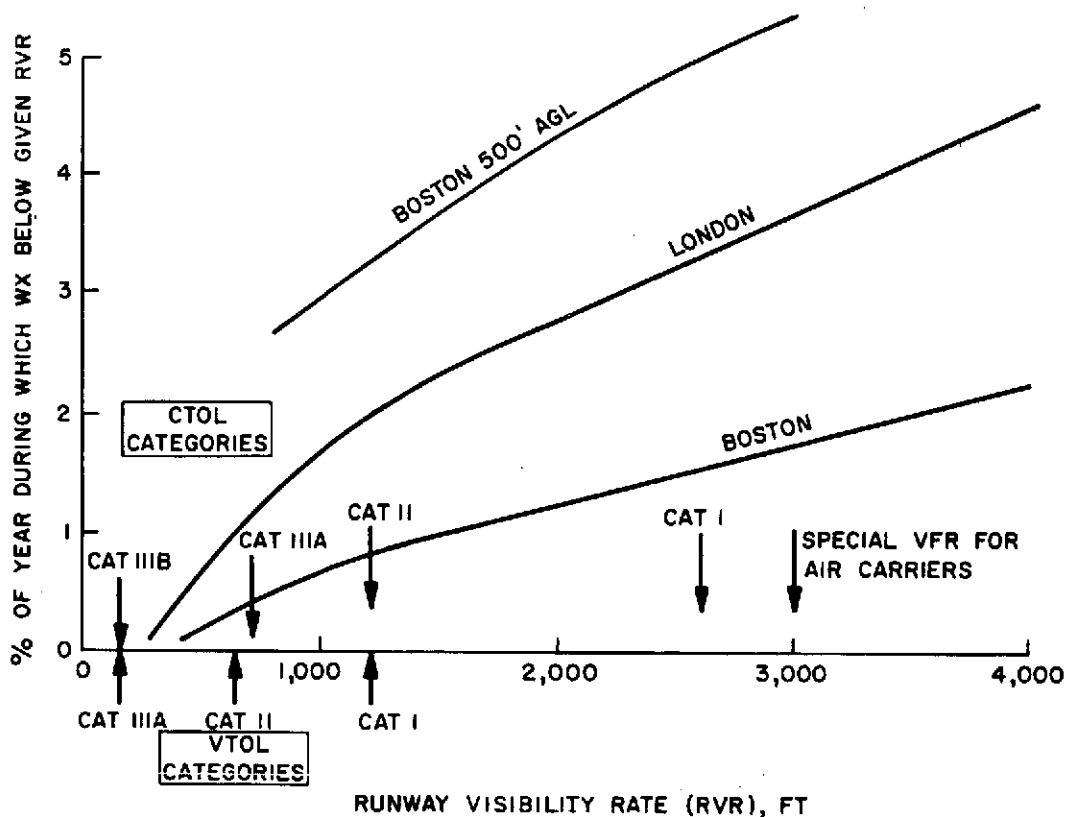
Figure 34. Probability of Low Visibility.

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Figure 35 relates the percentage of trips lost because the weather is below the minimums associated with a given navigation accuracy. Also shown is an approximate indication of the percentage of trips lost to other factors such as maintenance, lack of crews, etc. A commercial operator will not put a large investment into approach capability if the percentage of trips which require it is small relative to the percentage of trips lost to other factors. The point is that the percentage of trips which require VTOL CAT I or II is, at the present time, smaller than the percentage of trips lost to other factors. Consequently, it seems unlikely that VTOL Category III capability will be required for commercial operations within the next decade.
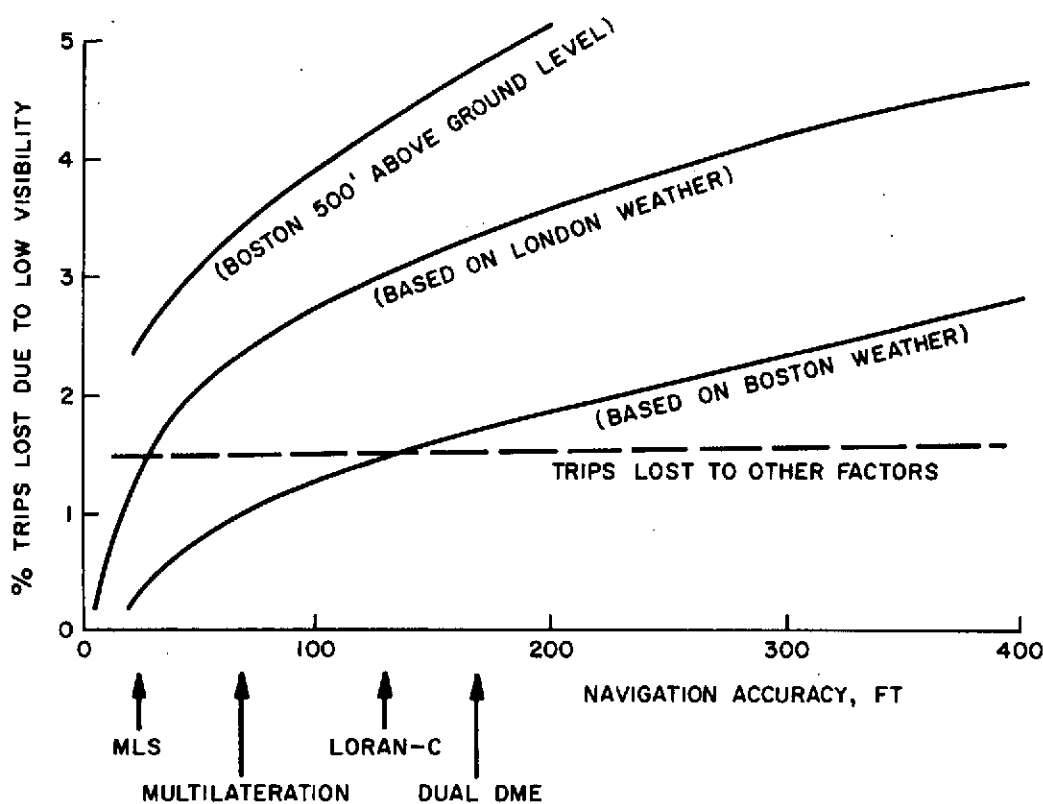
Figure 35. Schedule Reliability vs. Navigation Accuracy.

SECTION 4

VTOL NAVIGATION AND GUIDANCE SYSTEM

This section describes the straw-man navigation and guidance systems proposed for application to commercial VTOL operations. A computer simulation program was developed to provide a flexible tool for the evaluation of alternate navigator configurations, guidance schemes, estimator algorithms, error sensitivities, etc. The recursive Kalman filter formulation is developed, and error models are presented.

4.1   OVERALL SYSTEM DESCRIPTION

Operations of the proposed system are keyed to a fully automatic systems approach for navigation, guidance, and control, with the pilot as a monitor-manager. A functional block diagram of an automatic VTOL avionics system showing the flow of information and the relationships of the three principal subsystems (navigation, guidance and flight control) is presented in Figure 36.
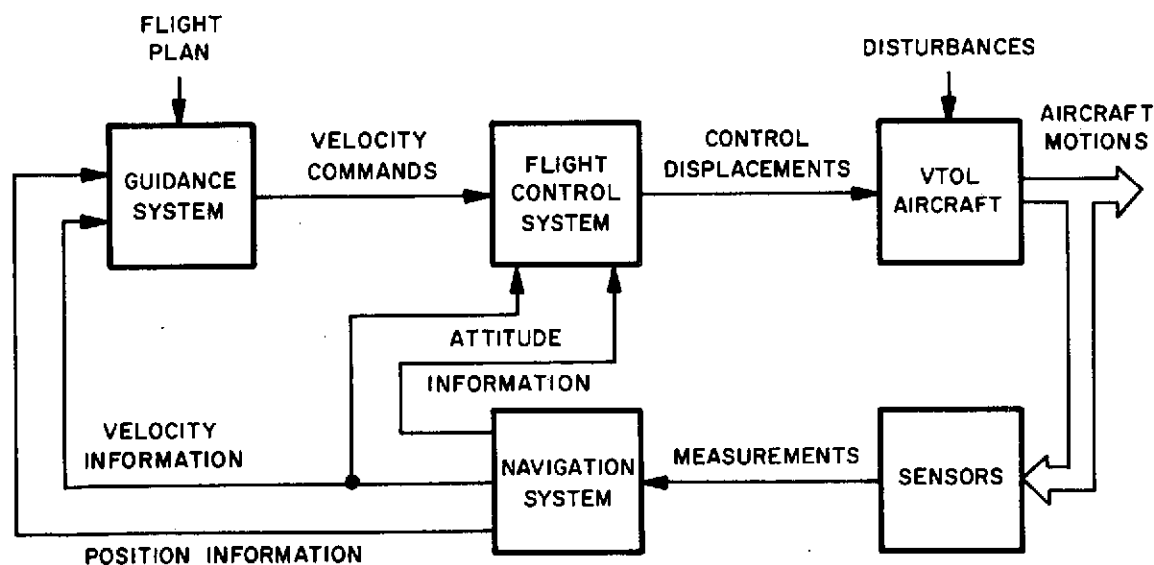
Figure 36. Block Diagram of VTOL Avionics Systems.

The function of the guidance system is to control the position and velocity of the rotorcraft in order to follow a specified flight plan; e.g., to transport connecting passengers from a downtown heliport to a conventional airport. To perform this task,

the guidance system requires position and velocity estimates from the navigation system.
It uses these data to generate velocity commands for the flight control system, which
provides the direct control of the vehicle maneuvers by displacement of the appropriate
controls.

4.1.1   CONFIGURATION

The basic configuration of the recommended navigation system is dictated by
the requirements for independent, all-weather VTOL operation. As discussed in
Section 2, RNAV capability is essential, with sufficient approach accuracy to ensure
schedule reliability to VTOL Category II weather minima. A general multi-configuration
straw-man system is shown in Figure 37, which indicates the principal subsystems and their
interactions. Several alternate sources of navigation information are included for the
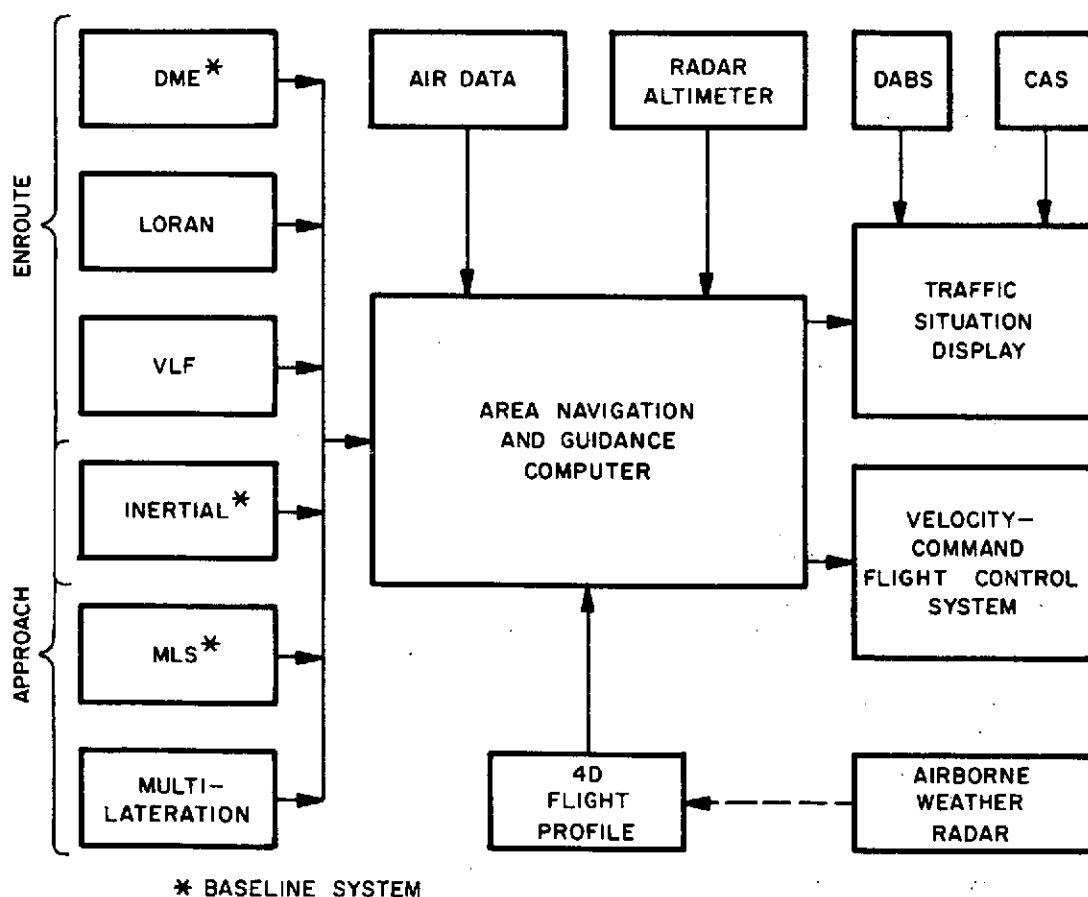
Figure 37. Straw-Man Navigation System for Commercial VTOL Operations.

enroute and approach phases of operation. It is not intended that all of these equip-
ments will be required; however, preliminary analysis indicates those shown could
satisfy the system requirements. Further evaluation is necessary for a final recommenda-
tion. On the other hand, the final system should possess the capability to accept
alternate or additional inputs.

- **Enroute Systems.** The enroute navigation system must provide
  area navigation capability. Four contenders are: Multiple DME,
  Loran, Omega/VLF, and INS.

- **Approach Systems.** Previous studies with the LaRC CH-46 tandem-
  rotor helicopter have indicated that an inertial navigation system
  is needed for the precision approach, hover, and landing phases
  of flight. The strongest alternate contender for approach navi-
  gation is the MLS. Consideration is also being given to a multi-
  lateration system.

The baseline straw-man system is a hybrid navigator which uses a relatively
low-cost inertial sensor with DME updates, and MLS as well in the approach/departure
phases. The selection is based on the requirements for independent, all-weather VTOL
operation. The requirement for independent operation dictates a capability for low
altitude airways, steep and curved approaches around obstacles, traffic, and noise
sensitive areas. This in turn implies a 4D RNAV capability at low altitude. The inclu-
sion of 4D RNAV capability would allow precise arrival times at the landing threshold,
initial and final approach fixes and, if required, intersections with CTOL routes. This
can be expected to lower the dispersion of arrival times to 5 seconds and offer a 30- to
40-percent increase in landing capacity (Ref. 50). Steep approaches can be performed
with a velocity control system and conventional display. The onboard traffic situation
display provides an independent means for separation assurance from other air traffic
and prominent ground obstructions. The use of airborne weather radar permits pilots to
recognize and avoid severe weather conditions while maintaining precise flight paths
with the RNAV system. Together these systems improve safety and expand all-weather
capability.

The requirement for all-weather VTOL operation also dictates a need for
reliable and redundant automatic landing capability, which places a specification on
the accuracy and dynamic response of the position and velocity data required. Hori-
zontal velocity accuracy of about 2 knots over a bandwidth of about 4 Hz, and position

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accuracy of about 25 feet over a bandwidth of about 1 Hz are needed for landing. Velocity information can be obtained from position measurements, but the specification on position data then must have higher accuracy over a wider bandwidth in order to meet the velocity specification. The accuracy requirement on the velocity information is only moderate for a velocity-sensing device such as an inertial system, but it is quite severe if the velocity is obtained from position data.

A basic argument for the hybrid navigator is the need for accurate velocity information over the high frequency portion of the vehicle's motion spectrum. The hybrid gives additional advantages in that the accuracy of the radio navigation system is enhanced over its unaided performance, and greater reliability is gained through redundancy.

The choice of an inertial system over air data or Doppler is based on cost and reliability. Attitude information is already required for IFR capability and a computer is necessary to provide the RNAV computations; the only additional components required for an inertial system are the accelerometers. The only existing navaid capable of providing position information sufficiently accurate to meet the velocity specifications is the MLS. However, loss of an MLS signal could leave the rotorcraft in a compromising control situation without velocity information. Airspeed and heading data are inadequate at low airspeeds near the ground. The choice of radio navaids for enroute navigation is not as compelling. None of the existing enroute systems is sufficiently accurate in its present form to provide approach guidance to even CTOL Category I minima. On the other hand, all are sufficiently accurate to satisfy enroute requirements and to place the rotorcraft within the window of an accurate landing guidance system. Both Loran and Omega require external velocity information in order to achieve the long averaging times necessary for accuracy.

4.1.2 OPERATION

The area navigation computer is the focal point of the straw-man system. Sensor inputs include DME ranges; Loran, Omega or VLF time difference measurements; inertial attitudes and velocities; MLS azimuth and elevation; multilateration ranges; and radar altitude. The air data system feeds pressure altitude vertical speed and airspeed to the system. Principal data inputs to the system are: estimated wind speed and direction; track/waypoint sequence; and ground-based system coordinates. The major

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outputs are velocity corrections to the flight control system, and position and heading to the TSD. The TSD accepts position information on other proximate aircraft or obstructions from DABS and/or CAS to provide a relative indication of potential hazards. The system would also be interfaced with conventional displays by providing distance-to-go, cross-track distance and track angle error.

The computer algorithms include:

- Linearized solution of position fix.
- Short term air data dead reckoning solutions which add position movements to aircraft lat/long, thereby compensating for position update delay times in the airborne computer.
- Coordinate conversion of coded waypoints whenever they are not in memory.
- Great circle solution for desired course.
- Wind solution for wind along-track, wind cross-track.
- Ground speed and actual track.
- Distance to go and time to go.
- Steering solution in terms of track angle error.
- Cross-track distance.
- Longitudinal, lateral and vertical velocity corrections for VCFCS.
- Limit logic computations.
- Automatic leg changeover.
- Automatic determination of Start Turn Point to achieve track-to-track change.

The variables would be computed in a single iteration and stored until displayed or dumped. Nondestructive readout of coded waypoints is assumed; storage is required for ground station frequencies, identification, and coordinates; waypoint storage including mandatory report logic is assumed; altitude processing for glide slope computation is included; flight plan storage is provided.

4.2 . VALT SIMULATION PROGRAM

A digital simulation program entitled VALT (VTOL Automatic Landing Technology) is being developed to analyze the straw-man navigation system performance and to conduct parametric studies of subsystem errors. Figure 38 is a general block

diagram depicting the major elements of the simulation. $\underline{x}$ is the state vector of the rotorcraft:
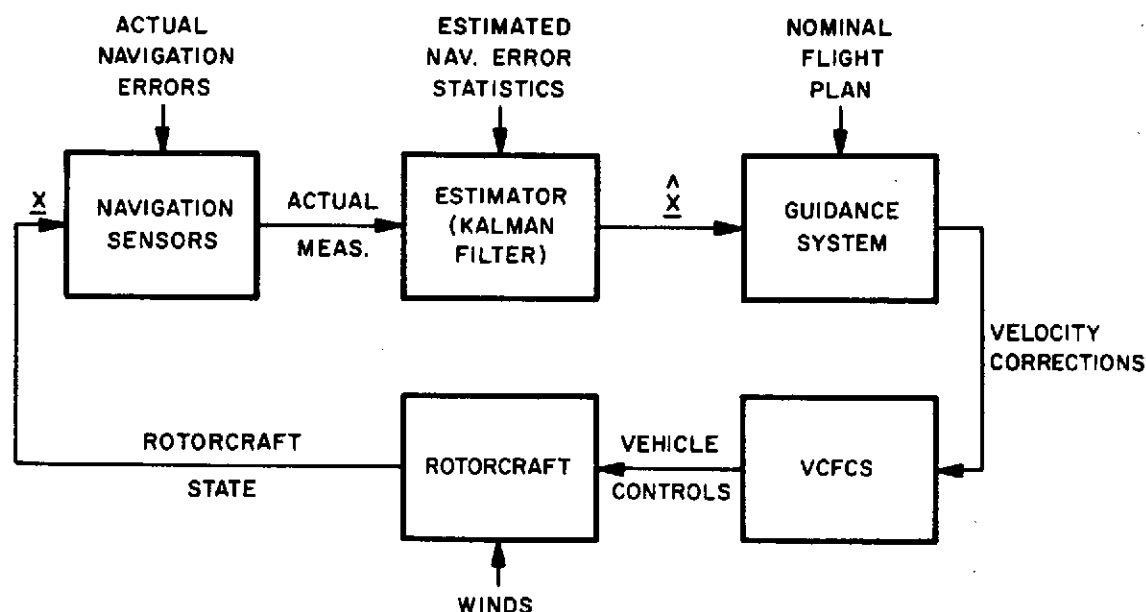
Figure 38. Block Diagram of Program VALT.

$$\underline{x} = \begin{bmatrix} V_N \\ V_E \\ V_D \\ L \\ \ell \\ h \end{bmatrix} \tag{6}$$

where V_N, V_E, V_D are the North, East and Down components of ground-referenced velocity; L, ℓ, h are the latitude, longitude and altitude position coordinates. Appendix A contains details of the equations of motion and the coordinate frames used in the analysis. The estimate of the state provided by the navigation system is $\hat{x}$. The guidance system generates velocity corrections, which the flight control system converts into rotorcraft attitude and thrust commands. Details of each element of VALT shown in Figure 38 are presented in the following discussions.

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4.2.1 ROTORCRAFT MODELS

An analytical model has been developed to represent the point-mass dynamics of a rotorcraft. This model, described in Appendix A, neglects the rotational dynamics of the vehicle and describes the rotorcraft translational motion in terms of the external forces acting upon it. For purposes of preliminary navigation and guidance system analyses, the vehicle and rotor attitude response dynamics are assumed to be negligible. The control inputs to the model, and the resulting external forces are summarized in Table 16.

Table 16. Rotorcraft Model Control Inputs and Resultant Forces.

Control Variables	External Forces
Rotor Thrust Collective (θ_o)	Rotor Forces (T, H, Y)
Rotor Thrust Orientation (β_1, β_2)	Airframe Drag (D_p)
Vehicle Turn Rate (r_c)	Gravitational Force (W)
Vehicle Pitch Attitude* (θ_c)	Wing Lift and Drag* (L, D_i)
Vehicle Roll Attitude* (ϕ_c)	Auxiliary Propulsion Thrust* (P)
Auxiliary Propulsion Throttle* (η)	

*Compound Helicopter Only.

The rotorcraft model is applicable to either the pure helicopter or the compound helicopter configuration. In the case of the pure helicopter, the wing lift L, induced drag D_i, and propulsion system thrust P are equal to zero.

For the compound helicopter, certain assumptions are necessary regarding the sharing of lift and control functions between the airframe and the rotor. In the speed range between zero and 80 knots, the Sikorsky Model S-65-200 compound behaves essentially as a pure helicopter, and all the lift is supplied by the rotor. From 80 knots up to the maximum flight speed of 261 knots, rotor thrust can be assumed to decrease linearly to a final value of about one-third of the value at 80 knots: the remaining lift is supplied by the wing. Control is provided entirely by moments due to the rotor up to 80 knots. From 80 to 140 knots, control is provided by a mixture of rotor moments and conventional airplane-type elevator-, aileron- and rudder-induced

moments. Finally, from 140 knots to 261 knots, control is entirely of the conventional airplane type.

4.2.2 FLIGHT CONTROL SYSTEM

Routine commercial VTOL operations under IFR flight conditions will undoubt-edly require an advanced flight control system. For this study, a velocity-command flight control system (VCFCS) has been assumed. Unfortunately, the development of such a system is a significant task, which has not been performed for the two Sikorsky models used for this study. In lieu of this, a VCFCS design developed for the LaRC YHC-1A tandem-rotor helicopter (Ref. 51) was selected for use in the simulation. However, dynamic responses with characteristic times of one second or less were ne-glected in the interests of simplicity and to conserve simulation time. The VCFCS is shown in Figure 39. The guidance commands V_{X_G}, V_{Y_G} and V_{Z_G} are the errors between desired and actual velocity components in the level-heading frame (defined in Appendix A). The VCFCS outputs are the rotor collective command θ_o, the rotor atti-tude commands β_1 and β_2, and vehicle-commanded yaw rate y_c. The lateral control axis shown in the lower half of the figure has two modes of operation. The "cruise" or high speed mode feeds back sideslip angle to provide coordinated turns. The "hover" mode attempts to maintain heading for speeds below 30 kt.

It is expected that the basic VCFCS shown in the figure should be adequate for analyzing these helicopters, although some adjustments might be necessary to the parameter values. In addition, appropriate limits are required on the VCFCS outputs. For example, the bank angle and yaw rate commands are limited to a "standard rate turn" of 3° per second.

The VCFCS in Figure 39 contains two integrations in the lateral axis hover mode. In addition, yaw rate must be integrated to yield yaw angle changes. These features require the addition of three state variables to the rotorcraft state vector $\underline{x}$ for the numerical integration of the system equations.

4.2.3 GUIDANCE SYSTEM

A simple perturbation guidance scheme (Ref. 52) has been developed to pro-vide the velocity corrections to the VCFCS. As described in Appendix B, this provides
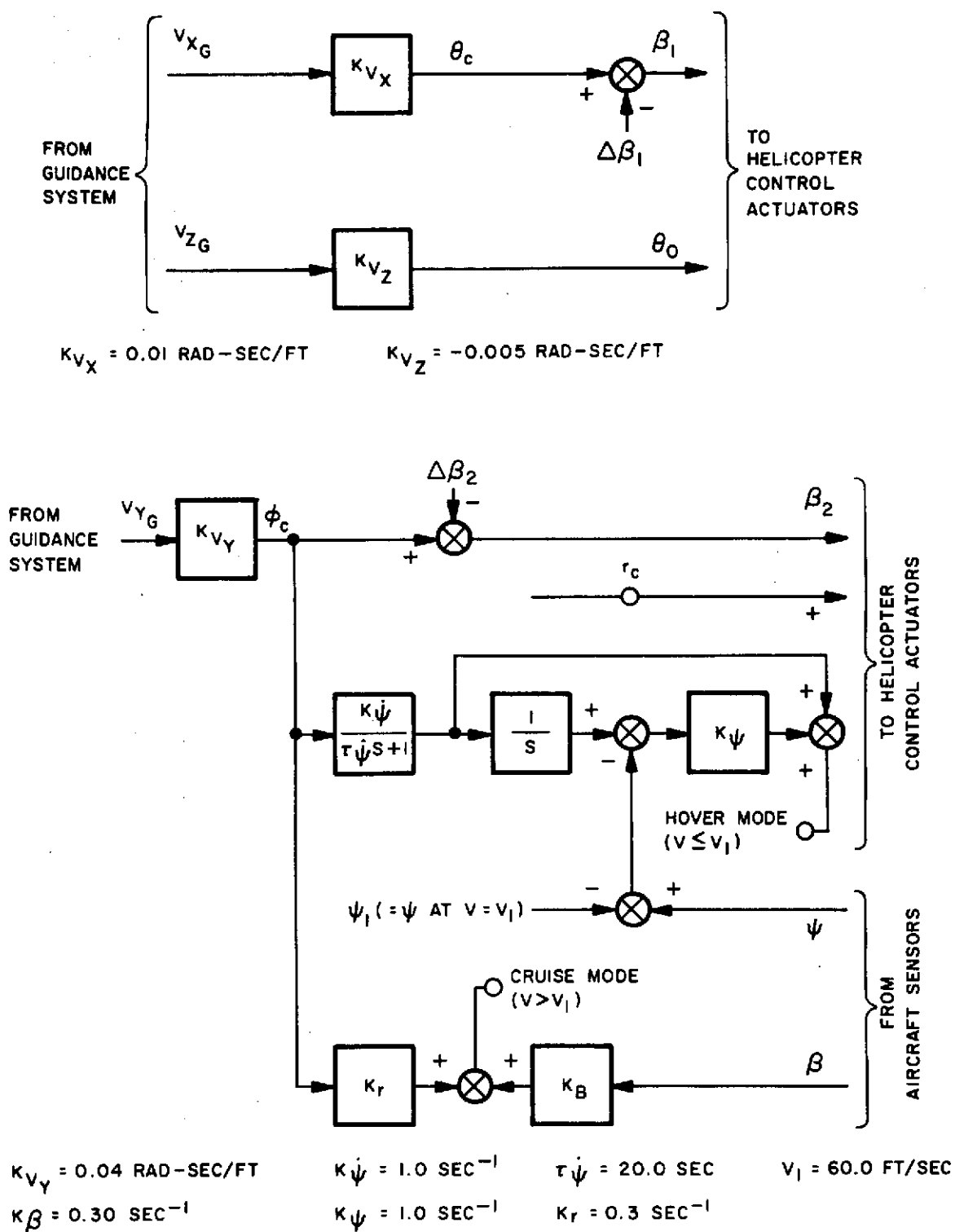
Figure 39. Velocity Command Flight Control System.

a linear feedback guidance law, based upon a specified nominal flight path. Figure 40 illustrates the guidance scheme. The estimated position coordinates $\hat{L}$, $\hat{\ell}$, $\hat{h}$ are compared with the values on the nominal flight path L^*, ℓ^*, h^*; any deviations produce velocity corrections δV_N, δV_E, δV_D. These corrections are subtracted from the corresponding nominal velocity components V_N^*, V_E^*, V_D^* to produce revised velocity commands. The components V_{X_G}, V_{Y_G}, V_{Z_G} input to the VCFCS in Figure 39 are obtained by subtracting the current velocity estimates, and converting the results into the vertical-heading plane.
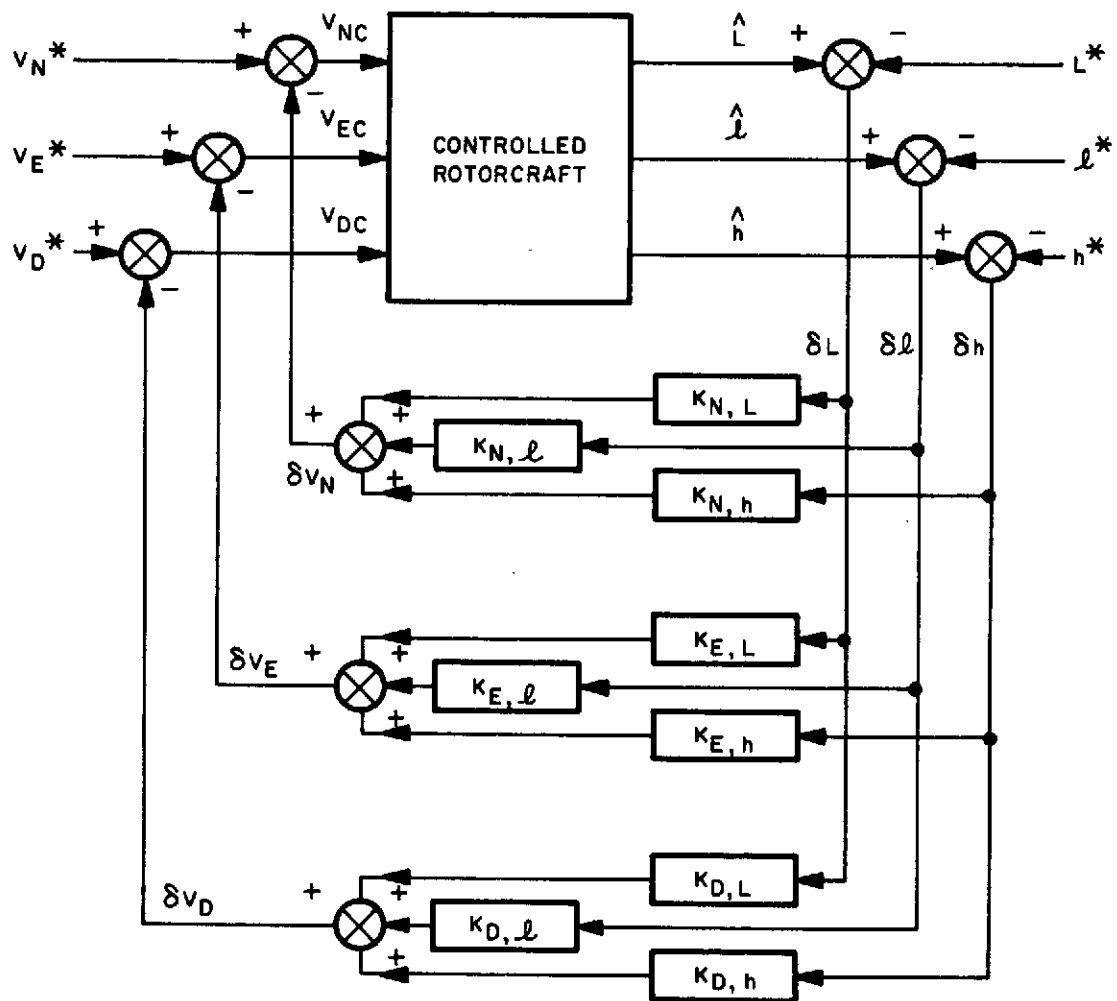
Figure 40. Rotorcraft Guidance Scheme.

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To implement the guidance scheme, the nominal state variables, the nominal control variables, and the feedback gains are precalculated and stored as functions of time in the onboard computer. During flight, the actual state variables are measured and their deviations from nominal used to calculate corrections to the stored nominal control variables.

An interesting problem in the guidance algorithm is determining the criterion used in changing from one leg of the nominal path to the next when in the vicinity of a waypoint. As illustrated in Figure 41(a), the rotorcraft will never pass a waypoint exactly due to system errors and dynamics. The approach taken was to specify a desired airway width, w, and changeover to the next leg when intercepting the extension of that leg-boundary (Fig. 41(b)). This provides lead in the turn when the aircraft is on the outside of the airway centerline, and lag when it is on the inside. To apply this criterion, the guidance system determines the estimated distance, d, from the extended centerline of the next leg, and compares it with w. From geometry,

$$d \approx \hat{r} (\Delta L \sin \Psi_{i+1} - \Delta \ell \cos L_{i+1} \cos \Psi_{i+1}) \tag{7}$$

where $\Delta L = \hat{L} - L_{i+1}$ and $\Delta \hat{\ell} = \ell - \ell_{i+1}$. The criterion then is:

$$|d| \begin{cases} > w & \text{continue on leg } i \\ \\ \leq w & \text{change to leg } i + 1 \end{cases} \tag{8}$$

4.3 HYBRID NAVIGATOR

The hybrid navigator accepts measurement data from the various systems shown in Figure 37, and processes them via a linear Kalman filter to provide the optimum estimate of the rotorcraft state $\hat{x}$ for the guidance system calculations. The following discussion describes the formulation of the recursive filter, the error models for the actual measurements, and the error models assumed by the onboard estimator.

4.3.1 RECURSIVE FILTER

The analysis is based on the minimum variance estimator as derived by Kalman for the discrete measurement case (Refs. 53, 54). The filter operates on a system of

(a)

(b)

(c)
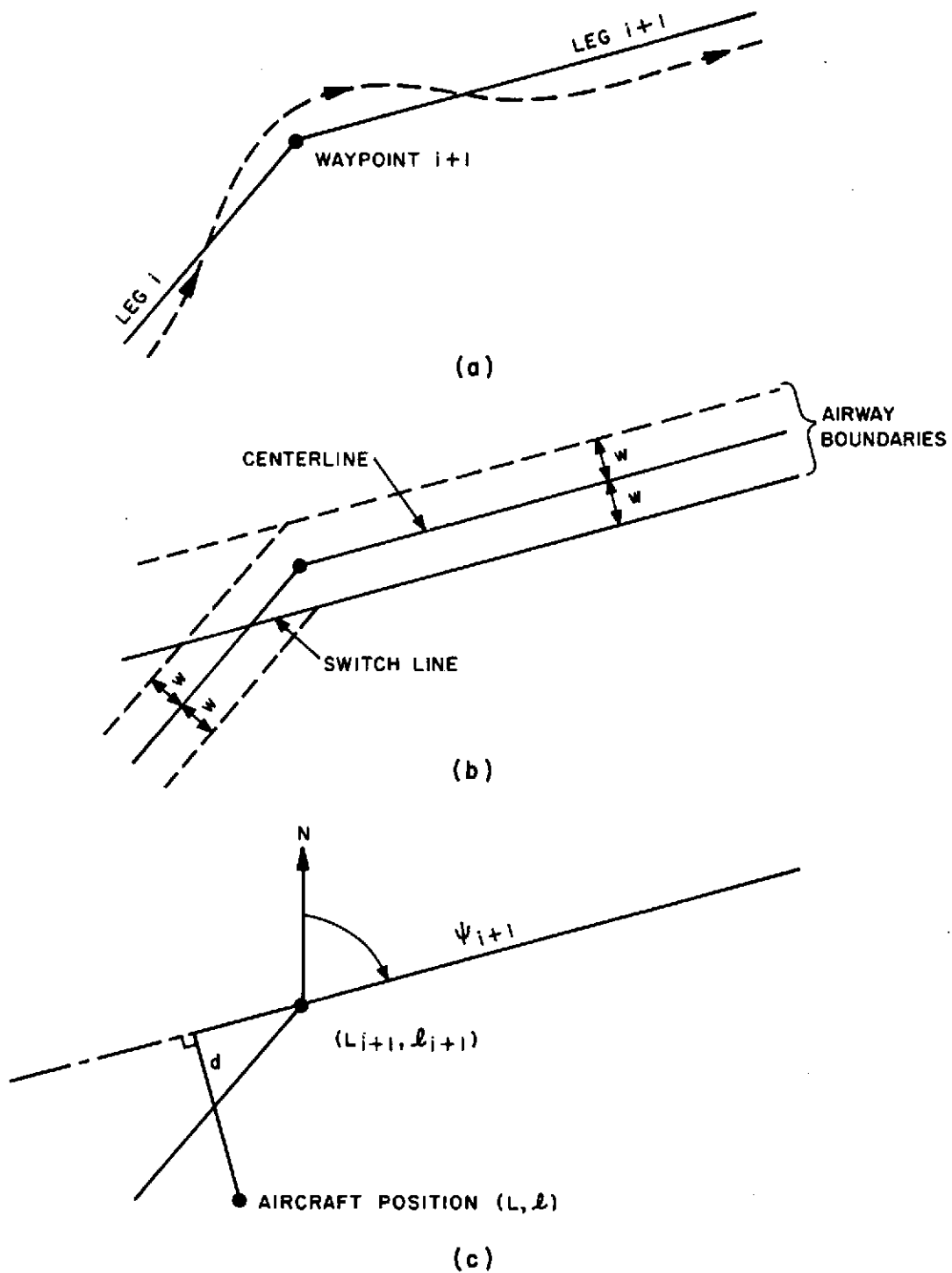
Figure 41. Guidance Leg Changeover.

navigation errors which are referenced to the nominal flight plan $\underline{x}^*$. The error equations for the hybrid navigation system are written in the conventional, first-order linear form:

$$\dot{\delta \hat{\underline{x}}} = F_1 \, \delta \hat{\underline{x}} + \underline{w}_1 \tag{9}$$

where $\delta \hat{\underline{x}} = \hat{\underline{x}} - \underline{x}^* = $ state vector of estimated navigation system errors

$\qquad \underline{w}_1 = $ vector of forcing functions

$\qquad F_1 = $ linearized system dynamics matrix

The formulation of the Kalman filter imposes the requirement that the system be driven by white (uncorrelated) noise. Because the system errors $\underline{w}_1$ are not necessarily modeled as white noise, "shaping filters" may be introduced to convert white noise inputs into appropriately shaped "colored" noises which describe the correlated statistical behavior of the error sources (Ref. 55). Thus, the estimator state must be augmented to include the shaping filter states:

$$\underline{y} = \begin{bmatrix} \delta \hat{\underline{x}} \\ \underline{b} \end{bmatrix} = \text{estimator state} \tag{10}$$

where $\underline{b}$ is a vector of assumed measurement errors (correlated noises, biases or scale factors). The error equations for the augmented estimator state are

$$\dot{\underline{y}} = F\underline{y} + \underline{w} \tag{11}$$

where F is the augmented system dynamics matrix and $\underline{w}$ is now a white noise vector.

The error covariance matrix of $\underline{y}$ is defined by

$$P = <\underline{y} \, \underline{y}^T> \tag{12}$$

where $< >$ indicates the expected value. Between measurements, the covariance matrix propagates by the following equation

$$\dot{P} = FP + PF^T + Q \tag{13}$$

where F and G are defined above, and the white noise strengths define Q:

$$< \underline{w}(t) \, \underline{w}(\tau)^T > \; = \; Q(t)\delta(t - \tau) \tag{14}$$

where $\delta(t)$ is the Dirac delta function.

The initial conditions for the covariance matrix must be specified

$$P(t_0) = \; < \underline{y}(t_0)\underline{y}^T(t_0) > \tag{15}$$

The noise strengths Q are assumed to be constants, which must also be specified. For an exponentially-correlated error, the noise strength is calculated from the variance (σ^2) and the correlation time (τ) of the noise:

$$Q = 2\sigma^2/\tau \tag{16}$$

To incorporate measurements, the recursive navigation technique (Ref. 56) will be used to avoid matrix inversion and to eliminate unnecessary computation on missing measurements. With this approach, each measurement will be a scalar:

$$\delta\hat{m} = \hat{m} - m^* = \underline{h}^T\underline{y} + r \tag{17}$$

$\underline{h}$ is a "geometry" vector which selects the components of the rotorcraft state error measured plus the measurement error; it is determined by the type and geometry of the measurement; r is assumed additive random noise in the measurement. $\hat{m}$ is the estimate of the measurement based on the linear error model of Eq. (11). In fact, the actual measurement is usually a nonlinear function of the actual rotorcraft state:

$$m = m(\underline{x}, t) \tag{18}$$

Whenever a measurement is taken, the estimate of the error state is updated as follows:

$$\underline{y}^+ = \underline{y} + \underline{K}(\delta m - \delta\hat{m}) \tag{19}$$

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where $\underline{y}$ is the estimate just before the measurement, and $\underline{y}^+$ is the estimate after incorporating the measurement. $\underline{K}$ is the vector of filter gains. As a result of the measurement, the error covariance matrix is updated as follows:

$$P^+ = (I - \underline{K}\,\underline{h}^T)P(I - \underline{K}\,\underline{h}^T)^T + \underline{K}R\underline{K}^T$$

$$= (I - \underline{K}\,\underline{h}^T)P - [P\underline{h} - \underline{K}(\underline{h}^TP\underline{h} + R)]\underline{K}^T \tag{20}$$

The optimum (Kalman) filter gains provide the minimum-variance estimate of the navigation system errors:

$$\underline{K}_{opt} = \frac{1}{\alpha}\,P\,\underline{h} \tag{21}$$

where

$$\alpha = \underline{h}^T P\underline{h} + R \tag{22}$$

$$R = < r^2 > = \text{random measurement error variance} \tag{23}$$

The optimum update of the covariance matrix is then

$$P^+ = (I - \underline{K}_{opt}\underline{h}^T)P = P - \alpha\underline{K}_{opt}\underline{K}_{opt}^T \tag{24}$$

The value of P^+ is used as the initial condition on P to start the next interval between updates.

4.3.2   NAVIGATION SENSOR ERRORS

Error models have been developed to represent the actual measurements which would be provided by each of the straw-man navigation systems.

● Air Data

The air data system measurements consist of airspeed, barometric altitude, and altitude rate. The principal error in the airspeed measurement $\tilde{V}_a$ is the wind, so instrument errors will be neglected:

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$$\tilde{V}_a = V_a = [(V_N - W_N)^2 + (V_E - W_E)^2 + (V_D - W_D)^2]^{1/2} \qquad (25)$$

where W_N, W_E and W_D are the North, East and Down components of the wind.

The horizontal wind can be approximated as a steady wind, plus an exponentially correlated wind with specified correlation distances (d) and standard deviations, plus random gusts. These are expressed in terms of the wind speed (V_w) and its direction (θ_w):

$$V_w = V_{w_s} + V_{w_c} + V_{w_g} = \sqrt{W_N^2 + W_E^2} \qquad (26)$$

$$\theta_w = \theta_{w_s} + \theta_{w_c} + \theta_{w_g} = \tan^{-1}(W_E/W_N) \qquad (27)$$

where

$$\dot{V}_{w_c} = -V_{w_c}/\tau_{v_w} + w_{v_w} \qquad (28)$$

$$\dot{\theta}_{w_c} = -\theta_{w_c}/\tau_{\theta_w} + w_{\theta_w} \qquad (29)$$

where $\tau = d/V_g$ is the effective correlation time and w is a white noise whose strength is obtained by Eq. (16).

The vertical wind is modeled as exponentially-correlated plus a random gust:

$$W_z = W_{z_c} + W_{z_g} = -W_D \qquad (30)$$

$$\dot{W}_{z_c} = -W_{z_c}/\tau_{w_z} + w_{w_z} \qquad (31)$$

The altimeter error is modeled as a scale factor error plus a random error

$$\tilde{h} = K_h h + w_h \qquad (32)$$

where the scale factor K_h is a constant

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$$\dot{K}_h = 0 \tag{33}$$

The vertical speed measurement is included primarily for damping of vertical motions. The steady state error is assumed to be negligible

$$\tilde{\dot{h}} = \dot{h} \tag{34}$$

● INS

The error model for a single axis of the inertial navigator is shown in Figure 42 based on Reference 28. The errors w and n are white noises of strengths W and N respectively. The strengths of N and W are shown in the figure for a typical 1-knot system. The INS measurements are:

$$\tilde{V}_{INS_N} = V_N + v_N \tag{35}$$

$$\tilde{V}_{INS_E} = V_E + v_E \tag{36}$$
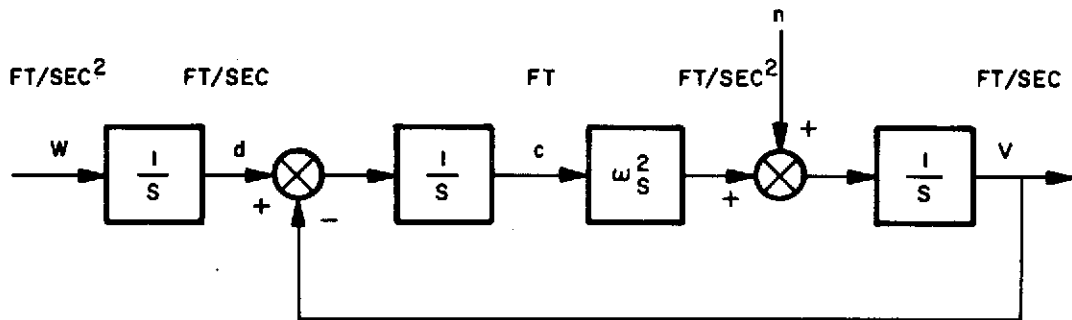
$$
\text{I KT INS} \begin{cases} N = 10^{-4} \text{FT}^2/\text{SEC}^3 \\ W = 10^{-2} \text{FT}^2/\text{SEC}^3 \end{cases}
$$

ω_S = SCHULER FREQUENCY $(\omega_S^2 = g/R_e)$
d = GYRO DRIFT RATE AS A VELOCITY
c = PLATFORM TILT AS A DISPLACEMENT

Figure 42. Error Model for Single Axis of an INS.

● DME

The major error in a DME measurement is a range bias with a standard deviation of about 500 feet. This bias may be estimated and subtracted out if there are

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redundant measurements (by using more than two DME stations or with a hybrid navigator, for instance). In that event the remaining error is white noise with a strength of about 10^5 ft^2 sec. The DME range measurement is therefore:

$$\tilde{R}_D = \left\{ r_e^2 \left[(L - L_D)^2 + \cos^2 L_D (\ell - \ell_D)^2 \right] + (h - h_D)^2 \right\}^{1/2}$$
$$+ b_D + w_D \tag{37}$$

where

$$\dot{b}_D = 0 \tag{38}$$

and L_D, ℓ_D, h_D are the coordinates of the DME ground station. The model assumes a reasonably high quality DME transceiver in the aircraft. At least a partial circuit of the DME facility is required to estimate the bias if the hybrid navigator is working with velocity information only.

- Loran

Atmospheric noise at the receiver is the major source of error in the Loran system. The accuracy depends on the signal to noise ratio, which varies with range and other factors. A white noise of strength 2×10^6 ft^2 sec is a representative value for the position error on the baseline. The geometry vector introduces further accuracy dilution for aircraft locations off the baseline. The measurement for each line of position is a range difference between stations A and B:

$$\tilde{\Delta R} = \rho_A - \rho_B + b_{\Delta R} + w_{\Delta R} \tag{39}$$

where

$$\rho_i = r_e \cos^{-1} \left[\sin L \sin L_i + \cos L \cos L_i \cos (\ell - \ell_i) \right] \tag{40}$$

with i = A, B.

- VLF/Omega

The most significant errors in VLF come from variations in the velocity of

- 128 -

propagation which are due primarily to changes in the reflecting properties of the ionosphere. These depend strongly upon the intensity and angle of incidence of solar radiation, and the errors are therefore a strong function of the time of day and time of year. The stability of the transmission time is on the order of one microsecond (1000 ft), but the ability to predict the transmission time is not yet as good at the propagational stability. Predictable corrections based on date, time of day and distance to the station are equivalent to about 3 or 4 miles in position and leave residual errors of one or two miles. This residual error can be modeled as exponentially correlated with a standard deviation of 1 nm (day) or 2 nm (night) and with a correlation time of 30 minutes. The remaining error is modeled as a white noise of strength 10^7 ft^2 sec, and includes error due to broad-band atmospheric noise at the receiver. The measurement equations are identical to those for Loran, Eqs. (39) and (40).

- MLS

   The position accuracy of the scanning beam MLS is a function of range: C-band accuracy is about 3 feet at 1000 feet range, while K_u-band accuracy is 3 feet at 10,000 feet range. The associated DME accuracy is to be about 25 feet independent of range. The equipment will be capable of providing a fix with a single scan; therefore, the time between fixes is the reciprocal of the scanning frequency, or one-tenth second. The principal position error can be modeled as a white noise of strength $R = \sigma^2 \Delta t$; reasonable values for R are 0.001 $degree^2$ sec for the glide slope and localizer, and 60 ft^2 sec for the DME. The MLS is also subject to a bias in elevation and azimuth of $0.05°$ and $0.09°$, respectively. The model for the MLS elevation measurement is

$$\tilde{\theta}_{el} = \tan^{-1}\left\{ \frac{h - h_m}{r_e[(L - L_m)^2 + \cos^2 L_m(\ell - \ell_m)^2]^{1/2}} \right\} + b_{\theta_{el}} + w_{el} \tag{41}$$

The azimuth measurement is

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$$\tilde{\theta}_{az} = \tan^{-1}\left[\frac{\cos L_m(\ell - \ell_m)}{L - L_m}\right] + b_{\theta_{az}} + w_{az} \tag{42}$$

The DME measurement is the same as in Eq. (37).

4.3.3 ESTIMATOR ERROR MODELS

The airborne estimator will attempt to estimate the rotorcraft state and selected measurement errors, based on a set of predicted error models which will always differ (at least slightly) from the actual errors.

- **Estimator State Vector**

The estimator state is usually selected as a compromise between accuracy and onboard computer requirements. For the present analysis, the estimator state vector is:

$$\underline{\chi} = \begin{bmatrix} \delta\hat{V}_N \\ \delta\hat{V}_E \\ \delta\hat{V}_D \\ \delta\hat{L} \\ \delta\hat{\ell} \\ \delta\hat{h} \\ \hat{W}_N \\ \hat{W}_E \\ \hat{b}_{D_1} \\ \hat{b}_{D_2} \\ \hat{b}_{D_3} \\ \hat{b}_{D_4} \\ \hat{v}_N \\ \hat{v}_E \end{bmatrix} \begin{array}{l} \left.\begin{array}{c} \\ \\ \\ \\ \\ \\ \end{array}\right\} \text{6 rotorcraft state errors} \\ \\ \left.\begin{array}{c} \\ \end{array}\right\} \text{North and East Wind Components} \\ \\ \left.\begin{array}{c} \\ \\ \\ \\ \end{array}\right\} \text{4 DME biases} \\ \\ \left.\begin{array}{c} \\ \end{array}\right\} \text{North and East INS Drifts} \end{array} \tag{43}$$

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For this estimator state, the system dynamics matrix in Eq. (11) is:

$$
F = \begin{bmatrix}
1/\tau_N & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1/\tau_E & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1/\tau_D & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1/R & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \dfrac{1}{R\cos L} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1/\tau_{W_N} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/\tau_{W_E} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/\tau_{v_N} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/\tau_{v_E}
\end{bmatrix}
\tag{44}
$$

The three rotorcraft velocity errors, two wind components and two INS drifts are all modeled as exponentially-correlated processes:

τ_N, τ_E, τ_D = correlation times for pilotage deviations from the nominal path

τ_{W_N}, τ_{W_E} = correlation times for North and East wind components

τ_{v_N}, τ_{v_E} = correlation times for North and East INS drifts

The driving noise in the estimator is

$$
\underline{w} = \begin{bmatrix} {}^{w}N \\ {}^{w}E \\ {}^{w}D \\ 0 \\ 0 \\ 0 \\ {}^{w}W_N \\ {}^{w}W_E \\ 0 \\ 0 \\ 0 \\ 0 \\ {}^{w}v_N \\ {}^{w}v_E \end{bmatrix}
\begin{array}{l} \left.\rule{0pt}{3em}\right\} \text{aircraft acceleration noise} \\ \text{about nominal} \\[3em] \left.\rule{0pt}{2em}\right\} \text{wind noise} \\[5em] \left.\rule{0pt}{2em}\right\} \text{INS accelerometer noise} \end{array}
\qquad (45)
$$

The Kalman filter estimates the perturbations $\underline{y}$ from the nominal path by using the perturbations in the measurement:

$$
\delta m = \frac{\partial m}{\partial \underline{y}} \bigg|^{*} \underline{y} + r = \underline{h}^T \underline{y} + r
\qquad (46)
$$

where r is a random measurement error and

$$
\underline{h}^T = \frac{\partial m}{\partial \underline{y}} \bigg|^{*} = [h_1, h_2, \dots h_{14}]
\qquad (47)
$$

Thus the geometry vector is the gradient of the measurement with respect to the esti-mator state, evaluated on the nominal path. For each measurement, the estimator must calculate the appropriate geometry vector and evaluate the equivalent measurement on the nominal path.

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• Air Data

Airspeed is assumed to be measured with a random measurement error of about 2 kt. The nominal path is defined as having no winds. Therefore, the nominal measurement is

$$\tilde{V_a}^* = \text{nominal ground speed} = [V_N^{*2} + V_E^{*2}]^{1/2} + r_{V_a} \qquad (48)$$

The non-zero elements of the measurement vector are

$$\left.\begin{array}{l} h_1 = V_N^*/[V_N^{*2} + V_E^{*2}]^{1/2} \\[12pt] h_2 = V_E^*/[V_N^{*2} + V_E^{*2}]^{1/2} \\[12pt] h_7 = -h_1 \\[12pt] h_8 = -h_2 \end{array}\right\} \qquad (49)$$

The altimeter error is modeled as a zero-mean bias plus a random error:

$$\tilde{h}^* = h^* + r_h \qquad (50)$$

$$h_6 = 1 \qquad (51)$$

The vertical speed measurement error is modeled as a random with a standard deviation of the order of 100 fpm:

$$\tilde{\dot{h}}^* = \dot{h}^* + r_{\dot{h}} \qquad (52)$$

$$h_3 = 1 \qquad (53)$$

• INS

The INS error is a correlated drift plus a random error:

$$\tilde{V}^*_{INS_N} = V^*_N + r_{INS_N} \qquad (54)$$

$$\left.\begin{array}{l} h_1 = 1 \\[1em] h_{13} = 1 \end{array}\right\} \qquad (55)$$

$$V^*_{INS_E} = V^*_E + r_{INS_E} \qquad (56)$$

$$\left.\begin{array}{l} h_2 = 1 \\[1em] h_{14} = 1 \end{array}\right\} \qquad (57)$$

- **DME**

The estimated DME errors are represented as biases plus random errors:

$$R^*_D = \left\{ r^2_e [(L^* - L^*_D)^2 + \cos^2 L^*_D (\ell^* - \ell^*_D)^2] + (h^* - h^*_D)^2 \right\}^{1/2}$$
$$+ r_D \qquad (58)$$

$$\left.\begin{array}{l} h_4 = r^2_e (L^* - L^*_D)/\tilde{R}^*_D \\[1em] h_5 = r^2_e \cos^2 L^*_D (\ell^* - \ell^*_D)/\tilde{R}^*_D \\[1em] h_6 = (h^* - h^*_D)/\tilde{R}^*_D \end{array}\right\} \qquad (59)$$

$$h_{8+i} = 1$$

- **Loran, VLF & Omega**

Range difference measurement errors are included as random errors:

$$\Delta\tilde{R}^* = \rho^*_A - \rho^*_B + r_{\Delta R} \qquad (60)$$

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$$\rho_A^* = r_e \cos^{-1}[\sin L^* \sin L_A^* + \cos L_A^* \cos (\ell^* - \ell_A^*)] \qquad (61)$$

$$\left. \begin{array}{l} h_4 = r_e(\cos \theta_B - \cos \theta_A) \\[2em] h_5 = r_e \cos L^* (\sin \theta_B - \sin \theta_A) \end{array} \right\} \qquad (62)$$

where

$$\tan \theta_A = \frac{\sin (\ell_A^* - \ell^*)}{\tan L_A^* \cos L^* - \cos (\ell_A^* - \ell^*) \sin L^*} \qquad (63)$$

- MLS

Elevation and azimuth errors are included as random measurement errors:

$$\tilde{\theta}_{el}^* = \tan^{-1} \left\{ \frac{h^* - h_m^*}{r_e[(L^* - L_m^*)^2 + \cos^2 L_m^* (\ell^* - \ell_m^*)^2]^{1/2}} \right\} + r_{el} \qquad (64)$$

$$\left. \begin{array}{l} h_4 = \dfrac{-r_e^2(L^* - L_m^*)(h^* - h_m^*)}{DS^2} \\[2em] h_5 = \dfrac{-r_e^2 \cos^2 L_m^* (\ell^* - \ell_m^*)(h^* - h_m^*)}{DS^2} \\[2em] h_6 = \dfrac{D}{S^2} \end{array} \right\} \qquad (65)$$

where

$$D = r_e[(L^* - L_m^*)^2 + \cos^2 L_m^*(\ell^* - \ell_m^*)^2]^{1/2}$$

$$s^2 = D^2 + (h^* - h_m^*)^2$$

(66)

$$\theta_{az}^* = \tan^{-1}\left[\frac{\cos L^*(\ell^* - \ell_m^*)}{L^* - L_m^*}\right] + r_{az}$$

(67)

$$h_4 = \frac{-\cos L_m^*(\ell^* - \ell_m^*)}{(L^* - L_m^*)^2 + \cos^2 L_m^*(\ell^* - \ell_m^*)^2}$$

(68)

$$h_5 = \frac{\cos L_m^*(L^* - L_m^*)}{(L^* - L_m^*)^2 + \cos^2 L_m^*(\ell^* - \ell_m^*)^2}$$

4.4   NORTHEAST CORRIDOR SCENARIO

In order to provide as realistic an environment as possible for evaluation of the straw-man VTOL navigation systems, a preliminary effort was undertaken to establish typical RNAV route profiles between Boston, New York, and Washington, D. C. These routes were selected with regard to the criteria discussed in Section 2; they were as expeditious as possible and yet avoided:

- obstructions.
- noise sensitive regions.
- controlled airspace.
- major uncontrolled airfields.

Furthermore, since these routes were to be examined as part of the flight evaluation program, an additional criterion was continuous coverage by the existing VORTAC system. The procedure adopted was to make a preliminary selection on the basis of the first four criteria. Then Program COVER (Appendix D) was used to ensure the availability of VOR/DME navigation information. The results of the flight evaluation program will be described in Section 5.

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The selected Zulu airways and Tango connectors are summarized in Figure 43. Detailed diagrams of the routes between Boston and New York City are illustrated on the aeronautical charts in Figures 44 through 46. These routes will form the basis of the straw-man systems parametric evaluation with Program VALT during the next phase of the investigation.
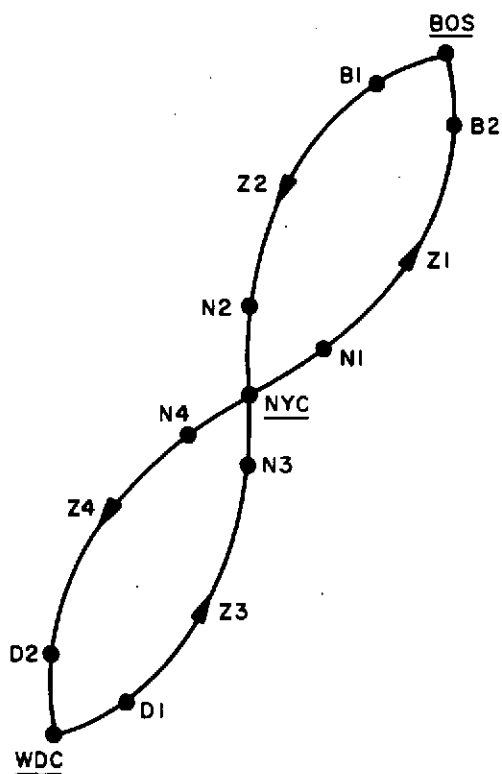
Figure 43. Zulu Airways and Tango Connectors.

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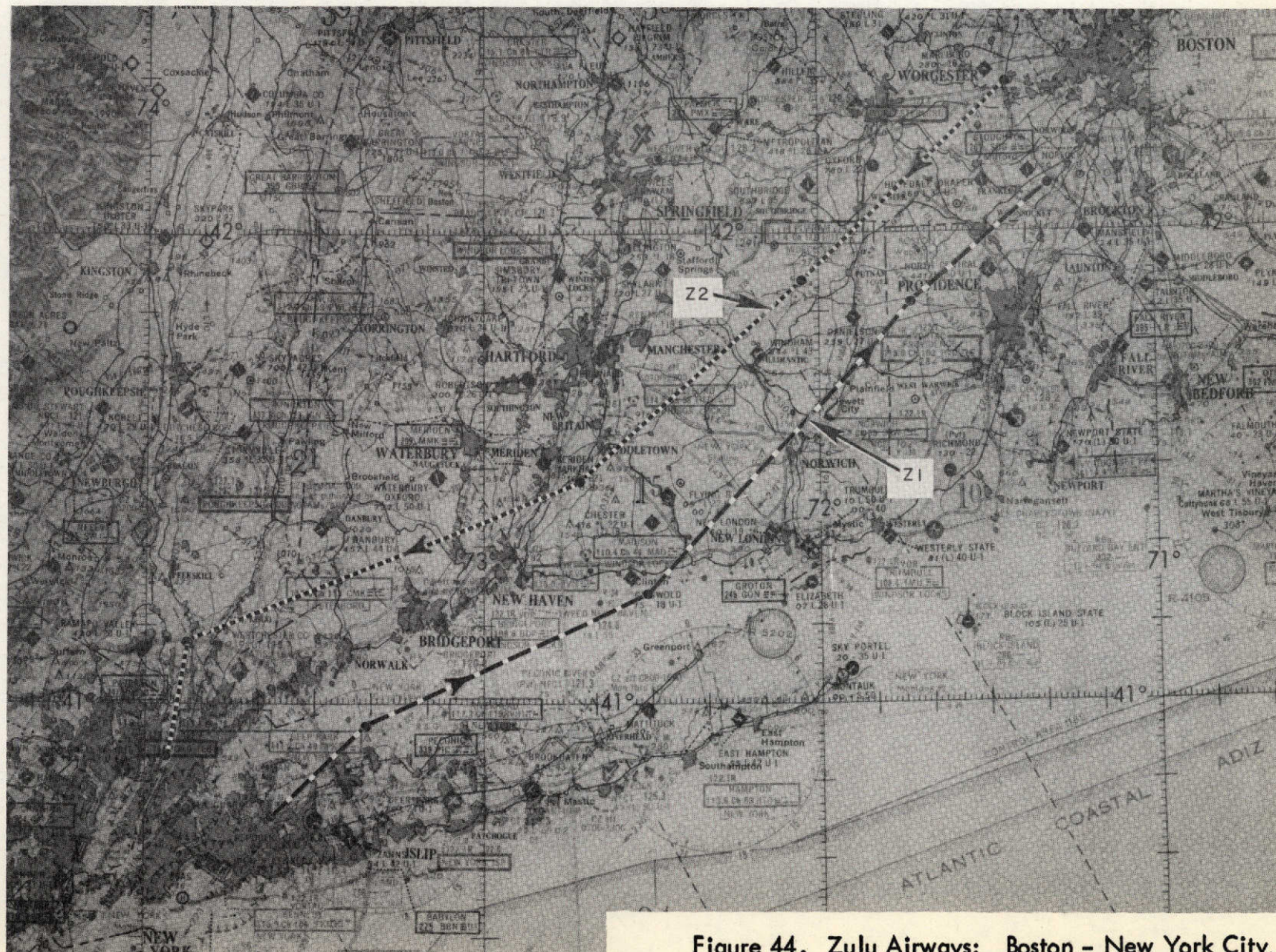
Figure 44. Zulu Airways: Boston – New York City.
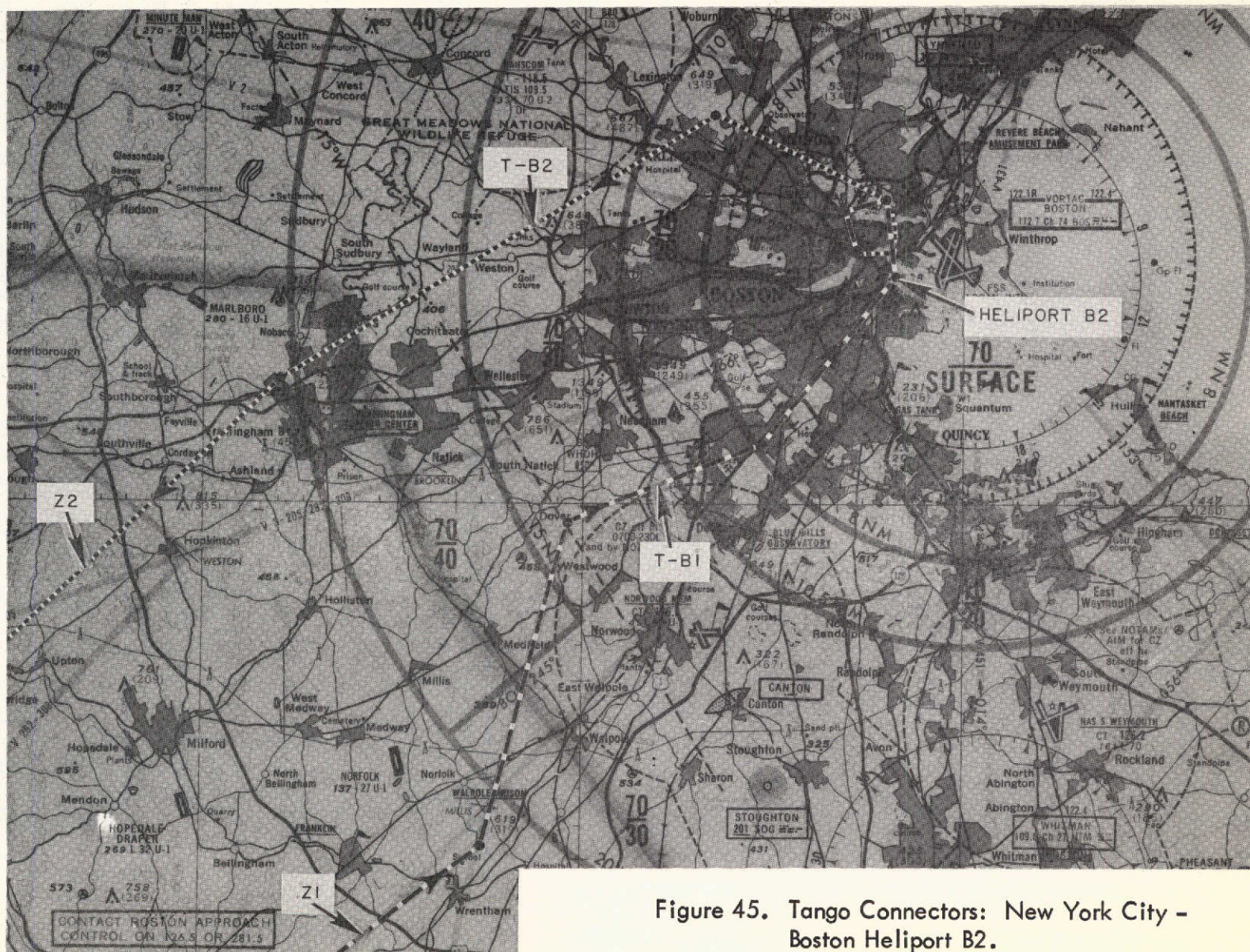
Figure 45. Tango Connectors: New York City –
Boston Heliport B2.

Figure 46. Tango Connectors: Boston – New York
Wall Street Heliport.
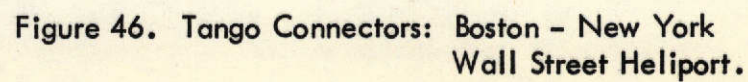
SECTION 5

FLIGHT EVALUATION PROGRAM

This section summarizes the results of the flight evaluation program which was conducted in conjunction with the analytical investigation of VTOL navigation requirements. A chronological summary of the individual flights is presented in Appendix E. Reference 57 contains detailed descriptions of planning, execution and analysis involved in the flight evaluation program.

5.1   INTRODUCTION

The objective of the flight investigation was to obtain:

- Real world orientation to analysis of current systems and their capabilities.
- Preliminary flight verification of the results obtained from the analytical tasks.

The flight program was designed and executed in two parts: Part I provided flight data applicable to the helicopter cruise and terminal area phases of flight for inter-urban VTOL operations; Part II provided flight data applicable to VTOL operations in the intra-urban environment. The flight data obtained included coverage of existing communication/navigation/surveillance systems, descriptions of CTOL pattern conflicts and encounters, low altitude route and heliport site evaluations, and descriptions of unique operational problems. These data were derived from a series of flights with three basic types of profiles:

A. Typical inter-urban, low-altitude, VOR/DME-based RNAV routes.

B. Typical intra-urban routes and segments.

C. Special items, route segments and maneuvers designed to check facility coverages or exercise existing capabilities.

Two different types of aircraft were used to achieve the flight evaluation goals under a tight schedule and at the minimum cost.

- A fixed-wing general aviation aircraft with IFR and VOR/DME RNAV capabilities.
- A commercial helicopter operating in the present intra-urban environment.

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For Part I, ASI leased aircraft and flew the appropriate profiles with its own personnel. The planning, flight evaluations, and post-flight data analysis were conducted by the same ASI engineers/pilots who performed the analytical tasks described in the previous sections. Part II was conducted by ASI under a teaming arrangement with New York Airways; the ASI engineers/pilots served as test planners, observers, and data analysts, drawing heavily on the expertise of those NYA pilots who participated in the flight evaluation program.

The fixed-wing aircraft was a 1963 Cessna 182, described in Table 17. Operating this aircraft in the flight program offered several advantages:

- Lower cost.
- Excellent avionics equipment.
- Good ground visibility for position checks (due to high wing design).
- Minimal noise generation at low altitudes
- High maneuverability.
- Good fuel efficiency.
- Low maintenance.

The main disadvantage was the low cruise speed (125 kt).

Table 17. Cessna Model 182 Fixed-Wing Aircraft Features.

Characteristics		Avionics
Gross Weight (lb.)	2800	Dual 360-Channel NAVCOMS
Empty Weight (lb)	1560	Course Line Computer (RNAV)
Cruise Speed (kt)	141	Pictorial Navigation Display
Range (nm)	787	DME
Length (ft)	29	Automatic Direction Finder
Height (ft)	9	Glide Slope Receiver
Power Plant	Continental 0470-R (230 HP)	Transponder
Propeller Diameter (in) (constant speed)	82	Three-Axis Autopilot With Altitude Hold

L. G. Hanscom Field in Bedford, Massachusetts, which is located within a few minutes of the ASI headquarters, served as the base of operations for the fixed-wing flights. Each flight was planned to combine elements from Profiles A and C; a total of 47.9 flight hours was accumulated in completing ten individual data-gathering flights.

The S-61L helicopters and crews that participated in Part II of the flight evaluation program were also part of the daily commercial operations by NYA. The S-61L is described in Table 18; it was flown for 7 hours on 3 different flights that combined elements from Profiles B and C. These dedicated flights occurred during the midmorning, off-peak hours in the New York City area. In addition, valuable insights into present-day commercial VTOL operations were acquired by the ASI engineer/pilots who rode as observers on several regularly-scheduled NYA flights.

Table 18. Sikorsky S-61L Commercial Helicopter Features.

Characteristics		Avionics
Gross Weight (lb)	19,000	Dual VHF Comms
Empty Weight (lb)	11,792	VOR Receiver
Cruise Speed (kt)	122	Glide Slope Receiver
Range (nm)	245	Marker Beacon Receiver
Length (ft)	73	Transponder
Height (ft)	17	MLS Receiver*
Power Plant (2)	1500 HP GE CT 58-140-2	DME**
		RNAV**
Rotor Diameter (ft)	62	
		*Temporary, for demonstration. **Under Consideration.

5.2 VTOL INTER-URBAN OPERATIONS

The examination of current and projected technology and systems has concentrated on several major issues, including coverage and accuracy. One goal of the flight evaluation program was the verification of the assumptions used in modeling the coverage and accuracy of existing systems. Program COVER (Appendix D) was

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developed to aid low altitude route determination using line-of-sight navigation, communication, and surveillance systems. To assess the usefulness of this program for route planning, comparisons were made between the VORTAC coverage predicted by Program COVER and that actually observed during flight evaluations.

5.2.1 LOW ALTITUDE VORTAC COVERAGE

The results from Program COVER are plots of predicted geographical coverage at various flight altitudes for selected facilities. The coverage plots are governed by known restrictions and the normal line-of-sight radio horizon. Consequently, it was easy to verify COVER predictions by plotting the flight results directly on the COVER plots.

The flight results were recorded by noting the status of the VORTAC signal at various locations. That status was described by a simple code, shown in Table 19, to facilitate the recording and the reduction of the data. Code 1 indicates the station was tuned and identified and that it provided apparently reliable bearing and DME readouts with no flags showing. Code 5 means one or more of the elements of the complete signal is unavailable. Consequently, these are the codes of primary interest, since they correspond directly to conditions inside or outside an area of coverage on the COVER plots.

Table 19. VORTAC Signal Status Code.

Code	Signal Status
1	Usable navigation signal received
2	OFF Flat not visible
2^+	OFF Flat half visible
3	ID is audible
4	Bearing information available
D	DME being received
E	DME not being received
5	Usable navigation signal not received

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The VORTAC signal status was recorded as Code 1 or 5 for 170 points; these results are compared to the COVER plots in Table 20.

Table 20. Comparisons Between Program COVER and Flight Evaluation Signal Codes.

		Predicted by COVER	
		Code 1	Code 5
Flight Evaluation Observations	Code 1	63	37
	Code 5	18	52

Two disparities are quite obvious: first, there were 37 points where coverage was not predicted but found to be adequate for navigation (5, 1); and secondly, there were 18 points where coverage was expected but not found (1, 5).

The first case is of less concern since the VORTAC s are range-limited by regulation rather than signal strength. The VORTAC navigation aids are classed according to their operational use (Table 21). Certain operational requirements make it necessary to use some of these aids at greater service ranges than are listed in the table. Extended range is made possible through FAA flight inspection. Some aids also have lesser service range due to location, terrain, frequency protection, etc.; these restrictions are listed in the Airman's Information Manual. The published restrictions and the range limits shown in Table 21 were implemented in Program COVER. The

Table 21. Altitude and Distance Limitations for VORTAC.

VORTAC/NAVAIDS Normal Usable Altitudes and Radius Distances		
Class	Altitudes	Distance (nm)
T (Terminal)	12,000 ft and below	25
L (Low altitude)	Below 18,000 ft	40
H (High altitude)	Below 18,000 ft	40

fact that these range limitations are somewhat conservative is illustrated by Figure 47, which shows a typical VORTAC signal strength as a function of range and altitude. The 5μvolt contour is shown because the OFF flag threshold is usually set between 1 and 5μvolt. In the fixed-wing test aircraft it was set at 1.12μvolt, for example.
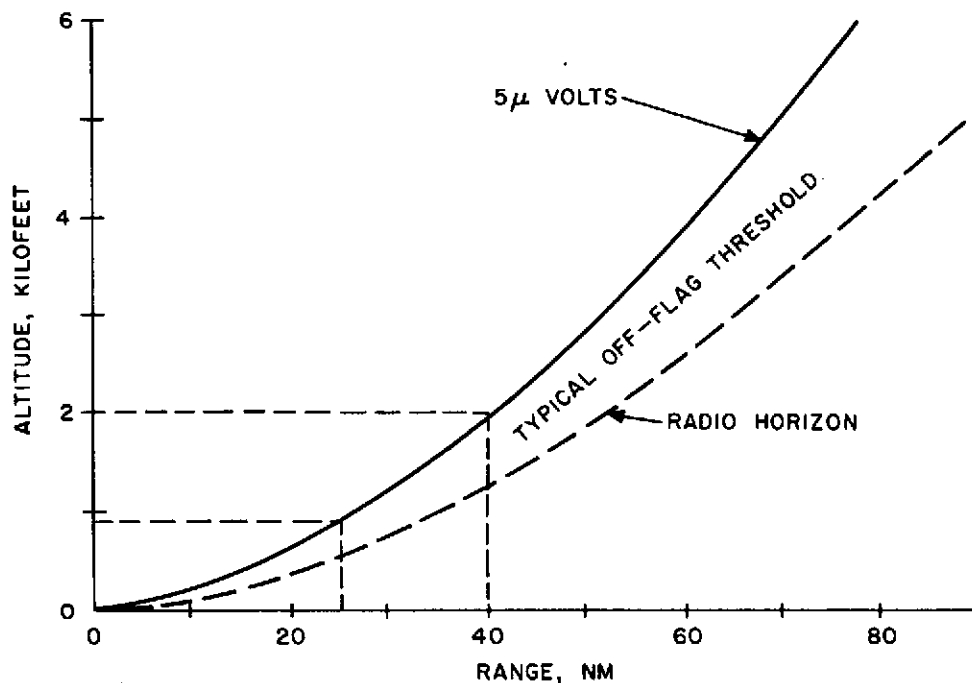
Figure 47. Typical VORTAC Signal Strength Profile.

The sensitivity of the signal strength to range and altitude displacement is shown as a function of range in Figure 48. It can be seen that the signal strength is much more sensitive to altitude variation than to range variation by a ratio of about 60 to 1. Consequently, predicting the altitude of the OFF flag threshold for a given position is more accurate than predicting the range of the threshold for a given altitude. Also, small changes in altitude are more effective for improving signal strength near the threshold than are changes in the range. This was used to great advantage in the flight evaluation program for evaluating Program COVER line-of-sight predictions.

The second case of disparity, i.e., predicted VORTAC coverage where no usable navigation signal was obtained, is of greater concern. However, the explanation again was found to be a result of the assumptions in Program COVER relating to line of sight (LOS) and the normal radio horizon. The equation in COVER which

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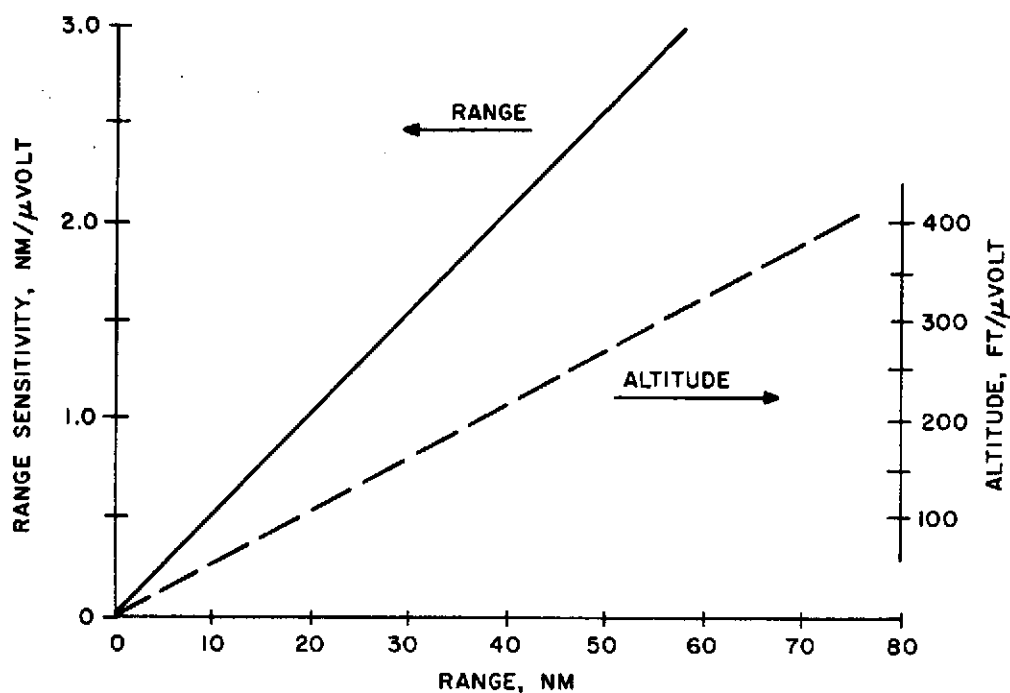
Figure 48. Typical OFF Flat Sensitivity vs. Range.

determines the LOS lower limit of the coverage assumes level terrain at the VORTAC
site (see Appendix D). Naturally this is not entirely accurate, and the flight evalua-
tion program results show that the bottom of the VORTAC coverage depends on LOS
projection across the predominant terrain features. This effect is shown in Figures 49
through 53.

These plots were obtained by flying along a designated VORTAC radial and
using alternate climbs and descents to acquire (Code 1) and lose (Code 5) usable navi-
gation signals. In every case the DME reception or loss determined the usability of the
total navigation signal. This is understandable because this signal is at a higher fre-
quency (UHF) than the VOR signal (VHF) and thus adheres more strictly to the LOS.
Altitudes were noted when the signal status changed between usable and unusable; and
these were subsequently plotted against range from the station. When these plots are
compared to the normal radio horizon generated by Program COVER, several incon-
sistencies can be seen. But when the dominant terrain profile under that radial is
introduced and the resulting LOS elevation angle is included, the corrected radio
horizon shows excellent agreement with the observed points of signal change.

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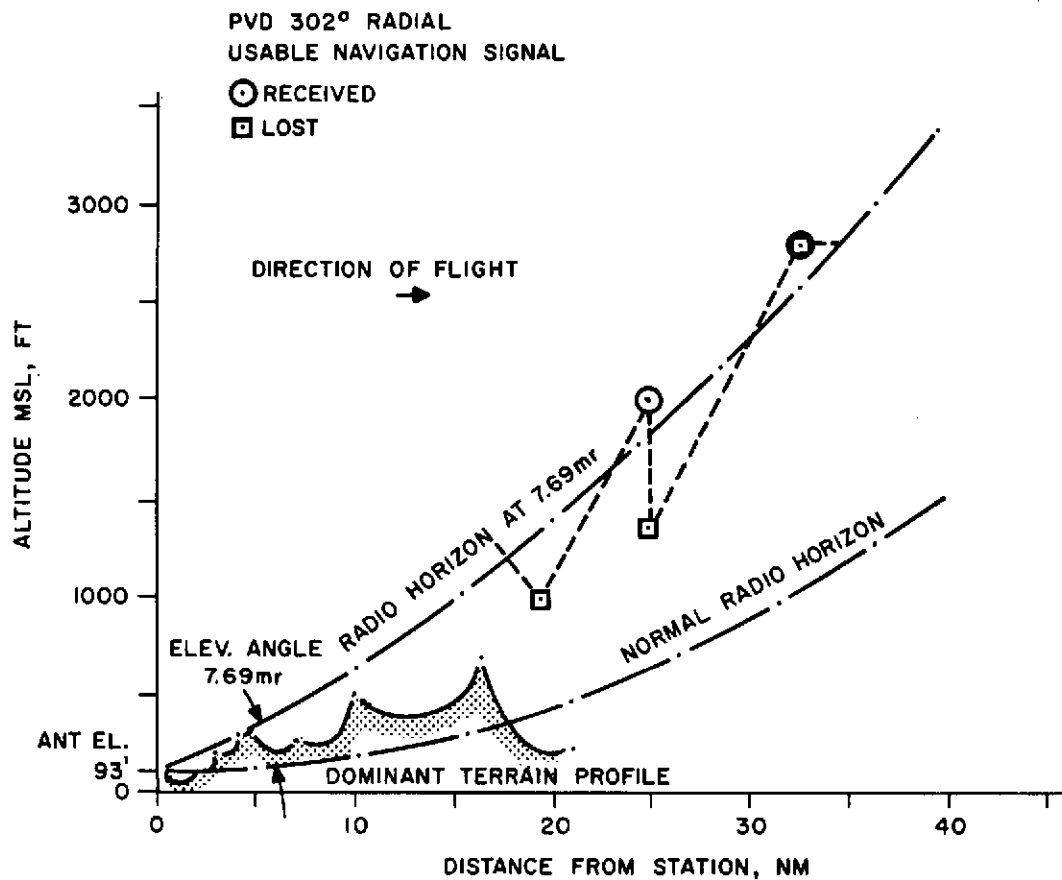
Figure 49. Sample VORTAC Coverage, Providence VOR.
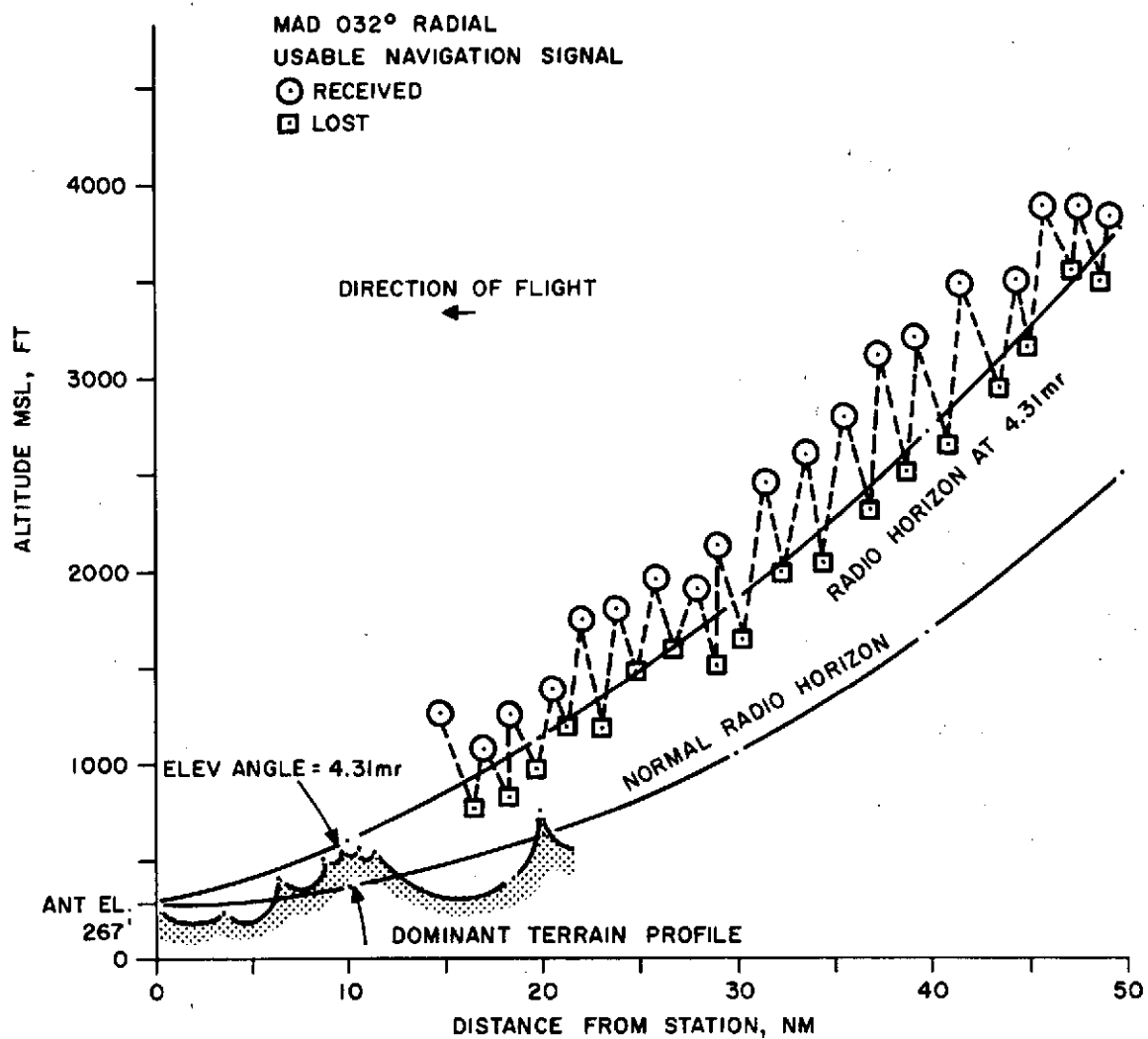
Figure 50. Sample VORTAC Coverage, Madison VOR.
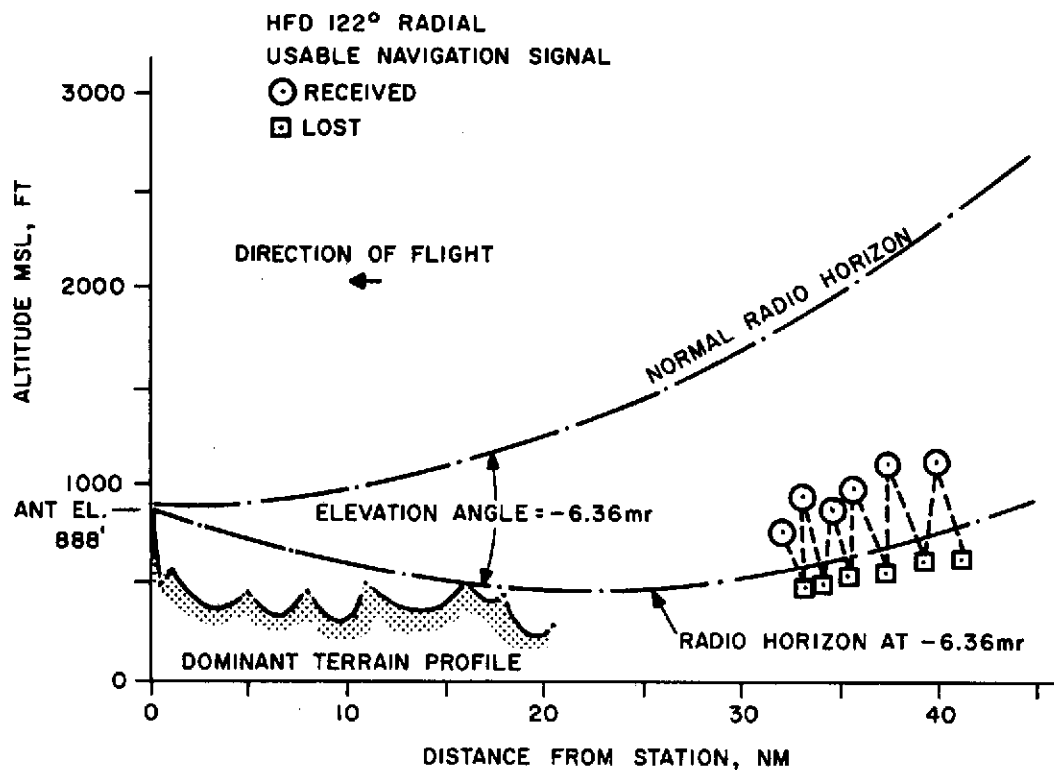
Figure 51. Sample VORTAC Coverage, Hartford VOR.
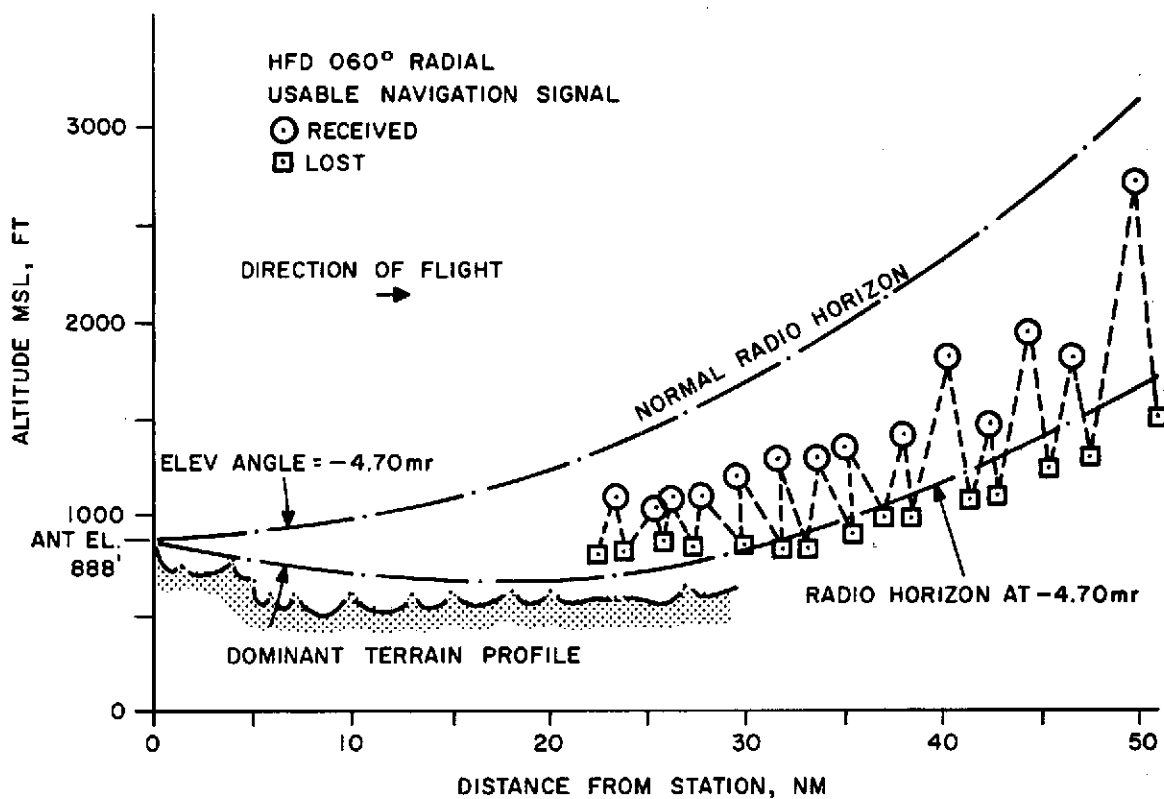
Figure 52. Sample VORTAC Coverage, Hartford VOR.

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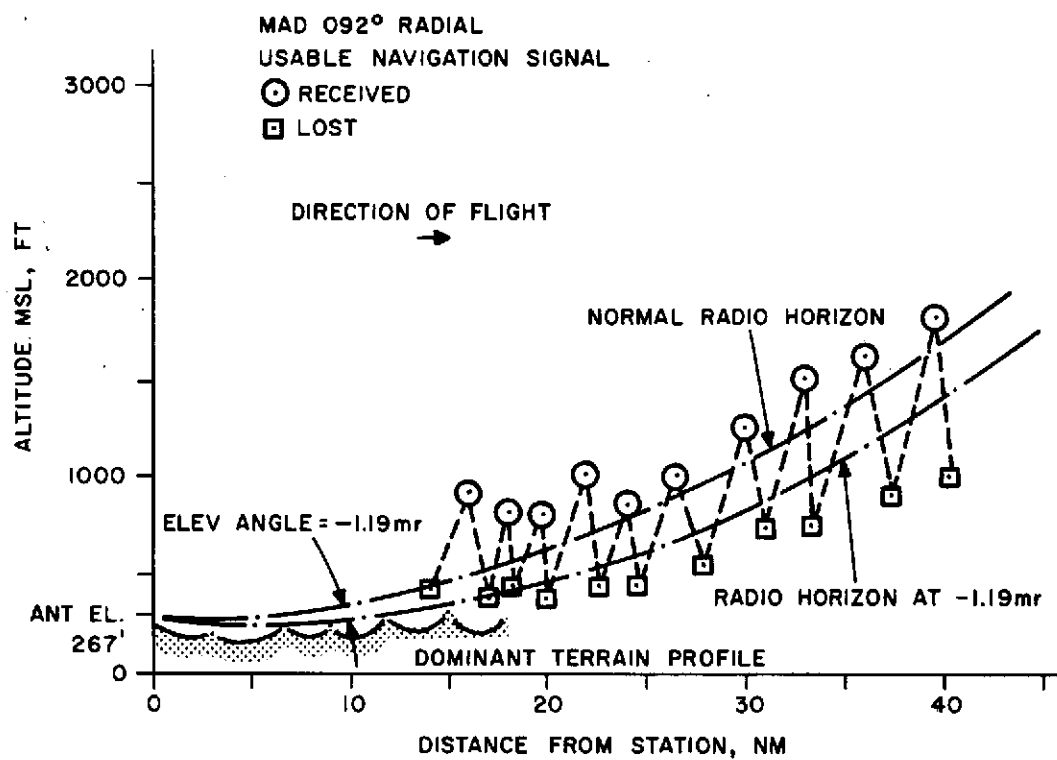
Figure 53. Sample VORTAC Coverage, Madison VOR.

Applying this terrain correction technique to the 18 points where usable signal navigation was predicted but not found, yields the results in Table 22. Fourteen of the eighteen points are explained by the dominant terrain profile under the radial. Two of the remaining four points are the result of skyline blockage, a more difficult effect to analyze than terrain features. The causes of the remaining two failures to acquire the expected signal could not be determined. Possible explanations might be: momentary power interruption; saturation of DME beacon; insufficient search time for DME lockon.

The effects of an urban skyline on the VORTAC signal were also explored with the helicopter. The NYA S-61 was flown up and down the Hudson River at altitudes of 300 feet, 500 feet, and 700 feet from a point abeam the south edge of Central Park to a point over the Statue of Liberty. The minimum reception LOS altitude for both LGA and JFK VORTAC's along the test route is predicted as 200 feet. This is based on the normal radio horizon and the respective antenna elevations of the two stations. Unreliable VOR navigation signals were observed intermittently on all runs. Skylines clearly offer a line-of-sight disruption, but this effect is much more irregular and unpredictable than that caused by most terrain features. While this is an obvious conclusion, it has a significant implication for low altitude operations in the urban environment: How can low altitude routes be planned to ensure uninterrupted VORTAC service to the RNAV equipment? This question can probably best be answered by flight test because it is so site-dependent.

In a 1962 FAA program, a helicopter was flown over approximately this same route segment (Ref. 58). It was equipped to measure continuous reception of the bearing and DME signals from the LaGuardia and Kennedy VORTAC's. This experiment showed that continuous usable navigation signals from Kennedy were available over the Hudson River at and above 1100 feet. In the same area the minimum reception altitude for the LaGuardia VORTAC was 1500 feet. The recently completed World Trade Center on the southwestern edge of Manhattan may alter these results, but the current flight evaluation program did not attempt to establish new VORTAC minimum reception altitudes because no DME receiver was available on the test helicopters.

A more recent flight test was performed in the New York City area in 1972 under the DOT Transportation Systems Center STOL Avionics Program (Refs. 59, 60). A

Table 22. Code 1/5 Summary.

Station, (Type)	Radial/DME, (deg /nm)	Altitude, (ft)	Elevation Angle, (mr)	Minimum Reception Altitude at This Point (ft)	Comments Based on Terrain Study
1. BOS (H)	245/20.8	2000	unknown	unknown	City profile not available on this radial
2. CMK (L)	085/37.1	2000	+2.10	2441	Terrain mask
3. EEN (L)	100/18.0	2900	10.01	2885	Possible error in elevation angle
4. HFD (L)	119/16.3	2500	−6.36	460	Terrain definitely not a factor
5. HTO (H)	337/29.1	2000	+8.95	2388	Terrain mask
6. HTO (H)	341/21.8	2000	8.95	1676	Restricted by AIM Part 4 for use below 2000ft
7. HTO (H)	347/21.8	2000	8.95	1676	Restricted by AIM Part 4 for use below 2000ft
8. HTO (H)	353/39.0	2000	8.95	3518	Terrain mask
9. IGN (L)	149/32.0	2000	6.06	3290	Terrain mask
10. MAD (L)	048/32.2	2000	4.31	2021	Terrain mask
11. MAD (L)	049/33.6	2000	4.31	2150	Terrain mask
12. ORW (L)	257/39.0	2300	2.40	3121	Terrain mask
13. ORW (L)	273/39.4	2000	2.19	2191	Terrain mask
14. PUT (H)	048/16.0	1000	3.32	1215	Terrain mask
15. PVD (H)	017/20.6	2000	unknown	unknown	City profile not available on this radial
16. PVD (H)	328/26	1600	6.51	1700	Terrain mask
17. PVD (H)	331/26	1800	6.51	1700	Possible error in elevation angle
18. TMU (T)	269/24.5	2000	~0	540	Terrain definitely not a factor

Convair 340 was flown over a similar route structure at 1100 ft MSL, with RNAV approaches to LaGuardia, Newark and Westchester down to 500 ft AGL. Dual VOR and DME receivers were tuned to the JFK and LGA VORTAC s throughout the flight. The VOR's gave numerous OFF flag indications, especially during the approaches. However, the DME's operated satisfactorily, except for one unlock at 500 ft over Newark.

Skyline blockage of signal coverage was also apparent for surveillance data in the low passes over the proposed heliport sites during the flight evaluation of the Boston Tango Connectors. When the test aircraft descended below the "average" Boston skyline as viewed from the radar site, the ARTS III system reverted to a coast mode until the aircraft ascended after the pass. More interesting was the aircraft's passage behind Boston's two skyscrapers. Even though each is relatively slender and stands well above surrounding buildings, radar track was disrupted each time the aircraft was masked from the antenna.

In summary, the flight evaluation program has shown that local terrain – including effective urban skylines – must be considered in predicting the low altitude coverage of LOS signals. If the normal radio horizon is employed, the results will be conservative in many cases, and insufficiently restrictive in others. This has not posed a problem for the FAA in their VORTAC facility flight checks because those checks are made only at CTOL IFR flight altitudes. These altitudes are above those under consideration for VTOL operations, so the existing restrictions would need re-evaluation for such applications.

Two procedures are available for developing feasible low altitude route structures for VTOL operations: 1) flight investigation of the areas under study to define coverage limits; and 2) analytical models of the terrain and its effects. Initially the first option appears to be the most reasonable. But once low altitude operations become more widespread and flexible, this may not be economically feasible. Instead, the terrain modeling approach may become more efficient in terms of time and fuel costs, particularly since the flight evaluation program has shown excellent correspondence between terrain modeling and actual LOS coverage.

5.2.2 LOW ALTITUDE VORTAC ACCURACIES

In addition to the low-altitude signal coverage, VORTAC accuracy was also assessed. The VORTAC bearing and DME readouts were compared to the position of the aircraft determined visually. One problem with this technique was the inaccuracy of the visual position locations; for example, over large wooded areas at low altitude, visual position could not be accurately charted. Another factor is the precision of the aeronautical charts used for reference; these are published for VFR use, are updated at six-month intervals, and frequently show significant discrepancies from the actual terrain.

Nevertheless, the method proved useful in assessing low altitude range and bearing accuracies of the VORTAC signals. These results, shown in Table 23, indicate no deterioration of accuracy in VORTAC signals at low altitudes even though they may be received below the normal radio horizon. Similar comparisons were made between RNAV readouts and visual waypoints when the Zulu routes were flown in cruise flight.

Table 23. VORTAC Bearing
and Range Accuracies.

	Bearing (deg)	Range (nm)
Mean	0.1	-0.1
Standard Deviation	2.7	0.7

The latter results, shown in Table 24, were much more accurate due to the continuous tracking of the tuned station and the smoothing inherent in this process. The accuracy shown is much better than the expected inaccuracies of visual position plotting. However, it must be stressed that the results in Table 24 represent a limited sample, and were obtained over a specific route for the most part.

In summary, VORTAC signal accuracy does not apparently deteriorate at low altitudes, since the results of the flight evaluation program are well within the tolerances specified by the FAA. Consequently, the RNAV capability at low altitude can approach the same degree of accuracy.

Table 24. Cross-track and Along-track
Errors at RNAV Waypoints.

	Cross-track Deviation (nm)	Along-track Deviation (nm)
Mean	0.0	0.0
Standard Deviation	0.1	0.5

5.3   VTOL INTRA-URBAN OPERATIONS

In examining the performance of current systems and their projected capabilities, one aspect of the flight evaluation program involved the feasibility of NYA providing IFR helicopter service between the Kennedy (JFK) and LaGuardia (LGA) airports. Three levels of navigation equipment were considered:

1. Existing facilities only.
2. Addition of DME.
3. Addition of DME and MLS.

In addition, a number of innovative ideas for IFR helicopters were examined.

5.3.1   EXISTING EQUIPMENT

At the time of the flight evaluation program, NYA S-61 s were equipped with the basic avionics shown in Table 18 without the MLS receiver. Therefore, the first effort at determining a suitable structure between the two airports involved using a VOR radial from one airport to find a marker beacon associated with an ILS approach to the other airport. The ILS approach had to be one which minimized CTOL interference; i.e., to an unused runway or to a departure runway.

The first step was to determine the principal CTOL patterns used in the NYC area with the aid of published instrument approaches, standard arrival and departure routes, technical reports, and airborne observations.

Many combinations of patterns for the three major New York City area airports are possible because of varying winds, the noise problem, and fluctuations in demand; however, the preferential runway plan that has been implemented for noise

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abatement limits the number of combinations when the wind speed is below 15 knots. This low wind condition usually exists concurrently with most of the low ceiling, low visibility conditions in the area. Table 25 shows the preferred CTOL runway combinations and the associated VTOL routes created for use during these conditions. These VTOL routes are described in Table 26.

At the suggestion of NYA, effort was concentrated on three routes: N-5, N-6, and N-8. Their experience has shown that these proposed routes use ILS approaches that are available most often during NYA weather cancellation periods. Consequently, these three routes were examined during the flight evaluation program.

N-8 was flown first (Fig. 54). Flight outbound from JFK on the 312° radial was timed to 8.6 nm, where the VOR receiver was switched (channel changeover) to the LGA Runway 4 ILS frequency to intercept the localizer. A strong headwind caused a slower groundspeed and led to an early channel changeover, but the previous heading was held until the localizer was intercepted about a mile outside the final approach fix. Although the turn required is 89 degrees, it was accomplished with no difficulty, and the remainder of the approach was a normal ILS down to 200 feet AGL.
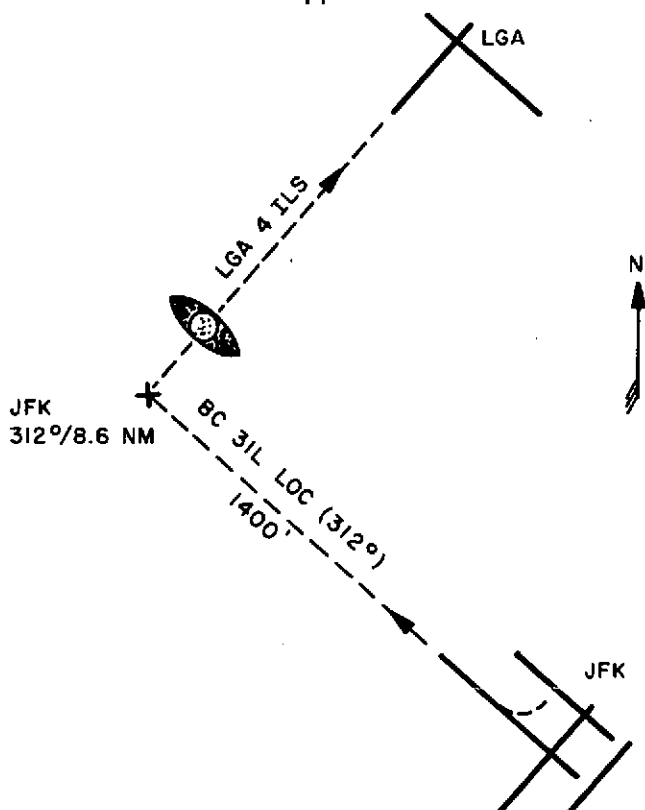
Figure 54. Proposed IFR VTOL Route N-8.

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Table 25. New York City CTOL/VTOL Pattern Summary.*

Wind Direction (Speed)	Airport	Runway		VTOL Route No.	
		Arrival	Departure	LGA → JFK	JFK → LGA
Calm (0 - 4 kt)	JFK	4LR	31LR	N-1	N-2
	LGA	22	31		
041° - 131° (5 - 15 kt)	JFK	4LR	13LR	N-5	N-8
	LGA	13	4		
131° - 221° (5 - 15 kt)	JFK	22LR	13LR	N-5	N-6
	LGA	22	13		
221° - 311° (5 - 15 kt)	JFK	31LR	31LR	N-3	N-2
	LGA	22	31		
311° - 041° (5 - 15 kt)	JFK	4LR	31LR	N-1	N-2
	LGA	4	31		

*Weather: 400 ft ceiling, 3/4 mile visibility.

N-5 was flown next (Fig. 55); the outbound radial was intercepted immediately and the calculated time for channel changeover was adjusted for the tailwind. The transition to the ILS localizer required only a 66-degree turn which was accomplished without difficulty. The turn increased the tailwind component dramatically, and a rapid rate of descent was needed to acquire the glide slope; the remainder of the approach was normal.

Next, N-6 was attempted (Fig. 56). It was interrupted before the second turn as the helicopter was observed to be deviating substantially from the intended track even though the VOR course indicator was centered. Visual corrections were made to avoid the Newark Airport traffic area. Subsequently, transition to the CMK 227° radial at a distance of 41 nm again led to questionable accuracy. Apparently,

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Table 26. Proposed IFR VTOL Routes Between LGA & JFK.

N-1: LGA to JFK

Air taxi over Inner Taxiway to intercept LGA 159 radial and climb outbound on that radial to 1600 ft to overhead JFK (9.8 DME). Proceed outbound (132°) on 31R ILS to Cedar LOM: then execute procedure turn and 31R ILS approach.

N-2: JFK to LGA

After liftoff climb on a heading of 040° to penetrate 31R departure wall and intercept JFK 016 radial. Climb to 1500 ft and continue outbound to 5.8 DME or radar fix for ILS Back Course approach to LGA RW 31.

N-3: LGA to JFK

After liftoff climb on a heading of 040° to penetrate RW 31 departure wall; then turn right to heading 090° to intercept SAX 128 radial. Climb to 2000 ft and proceed outbound on that radial to 42.8 DME or Jockey OM for right turn to inbound on JFK 22R ILS.

N-5: LGA to JFK

After liftoff climb on a heading of 190° to intercept LGA 188 radial. Climb to 1500 ft and proceed outbound to 5.7 DME or Aqueduct OM. Turn left to inbound on the JFK 13L ILS.

N-6: JFK to LGA

After liftoff climb on a heading of 240° to intercept the JFK 292 radial. Climb to 1700 ft and proceed outbound to 12.6 DME or the SAX 148 radial. Fly inbound (328°) on that radial from 32.8 DME to 29.1 DME or the CMK 227 radial. Climb to 1800 ft and fly inbound (047°) on that radial from the 41.4 DME to 32.5 DME or the Palisades Park LOM. Turn right to inbound on the LGA 13 ILS.

N-8: JFK to LGA

After liftoff climb outbound (312°) on the 31 L ILS Back Course to 8.6 DME on 312 radial of JFK. Climb to 1400 ft, intercept and fly inbound on the LGA 4 ILS.

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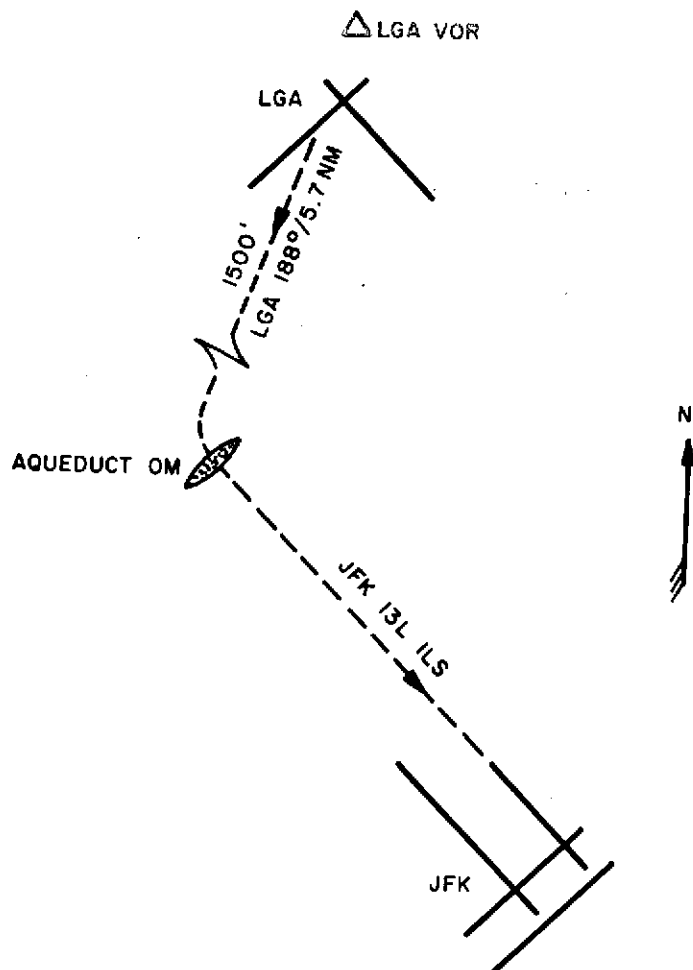
Figure 55. Proposed IFR VTOL Route N-5.
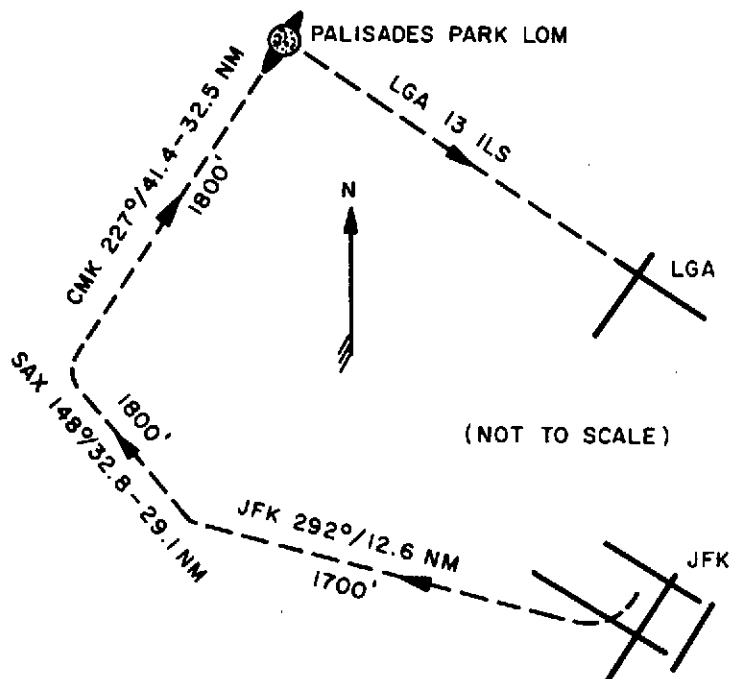
Figure 56. Proposed IFR VTOL Route N-6.

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the relatively long distances and uneven urban skyline produced significant bends in the selected radials. These deviations were not completely surprising, but it had been hoped that the more distant VOR s could support the NYA IFR operations. Once the outer marker for the ILS to LGA was reached, this approach was discontinued.

These three flights provided several interesting results. First they affirmed that rotor modulation of VOR/ILS signals is not a problem in the NYA S-61. Secondly, they showed that VOR radials can be used for transition to ILS localizers if the station is not too distant. Third, they showed that full ILS approaches waste the maneuverability and flexibility inherent in the basic helicopter design. Fourth, they demonstrated the desirability of DME for such operations.

5.3.2 ILS AND SIMULATED DME

The second group of tests in the NYA helicopter attempted to use existing facilities and simulated DME to examine abbreviated ILS s for IFR flights between LGA and JFK. The midpoint of the conventional ILS final approach path at the destination airport was connected to a radial from the VOR at the originating airport. Thus, the new approach profile was equivalent to a normal ILS with a dog-leg at the midpoint of the final approach. The first half of the new approach was to be flown along the selected VOR radial toward the ILS midpoint with the same descent gradient as the normal approach. The initial descent point and channel changeover point were determined by DME, which was simulated by visual reference points at specific distances from the VOR. The pilot was not authorized to descend below the normal midpoint altitude until the ILS localizer and glide slope were being tracked. Two of these "half-ILS" approaches were flown successfully. This technique could possibly be used as an interim solution to the VTOL IFR approach problem when the normal ILS s are available.

Addition of DME to the NYA fleet could also eliminate the difficulty encountered on route N-6 in using VOR radials at relatively large distances from the stations. Instead of using two inaccurate radials to transition from the JFK 292° radial to the LGA 13 ILS, a single DME arc from JFK could be used.

In addition to the half-ILS s a further attempt was made to adapt the conventional ILS capability by exploring higher glide slope lobes for steeper approaches.

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Three attempts to fly such a lobe were unsuccessful in the NYA S-61; in each case, reliable upper lobe glide slopes could not be located and/or tracked. This is probably explained by the fact that the next stable lobe is at 9°, and the glide slope beam width at the transition altitude is only about 1/4 nm. Hence the pilot has very little time to capture the beam. Although cases have been reported of a secondary glide slope being successfully flown, these were initiated at higher altitudes (~ 5000 ft) where the beam width would be wide enough to stabilize on. More flight tests are needed in this area before a firm conclusion can be reached.

Steep approaches in the S-61 pose other problems, though. The airspeed required to maintain a suitable degree of stability produces a high rate of descent (greater pilot workload) at angles much above 6°. Evidence of this was also found in the third group of tests which involved the microwave landing system.

5.3.3 MLS

A TALAR MLS was temporarily installed for demonstrations at the Morristown, N.J. airport during the ASI/NYA flight evaluation program. This equipment was used to simulate several IFR approaches in the NYA helicopters: five were flown with a glide slope of 4.5°, and four with a glide slope of 6°. The basic piloting skills required to fly the MLS are the same as for a normal ILS; however, some differences in technique were noticed. In the standard ILS, the glide slope antenna is closer to the touchdown zone than the localizer antenna, while the TALAR system antennas are coincident. As a consequence, the localizer needle for the MLS appears to be more sensitive than for a standard ILS. Slower airspeeds were used in some approaches to reduce the apparent needle sensitivity, but a definite tradeoff between workload associated with maneuvering the vehicle and that associated with keeping the needles centered was noted. The optimum airspeed appeared to be around 60 knots in the S-61 for both the 4.5° and 6° glide slopes.

The most impressive feature of the MLS demonstrations was the flexibility offered for VTOL operations. With this equipment the IFR routes described earlier could be made nearly direct, since the approach centerlines could be arbitrarily aligned for the helicopters' convenience. Moreover, the TALAR antenna could conceivably be mounted on a turntable to accommodate sequenced approaches from different directions.

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The TALAR MLS localizer signals cover a sector approximately 30 degrees on either side of the approach centerline. The receiver antenna pattern is approximately 65 degrees on either side of the longitudinal axis of the aircraft; the vertical limits are 18 degrees above and below the horizontal plane. These limits were explored by observing the appearance and disappearance of the Glide Slope and Localizer OFF flags on the MLS cockpit indicator during the flight program. Table 27 shows the azimuth coverage observed during the flight evaluation program. The coverage exceeded the anticipated coverage in every case. The values were recorded with the station well within the receiver antenna pattern angle. Three points were measured on the north side of the centerline and three were obtained on the south side. The limit was defined as the point where the flag status changed. In all six cases the two OFF flags changed simultaneously.

Table 27. TALAR Azimuth
Coverage in Degrees.

North Side	South Side
54 A*	44 A
49 D**	35 D
69 A	45 A

*A OFF flags Appeared.
**D OFF flags Disappeared.

Table 28 shows the horizontal coverage of the receiver antenna observed during turning tests conducted within $\pm 20°$ of the centerline. In these tests the flags tended to disappear together at the limit, but the localizer flag reappeared at a greater "look" angle than the glide slope flag. In attempts to check the vertical limits of the receiver antenna, aircraft pitch angles of 20 degrees down and 25 degrees up produced no apparent signal loss. These results show that the TALAR coverage is greater than that of a standard ILS; and, hence, more suitable for larger localizer interception angles and higher glide slopes which are preferable for VTOL operations.

5.3.4   INNOVATIVE CONCEPTS

The fourth major flight test area involved descending spirals in the NYA

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Table 28. MLS Receiver Antenna Limits in Turns.

Left Look		Right Look	
Localizer OFF Flag	Glide Slope OFF Flag	Localizer OFF Flag	Glide Slope OFF Flag
167 A RT*	137 A RT	133 D RT	133 D RT
163 A RT	127 A RT	145 D RT	145 D RT
99 D LT**	99 D LT	93 D RT	93 D RT
119 D LT	119 D LT	121 D RT	121 D RT

* in right turn.
** in left turn.

helicopters. This maneuver and its potential application have already been discussed in Section 2. In the flight evaluation program, the workload and ride quality associated with the execution of descending spirals were examined. The parameters were varied as shown in Table 29. Finally, some spirals were combined with the MLS approaches.

Table 29. Spiral Descent Parameters.

Bank Angle (deg)	Descent Rate (fpm)	Airspeed (kt)	Altitude Change (ft)	Turn Radius (ft)
9	500	60	1000	2690
9	1000	60	1000	2690
20	500	80	1000	1558
30	500	80	1000	983
20	1000	80	1000	1558
30	1000	80	1000	983
18*	500	80	1000	1745
30*	1000	80	1000	983

*These spirals were followed by transition to an MLS approach.

The workload assessments were based on qualitative comments from the pilot, who felt that none of the spirals was overly difficult to perform. Of most concern was the increased uncertainty of position and orientation at the completion of the maneuver. This result supports the need for the development of spiral guidance laws and algorithms for automatic control or flight director commands. Transition to the MLS approach at the end of a spiral offered no unusual problems either. The pilot simply leveled off at the proper altitude after the spiral descent and continued the turn (if necessary) to acquire the MLS signals and then intercept the localizer and glide path.

The ride quality associated with the spirals was measured both qualitatively and quantitatively. The qualitative assessment, provided by members of the investigative team riding in the passenger compartment, was that no uncomfortable sensations were experienced during the spirals or the recoveries. The quantitative evaluations of ride quality are being conducted by the University of Virginia (under separate contract with LaRC), who recorded accelerometer outputs during the MLS evaluation flights. The results are not yet available, but will eventually provide a preliminary, quantitative evaluation of the spiral descent for commercial VTOL operations.

5.4   SPECIAL LOW ALTITUDE OPERATIONAL FACTORS

The desirability of low altitudes for VTOL operations has been discussed in Section 2. An effort was made during the flight evaluation program to examine potential operational problems associated with such flight. Three special considerations which could affect flight safety are terrain and obstacle clearance, CTOL encounters, and pilot workload. Qualitative assessments of these considerations were obtained during simulated IFR flights along the Zulu Airways and by simulated IFR and VFR flights along the Tango Connectors.

5.4.1   TERRAIN AND OBSTACLE CLEARANCE

Terrain and obstacle clearance is a paramount consideration in basic route planning. Altimetry and navigational accuracies can be employed to determine minimum altitudes in the vicinity of charted terrain and obstacles, but the result will be only as good as the charts themselves. Although such information is reasonably accurate for terrain features, shortcomings in obstruction data often occur due to the

lag between the completion of an obstruction and its appearance on a new chart edition. Naturally, any low altitude airways would require careful flight checks periodically to ensure safe obstruction clearance.

As an example of this lag, a large smokestack was observed near the proposed heliport site during the first flight along the Boston Tango Connectors. Although the current chart showed only a 345-foot obstruction at the location, subsequent investigation revealed that a new stack was completed in summer 1973, and reached to a height of 537 feet MSL. New maps for which corrections have been noted as a result of this flight evaluation program are scheduled for publication in June 1974; thus, a one year lag is evident in publishing this 200 ft change in height.

In the urban environment, it is not uncommon for a temporary or mobile obstruction to arise near a landing site and penetrate the safe clearance criteria. A typical example was observed during one approach to the Wall Street Heliport, when a barge with a tall crane (approximately 100 ft) had docked just north of the landing pier. Although the crane offered no danger to normal visual approaches, it undoubtedly would have violated the clearance criteria for a projected IFR missed approach path. A second approach to the landing site, for worst case wind direction, missed the top of the crane by approximately 150 feet laterally and 20 - 30 feet vertically. Again, the margin of safety was sufficient for daylight visual flight, but it would have been significantly decreased for an IFR or a night-time approach.

5.4.2 CTOL ENCOUNTERS

VTOL operations at low altitudes will undoubtedly encounter other uncontrolled aircraft (both fixed-wing and rotary-wing) more frequently than at high altitudes due to the higher activity of general aviation. Since regulations forbid aircraft operations in controlled airspace without authorization during IFR weather, the low altitude IFR VTOL operation could be conducted with a sufficiently high degree of safety. However, during VFR weather and outside of controlled airspace, that assurance cannot be guaranteed. Numerous sightings of other aircraft at low altitude during the flight evaluation program support the contention that some form of proximity alerting device will be necessary for the required safety levels on these low altitude routes.

5.4.3   PILOT WORKLOAD

On the Zulu routes, pilot workload associated with RNAV and low altitude flight was not difficult since a three-axis autopilot with altitude hold was used. The RNAV waypoints were usually about ten minutes apart; selection of a new waypoint required an average of twenty seconds to change VORTAC frequency and/or the waypoint definition. Another 20 - 30 seconds was used by the pilot to identify the VORTAC station and verify the waypoint definition. This second time span followed the first, but not immediately. Then the pilot spent a few moments looking for agreement between the RNAV readouts and the heading and distance shown on the flight plan for the next waypoint.

The flight evaluation program did reveal the susceptibility of the crew to waypoint definition errors. For the majority of actions taken by a pilot to adjust his navigation and guidance aids, he receives some kind of feedback for verification (e.g., Morse code identification, a mode-select light, appearance of steering needles). However, this feedback is generally lacking in RNAV waypoint definition; i.e., inserting in a particular radial and distance. The only cross check available is for the pilot to compare his knowledge of the bearing and distance to the desired waypoint with the RNAV readouts. Of course, he can double check the RNAV inputs for the correct parameters, but that is certainly not error proof.

During the early stages of the flight evaluation program some waypoint definition errors occurred by accident. Most were caught through the check and double check technique, but two were discovered only when the visual position plot began diverging from the charted course. This indicates a need for some type of feedback to the pilot once he has entered a waypoint into the RNAV system.

Flights along the Tango Connectors and flights in the intra-urban environment produced greater pilot workloads because of the departure and arrival maneuvers, the shorter time intervals between waypoints, and the increased communications workload. However, more advanced RNAV equipment would undoubtedly provide multiple waypoint storage and automatic switching, thus relieving the pilot of these tasks under normal conditions. Furthermore, communications procedures would become routine and, hopefully, independent of CTOL operations. Nevertheless, for short intra-urban routes,

continuous helicopter IFR operations may have to consider fatigue as more of a limiting factor than it is for CTOL IFR operations. Since elementary stages of fatigue affect response time more than accuracy of performance, it would be more of a factor during inflight anomalies than during normal operations. Consequently, fatigue as a product of workload versus time can be a significant consideration in low altitude operations.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

This section presents a summary of the principal results and conclusions of the study and brief discussions of several areas which have been identified as potential candidates for additional research.

6.1 CONCLUSIONS

Navigation requirements have been identified for commercial VTOL operations providing inter-urban, intra-urban and conventional airport services. The major general requirement is that it must provide the information, accuracy, coverage, and reliability to permit VTOL operations independent, or essentially independent, of conventional fixed-wing traffic. Consequently, the navigation system must have area navigation capability and permit all-weather operation to at least the same minima as most conventional traffic.

Proposed IFR approach categories have been defined for VTOL aircraft which recognize the unique capabilities of such vehicles. Thus, weather permitting a VTOL Category I approach would require a CTOL Category II approach. However, most commercial operations probably would not require VTOL Category II capability, and even fewer would need VTOL Category III. The equipment costs (ground and air, for both installation and maintenance) and the costs of maintaining pilot proficiency would generally not be justified by the very small number of cancelled flights they would avoid.

The feasibility of low-altitude, RNAV routes has been established for commercial VTOL services in the Northeast Corridor. A set of typical one-way, inter-city 'Zulu' airways and associated 'Tango' transition routes has been defined between the Boston, New York City and Washington, D.C. metropolitan areas. These routes permit nearly direct service (significantly shorter than the existing "preferred," low altitude Victor airways for conventional IFR traffic) beneath the conventional traffic and provide continuous VORTAC navigation coverage. Furthermore, they avoid congested noise-sensitive areas, obstacles and major CTOL aerodromes. The flight evaluation program subsequently verified the practicality of these routes for independent VTOL operations.

The existing VORTAC system has been demonstrated to provide satisfactory enroute and terminal area navigation at low altitudes over most of the routes studied. A VOR/DME, general-aviation RNAV system with single waypoint entry exhibited surprising accuracy in the flight evaluation program. Although the flight program was relatively limited, the results indicate that even simple RNAV equipment can provide the necessary navigation accuracy. More elaborate systems using dual DME and having multiple waypoint storage would significantly improve the accuracy and would substantially reduce the associated pilot workload.

Analytical predictions of line-of-sight signal coverage were verified by the flight evaluation program. A computer program (COVER) was developed to generate line-of-sight coverage overlays for aeronautical charts. These predictions, which did not include local terrain effects, were shown to be reasonably accurate — usually conservative — by the flight evaluation data. Post-flight analyses of the results using local terrain contours indicate excellent agreement between the predicted and observed signal coverages.

An omnidirectional approach capability is not generally necessary for VTOL operations. Crosswind approaches and landings do not pose a problem for rotorcraft; however, a tailwind cannot be tolerated, principally because of the vortex ring state. Consequently, all wind directions can be accommodated with a minimum of two approach directions. Furthermore, the surrounding geography at a specific site will nearly always impose constraints on the approach and departure paths for noise abatement and obstacle clearance. In addition, the VTOL route structure will establish a finite number of approach directions from the other heliports served. Finally, discrete 3D or 4D transition RNAV routes will undoubtedly be required to achieve independence from the CTOL traffic.

On the other hand, curved decelerating approaches will be required for safe, efficient, and independent VTOL operations. A spiral descent technique has been proposed as a possible standard VTOL approach procedure. The spiral descent uses minimal airspace, accommodates arrivals from any direction, and can service multipad landings. The spiral approach also provides the features of a vertical descent, but avoids the vortex ring state, maintains a stable airspeed, and uses less fuel. Flight evaluations conducted for several spiral descents have demonstrated their feasibility in terms of ride quality, vehicle capability and pilot workload.

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The flight evaluation program has shown that limited helicopter IFR operations are feasible in the New York City area with existing navigation equipment (VOR, DME, ILS, marker beacon, transponder). These operations can be established with VOR radials, DME arcs, ILS localizers and abbreviated ILS approaches to runways not in use for CTOL arrivals. Such procedures can provide reasonably efficient helicopter service between LGA and JFK to CTOL Category I minimums, with little interference to CTOL traffic. The addition of RNAV and MLS to the existing equipment would permit reliable, nearly-independent VTOL operations in the New York City area, between the principal CTOL airports and other heliports such as Wall Street.

A multi-configuration, straw-man navigation and guidance system was developed for future commercial VTOL operations with advanced rotorcraft. This system allows the formulation and evaluation of a variety of avionics system configurations. A baseline hybrid navigation system using INS, DME and MLS data was selected as the most likely candidate for the 1980 s time period. This system uses a low-cost INS with DME updating in the enroute and terminal phases, and combines INS and MLS information for the approach and landing phase. The hybrid navigator provides increased accuracy and greater reliability by combining redundant navigation information from separate sensors. A recursive filter is used to generate the optimum position and velocity estimates for a velocity-command guidance and control system.

The straw-man design also provides for the possible utilization of VLF inputs for enroute/terminal navigation, and for a multilateration ranging system in the approach/landing phase. Thus, the multi-configuration system provides maximum flexibility for alternate applications (e.g. remote areas), and increased adaptability for equipment modifications. Other straw-man system inputs include air data, radar altimeter and a 4D RNAV flight plan. A weather radar allows the pilot to modify the flight plan for increased safety and passenger comfort. A key element of the recommended straw-man system is an onboard traffic situation display (TSD) which provides an independent capability for ensuring airborne separation from other traffic, including other VTOLs as well as CTOLs or STOLs. The TSD requires position information on all proximate air traffic, which could be provided by DABS or Syncho-DABS, or an air-derived collision avoidance system.

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To evaluate the straw-man navigation system, a digital computer simulation program (VALT) was developed and demonstrated on the LaRC CDC 6400/6600 computer facility. Program VALT is a flexible tool for analyzing the performance of candidate VTOL navigation and guidance systems and evaluating various rotorcraft and operational constraints. Error models were developed to represent the actual navigation sensors (INS, DME, air data, etc.), and a linear Kalman filter was designed to calculate the optimum error estimates for a set of simpler, estimator-assumed error models. A simple perturbation scheme was developed to provide path guidance about a desired nominal flight plan. The guidance system produces velocity correction commands to a velocity-command flight control system, which is based on an earlier NASA-designed system for the CH-46 helicopter. A new point-mass dynamic model was developed to simulate the translational motions of a pure or compound helicopter. Program VALT will be extensively utilized in the second phase of the study for parametric investigations to examine the effects of sensor and subsystem errors, and alternate system configurations.

6.2   RECOMMENDATIONS FOR ADDITIONAL RESEARCH

During the course of the study, several areas have been identified in which additional research is needed to advance the navigation and guidance system technology for commercial VTOL operations. These subject areas are outlined below:

●   FILTERING TECHNIQUES FOR VTOL NAVIGATION

The configuration and associated algorithms to be implemented in the navigation system estimator require further analysis, particularly the tradeoffs among accuracy, computing efficiency and simplicity. Program VALT provides an ideal tool to evaluate the performance of candidate optimum and sub-optimum filters in terms of accuracy, computing time, program complexity, capacity requirements, and stability. The results should be analyzed to determine the relative advantages and disadvantages of each candidate, and one or more techniques should be recommended for evaluation in the NASA VTOL flight test program.

●   SPIRAL DESCENT GUIDANCE FOR VTOL OPERATIONS

The navigation and guidance system requirements should be determined for IFR VTOL spiral descents in the presence of winds. The study should: establish recommended values for airspeed, bank angle, descent rate and protected airspace; formulate a number

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of feasible guidance laws for spiraling flight; and develop filtering algorithms for navigation during this phase. The guidance and navigation algorithms could be evaluated with Program VALT. The necessary commands to display on a flight director and/or the signals to feed an automatic pilot should be established. Finally, one or more spiral guidance laws should be recommended for further evaluation in the LaRC VTOL real-time simulation, and eventual implementation in the VTOL flight test program.

- RNAV/MLS FLIGHT EVALUATION

A flight program should be conducted to provide a realistic evaluation of the use of RNAV and MLS for helicopter operations in the intra-urban/conventional airport services. A carefully organized parallel approach could provide the most beneficial results. On one hand, authentic operational data with existing equipment could be obtained by a relatively low-cost joint ASI/NYA effort that would extend the flight evaluation conducted under Phase I of this contract. The RNAV and MLS equipment would be obtained on a lease or demonstration basis and the airborne units installed in an NYA S-61 helicopter. Working closely with the FAA, a set of RNAV routes and MLS approach procedures would be devised for the New York City area to provide minimum interference with existing CTOL traffic. The resulting system would be flight evaluated under simulated IFR conditions for operational feasibility. At the same time, further ground-based analysis should be performed using both fast-time and real-time simulations to refine the navigation requirements for advanced systems that would eventually be evaluated in the NASA VTOL flight test program. Both elements of the investigation would draw heavily on the outputs of the present study, and each would provide valuable inputs to the other. The successful completion of such a program would unquestionably provide a significant advancement toward the eventual goal of the VALT project.

- FLIGHT EVALUATION OF VLF NAVIGATION SYSTEMS FOR VTOL

The use of VLF navigation (including Omega or Loran) for VTOL could provide unrestricted low altitude coverage with little or no station switching necessary. A flight evaluation program, similar to that described for the previous recommendation, should be conducted to examine the feasibility of low frequency RNAV for commercial VTOL operations. Terminal phases could be tested with an NYA S-61 helicopter; a low-

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cost, fixed-wing aircraft could be used to obtain data appropriate to the enroute phases of commercial helicopter routes. The static and dynamic accuracy of the low frequency system would be determined by airborne recording of the indicated position as compared to visual checkpoints, ILS localizer or ground radar. Comparisons of coverage, aircraft maneuver effects, signal loss, pilot workload, accuracy, etc. would be made. Analytical models would be formulated and evaluated with fast-time and real-time simulations to provide comparisons with the operational results, and to suggest VLF implementations in the NASA VTOL flight test program.

- NAVIGATION AND TRAFFIC SITUATION DISPLAY FOR VTOL

A key element in the proposed VTOL straw-man navigation system is a Traffic Situation Display to visually display to the pilot the immediate air traffic environment and to assist him in navigation and precise spacing and merging. Considerable work has been done at MIT, NASA/LaRC and elsewhere on experimental TSD simulations for CTOL aircraft. A research program is recommended to evaluate a TSD for a helicopter in an independent VTOL environment; this could be achieved by minor modification of the existing MIT or LaRC TSD simulation facility. The rotorcraft equations of motion developed under the current contract would be incorporated into the TSD simulation in place of the present Boeing 707 model. The simulation would utilize a velocity-command control system similar to the one used in Program VALT. A commercial helicopter scenario would be included in the existing simulation (including Zuly routes, Tango connectors and helicopter terminal approach procedures). These would be presented on the display relative to the navigation coordinate grid centered at the simulated helicopter position. Simulation studies would examine the effects of navigation coverage, pilot workload, traffic sequencing and spacing, conflict avoidance, and guidance commands. Both VTOL and CTOL air traffic should be simulated to investigate the ability of a single helicopter to operate in the high density mixed environment with the proposed system.

- IMPROVED ANALYTICAL COVERAGE PREDICTIONS

Results of the flight evaluation program have shown excellent agreement with the analytical predictions of line-of-sight signal coverage generated by Program COVER, when the local terrain is taken into consideration. A very accurate and

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useful tool could be developed for prediction of low-altitude signal coverage by modifying Program COVER to include these terrain effects. This could be accomplished by examining the terrain surrounding the ground stations, either visually or by reference to topographic charts, to determine the line-of-sight elevation angle to the terrain horizon as a function of azimuth angle. The data could then be utilized in the coverage calculations in much the same way as the published FAA restrictions are presently handled. The resulting program would be a valuable aid for defining low altitude VTOL routes, for selecting the optimum stations to be used for each segment of a route (discussed below), and for establishing the need for additional ground stations and their suggested locations.

The baseline straw-man navigation system uses DME updating of a low-cost INS for the enroute and terminal area phases of flight. The overall accuracy of this system therefore depends upon the relative geometry, accuracy, and frequency of the DME measurements, which are limited by the line-of-sight signal coverage. A competing factor is the desire to minimize, or at least limit, the number of DME channel switches to reduce pilot workload, search and lock-on delays and computer storage requirements. Program COVER could be modified and extended to automatically schedule the optimum DME station selections along the flight path. The coverage calculations, corrected for terrain effects, would indicate the stations available for navigation, and the relative geometry for each of these would be examined to determine the combinations for best accuracy (ideally taking the previous measurement histories into consideration). Finally, the program would evaluate the number and frequency of channel switches, and the number and utilization of the stations selected, to generate an optimum DME measurement schedule.

- FUEL ECONOMY IN COMMERCIAL VTOL OPERATIONS

The energy shortage is dictating careful evaluation of the amount of fuel consumed by various forms of transportation. In the past, the case for VTOL has been justified principally on the basis of saved time; in the future, it will be necessary to weigh fuel economy more heavily. Consequently, the feasibility of commercial VTOL operations will depend on the ability of the VTOL to economize on fuel relative to previous non-fuel-constrained operations, as well as vis-a-vis the CTOL and other transportation forms. A comparative study of the fuel economy of the helicopter

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relative to conventional aircraft and other competitive transportation forms should be conducted, including optimization analyses of helicopter operations using fuel instead of time as the cost function. The impact on VTOL fuel consumption of each of the operational constraints identified in the present study should be evaluated. Specific existing and proposed rotorcraft should be analyzed for fuel saving operational procedures, such as spiral descents. The study should investigate the sensitivity of helicopters' operating costs to the cost of fuel, and examine the influence of fuel economy on VTOL guidance and navigation requirements.

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APPENDIX A

POINT-MASS VTOL DYNAMIC MODEL

This appendix describes the mathematical model developed to represent the dynamics of the rotorcraft for the navigation system analyses. For simplicity, a point-mass model was selected over a full six-degrees-of-freedom representation. The navigation and guidance systems are concerned with the position and velocity of the aircraft center of mass (c.m.); the higher-frequency attitude motions about the c.m. are controlled by the flight control system inner loops and are above the bandwidth of the navigation and guidance systems.

A.1   REFERENCE FRAMES

The analysis of VTOL navigation requires the precise definition of several coordinate frames. Each of the five frames defined below is an orthogonal, right-handed coordinate frame. The nomenclature follows that of Britting (Ref. 61). The relationships between the various coordinate frames are given in terms of the relative angular velocity (ω) and the coordinate transformation matrix (C) between the two frames.

A.1.1   INERTIAL FRAME (i Frame; x, y, z Axes)

The inertial frame is defined as having its origin at the Earth's center, as illustrated in Figure 57. The x and y axes lie in the equatorial plane and the z axis is coincident with the Earth's axis of rotation. For the purposes of the present study, the rotation of the Earth is neglected in the equations of motion; hence, the inertial frame is an Earth-fixed frame. The axes are arranged such that the inertial reference meridian is coincident with the local meridian at the navigation starting time:

ℓ = terrestrial longitude from Greenwich

ℓ_o = initial terrestrial longitude = inertial reference meridian

A.1.2   GEOGRAPHIC FRAME (n Frame; N, E, D Axes)

The geographic frame is a local navigational frame which has its origin at the vehicle's c.m. and its axes aligned with the North, East, and Down directions.

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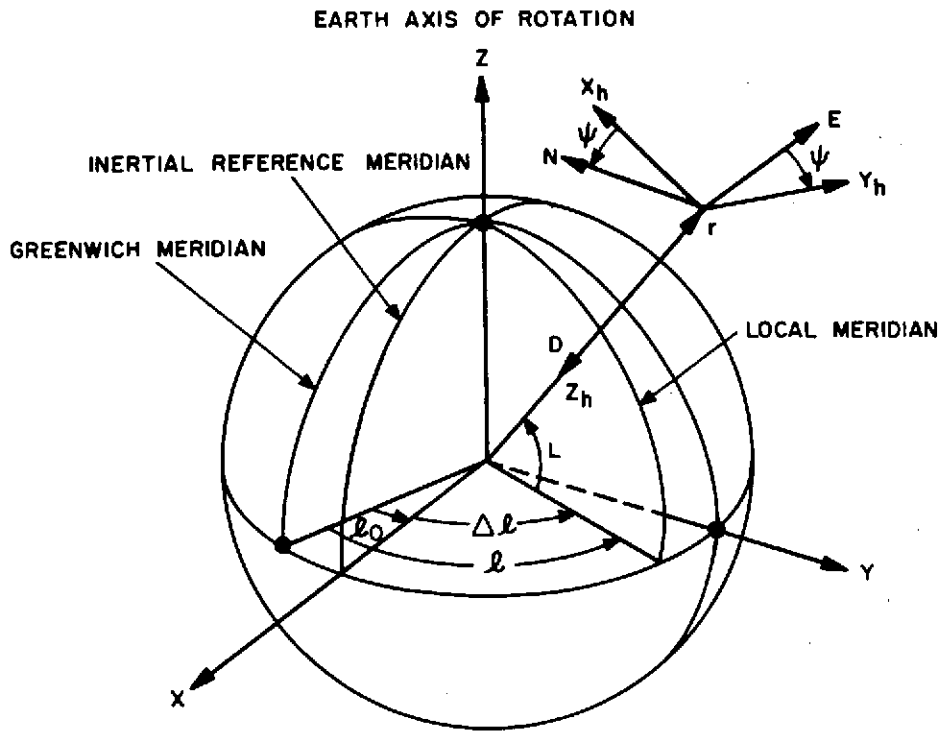
Figure 57. Coordinate Frame Geometry. (N, E, D) – Geographic;
(x, y, z) – Inertial; (x_h, y_h, z_h) – Level Heading.

The earth is assumed to be spherical, and Down is coincident with the local vertical. The North and East axes are in the local horizontal plane (Fig. 57).

The _inertial-geographic_ coordinate frame relationships are:

$$\omega_{in}^n = [\dot{\ell}\cos L, \; -\dot{L}, \; -\dot{\ell}\sin L]^T \tag{69}$$

$$\omega_{in}^i = [\dot{L}\sin \Delta\ell, \; -\dot{L}\cos \Delta\ell, \; \dot{\ell}]^T \tag{70}$$

$$C_n^i = \begin{bmatrix} -\sin L \cos \Delta\ell, & -\sin \Delta\ell, & -\cos L \cos \Delta\ell \\ -\sin L \sin \Delta\ell, & \cos \Delta\ell, & \cos L \sin \Delta\ell \\ \cos L, & 0, & -\sin L \end{bmatrix} \tag{71}$$

where $\Delta\ell = \ell - \ell_o$ = change in terrestrial longitude from start of navigation (t = 0)

$\qquad$ L = geographic latitude.

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A.1.3 LEVEL-HEADING FRAME (h Frame; x_h, y_h, z_h Axes)

The level-heading frame is a body-fixed frame which has its origin at the vehicle c.m. and its z axis coincident with the Down axis of the geographic frame. The x axis is rotated about the z axis away from North by the aircraft heading angle ψ. Thus the x axis is the projection of the aircraft's longitudinal body axis onto the local horizontal plane. This frame is convenient for describing the rotor forces acting on the vehicle (Fig. 57).

The relationships between the level-heading and geographic frames are:

$$\omega_{nh}^n = \omega_{nh}^h = [0, 0, \dot{\psi}]^T \tag{72}$$

$$C_h^n = \begin{bmatrix} \cos \psi, & -\sin \psi, & 0 \\ \sin \psi, & \cos \psi, & 0 \\ 0, & 0, & 1 \end{bmatrix} \tag{73}$$

A.1.4 BODY FRAME (b Frame; R, P, Y Axes)

The Body frame constitutes the familiar vehicle axes of yaw, pitch, and roll which has its origin at the vehicle c.m. As illustrated in Figure 58, the roll axis points forward, the pitch axis points out the right-hand side, and the yaw axis points down, all with respect to the vehicle.

The relationships between the geographic and body frames are determined by the rotation sequence: yaw, pitch and roll.

$$\omega_{nb}^n = [-\dot{\psi} \sin \theta, \ \dot{\psi} \cos \theta \sin \phi, \ \dot{\psi} \cos \theta \cos \phi]^T \tag{74}$$

$$C_b^n = \begin{bmatrix} \cos \psi \cos \theta, & \cos \psi \sin \theta \sin \phi - \sin \psi \cos \phi, & \cos \psi \sin \theta \cos \phi + \sin \psi \sin \phi \\ \sin \psi \cos \theta, & \sin \psi \sin \theta \sin \phi + \cos \psi \cos \phi, & \sin \psi \sin \theta \cos \phi - \cos \psi \sin \phi \\ -\sin \theta, & \cos \theta \sin \phi, & \cos \theta \cos \phi \end{bmatrix} \tag{75}$$

where ψ, θ and ϕ are the yaw (or heading), pitch, and roll angles. The attitude rates $\dot{\theta}$ and $\dot{\phi}$ have been neglected for navigation and guidance analyses.

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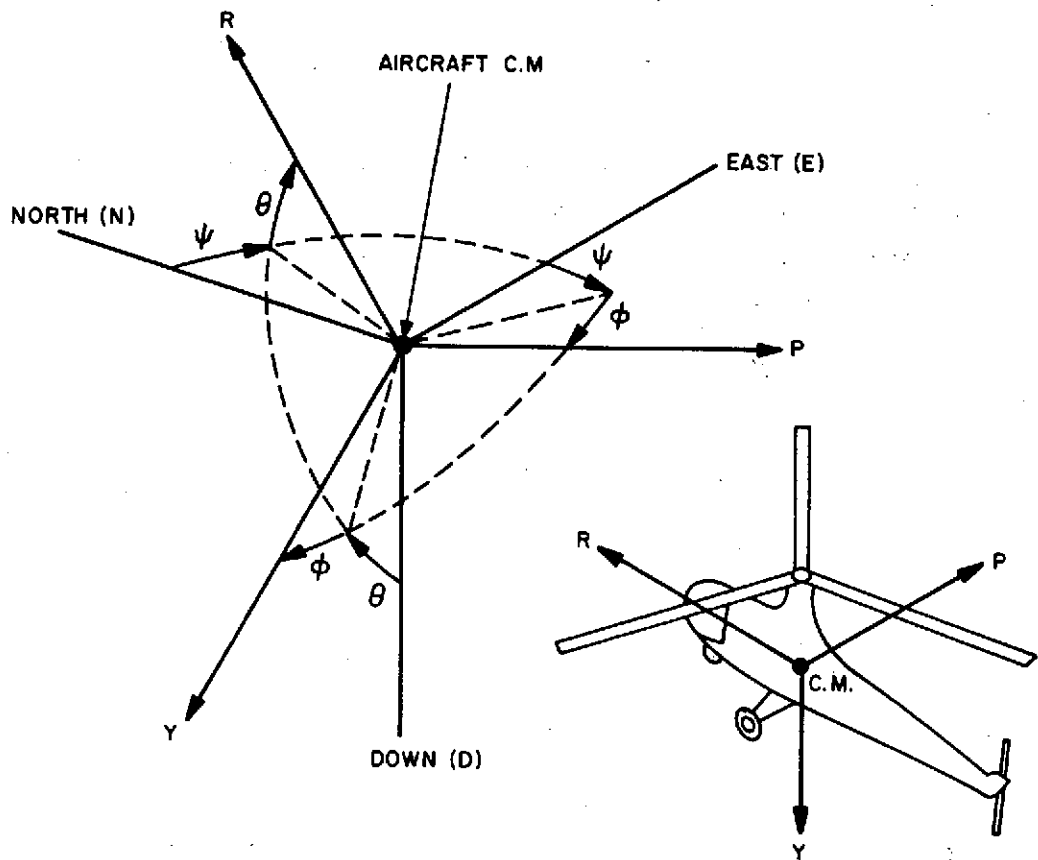
Figure 58. Body Coordinate Frame (R, P, Y Axes).

A.1.5   STABILITY FRAME (s Frame; x_s, y_s, z_s Axes)

This is a body-centered reference frame which has its x_s axis aligned with the relative wind vector, $\overline{V}$. It is obtained from the geographic frame by an azimuth rotation λ and an elevation rotation γ (Fig. 59). The transformation matrix is

$$
C_s^n = \begin{bmatrix} \cos\lambda\cos\gamma, & -\sin\lambda, & \cos\lambda\sin\gamma \\ \sin\lambda\sin\gamma, & \cos\lambda, & \sin\lambda\sin\gamma \\ -\sin\gamma, & 0, & \cos\gamma \end{bmatrix} \tag{76}
$$

The relationship between the stability frame and the body frame is expressed in terms of the angle of attack α and the sideslip angle β (Fig. 59):

- 200 -
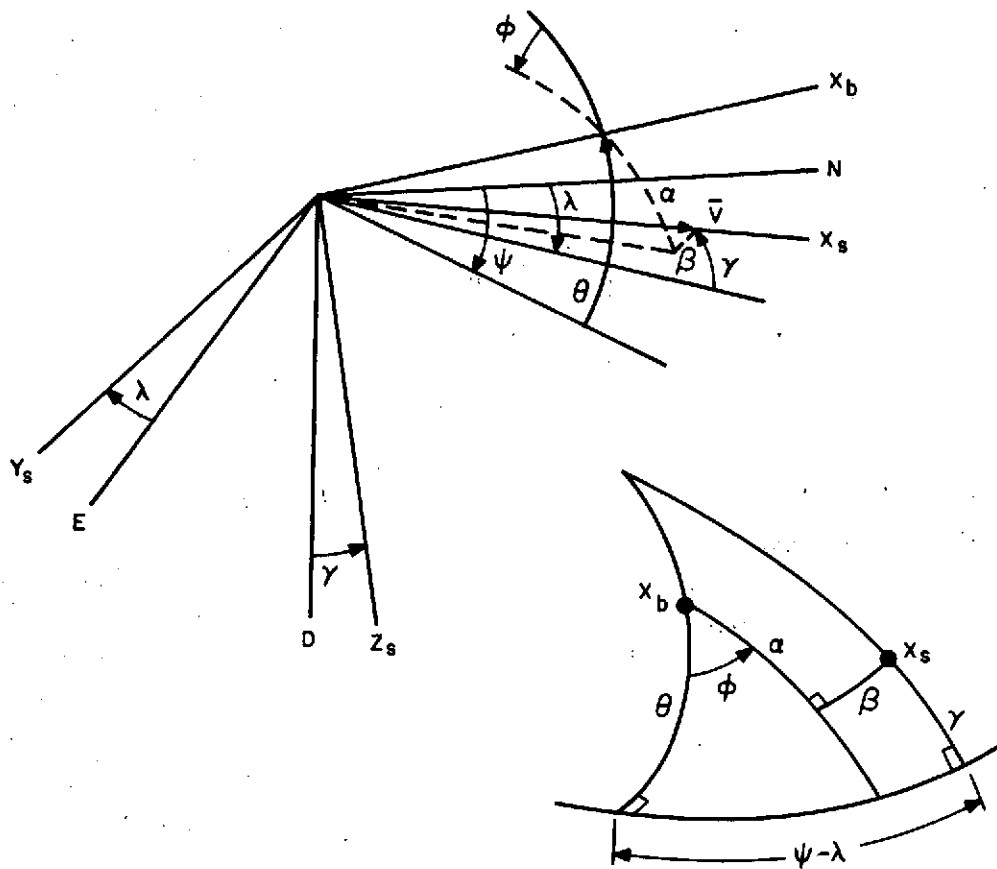
Figure 59. Relative Orientations of Geographic (N, E, D), Stability (x_s, y_s, z_s), and Body (x_b) Frames.

$$C_s^b = \begin{bmatrix} \cos\alpha\cos\beta \, , & \cos\alpha\sin\beta, & -\sin\alpha \\ -\sin\beta \, , & \cos\beta \, , & 0 \\ \sin\alpha\cos\beta, & \sin\alpha\sin\beta \, , & \cos\alpha \end{bmatrix} \qquad (77)$$

A.1.6   WIND EFFECTS

The velocity of the local air mass is defined in the geographic coordinate frame:

$$W^n = \begin{bmatrix} W_N \\ W_E \\ W_D \end{bmatrix} \tag{78}$$

Thus, the speed of the aircraft relative to the air mass is given by

$$\overline{V}^n = V^n - W^n = \begin{bmatrix} V_N - W_N \\ V_E - W_E \\ V_D - W_D \end{bmatrix} \tag{79}$$

The azimuth and elevation angles which define the stability coordinate frame in Figure 59 are now found to be

$$\lambda = \tan^{-1}(\overline{V}_E/\overline{V}_N) \tag{80}$$

$$\gamma = \tan^{-1}(-V_D/\sqrt{V_N^2 + V_E^2}) \tag{81}$$

The angle of attack α and sideslip angle β can now be determined, since

$$\overline{V}^n = C_s^n \overline{V}^s = C_b^n C_s^b \overline{V}^s \tag{82}$$

The results are

$$\sin \beta = \sin \theta \sin \phi \cos \gamma \cos(\psi - \lambda) - \cos \phi \cos \gamma \sin(\psi - \lambda)$$
$$- \cos \theta \sin \phi \sin \gamma \tag{83}$$

$$\sin \alpha = [\sin \theta \cos \phi \cos \gamma \cos(\psi - \lambda) + \sin \phi \cos \gamma \sin(\psi - \lambda)$$
$$- \cos \theta \cos \phi \sin \gamma]/\cos \beta \tag{84}$$

A.2   EQUATIONS OF MOTION

The equations of motion for the VTOL dynamic model are written with

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respect to the Earth-fixed inertial reference frame, in terms of the vehicle's latitude, longitude and radius from the Earth's center:

$$\ddot{L} = \frac{1}{r}\left(\frac{F_N}{m} - 2\dot{L}\dot{h} - r\dot{\ell}^2 \sin L \cos L\right) \tag{85}$$

$$\ddot{\ell} = \frac{1}{r \cos L}\left(\frac{F_E}{m} + 2r\,\dot{\ell}\dot{L}\sin L - 2\dot{h}\,\dot{\ell}\cos L\right) \tag{86}$$

$$\ddot{h} = r\left(\dot{L}^2 + \dot{\ell}^2 \cos^2 L\right) - \frac{F_D}{m} \tag{87}$$

where

$$r = r_o + h \tag{88}$$

and r_o is the mean radius of the earth (~ 3438 nm). F_N, F_E, and F_D are the external forces acting on the vehicle.

The components of velocity in the geographic frame are

$$V_N = r\dot{L} \tag{89}$$

$$V_E = r \cos L\,\dot{\ell} \tag{90}$$

$$V_D = -\dot{h} \tag{91}$$

For simulation purposes, the equations are more conveniently expressed in terms of the geographic frame. Differentiating Eqs. (89 – 91) and using Eqs. (85 – 88) we obtain:

$$\dot{V}_N = \frac{F_N}{m} + \frac{1}{r}\left(V_N V_D - V_E^2 \tan L\right) \tag{92}$$

$$\dot{V}_E = \frac{F_E}{m} + \frac{V_E}{r}\left(V_D + V_N \tan L\right) \tag{93}$$

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$$\dot{V}_D = \frac{F_D}{m} - \frac{1}{r} (V_N^2 + V_E^2) \tag{94}$$

The position coordinates are obtained by using Eqs. (89 - 91):

$$\dot{L} = \frac{V_N}{r} \tag{95}$$

$$\dot{\ell} = \frac{V_E}{r \cos L} \tag{96}$$

$$\dot{h} = -V_D \tag{97}$$

Thus, the six equations which must be integrated to determine the aircraft's position and velocity components are given by Eqs. (92 - 97).

A.3   ROTORCRAFT EXTERNAL FORCES

The external forces acting on the rotorcraft consist of aerodynamic, propulsive, and gravitational forces. For the pure helicopter, the non-gravitational forces are due to the rotor and airframe. The compound helicopter has additional forces due to the wing and the auxiliary propulsion system.

A.3.1   ROTOR FORCES

The components of rotor force are the thrust T, defined as perpendicular to the tip path plane of the blades; and the longitudinal and lateral forces H and Y, defined as parallel to the tip path plane. The tip path plane is inclined to the vertical axis of the level-heading frame by a pitch angle β_1 about y_h, and a roll angle β_2 about x_h (Fig. 60).

Considering the rotor blade element shown in Fig. 61, the elemental lift is given approximately by

$$dL \approx \frac{1}{2} \rho \, ac \, U_T^2 \left[\theta - \frac{U_p}{U_T} \right] dr \qquad U_p \ll U_T \tag{98}$$

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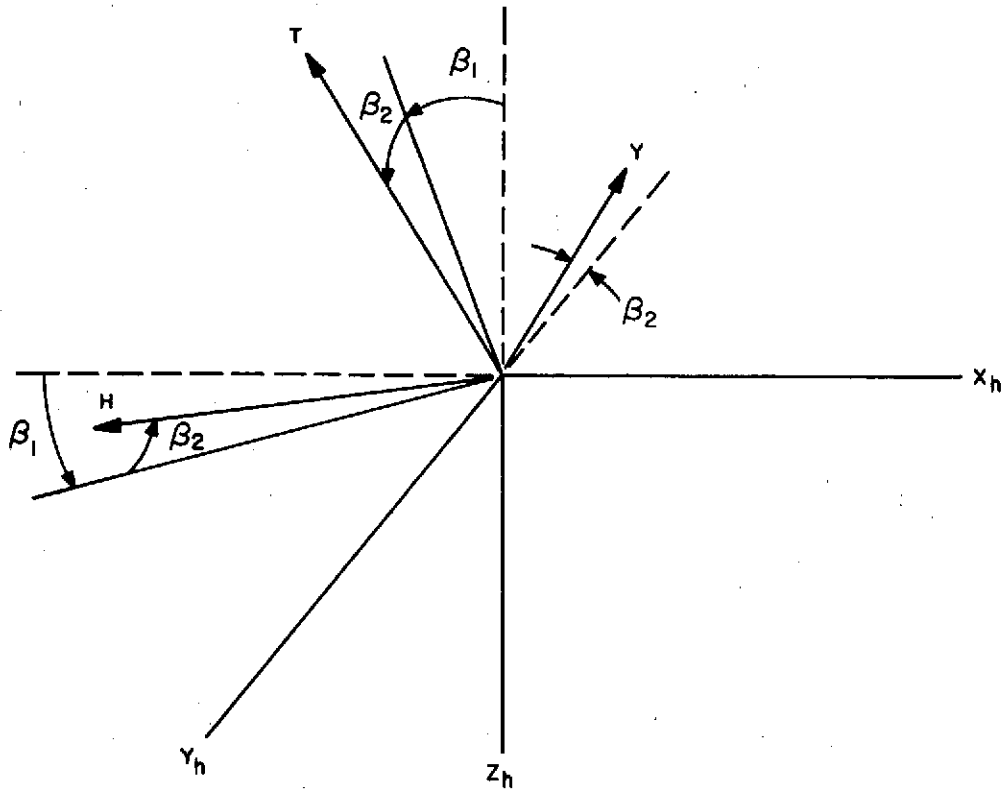
Figure 60. Rotor Forces.

where $U_T = \Omega + \mu_x \Omega \sin \psi$

$U_p = \lambda \Omega R + (r - e_b)\dot{\beta} + \mu_x \Omega \beta \cos \psi$

$\theta = \theta_0 + \theta_1 \cos \psi + \theta_2 \sin \psi + \beta \tan \delta_3$

and ρ = air density

a = blade airfoil lift curve slope

c = blade chord

r = radial location of blade element

Ω = rotor rotational speed

R = rotor radius

The rotor advance ratio and rotor inflow ratio are given by
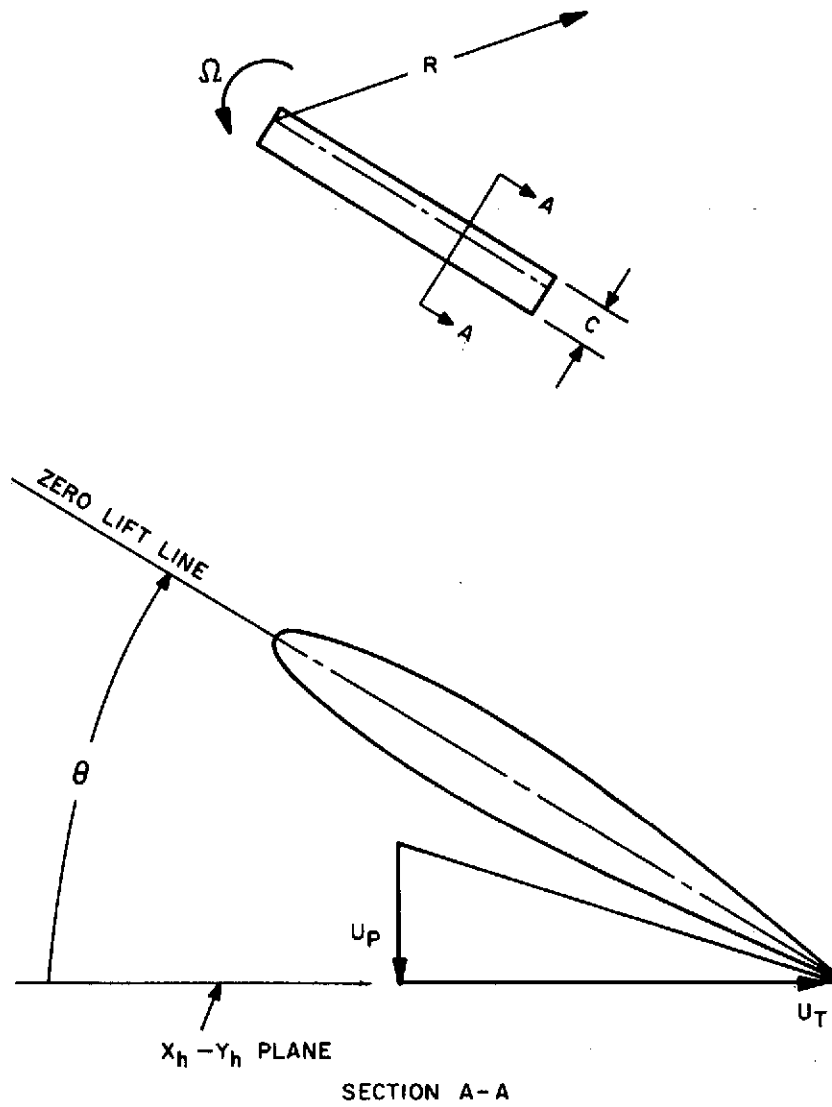
Figure 61. Rotor Nomenclature.

$$\mu_{x,y,z} = \text{rotor advance ratio} = \frac{\bar{V}_{x,y,z}}{\Omega R} \tag{99}$$

$$\lambda = \text{rotor inflow ratio} = -\mu_z + \frac{C_T}{2[\mu_x^2 + \lambda^2]^{1/2}} \tag{100}$$

and

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$$\bar{V}_{x,y,z} = V_{x,y,z} - \Delta V_{x,y,z}$$

$\Delta V_{x,y,z}$ = components of wind velocity along x_h, y_h, z_h axes

e_b = radial location of blade flapping hinge

β = blade flapping angle with respect to $x_h - y_h$ plane

ψ = blade azimuth angle

θ = blade pitch angle with respect to $x_h - y_h$ plane

δ_3 = blade pitch-flap coupling parameter

The rotor thrust is given approximately by

$$T \triangleq \rho\pi R^2 (\Omega R)^2 C_T \approx \frac{b}{2\pi} \int_0^{2\pi} \int_0^R \frac{dL}{dr} \, dr \, d\psi \tag{101}$$

where b = number of blades

thus

$$C_T \approx \frac{\sigma a}{4} \left[\frac{2}{3} \theta_0 \left(1 + \frac{3}{2} \mu_x^2 \right) + \mu_x \theta_2 - \lambda \right] \tag{102}$$

where σ = rotor solidity = $\dfrac{bc}{\pi R}$

Substituting the value of θ_2 required for trimmed flight (which will be derived in Section A.4), the expression for thrust coefficient becomes

$$C_T = \frac{\sigma a}{4} \left[\frac{2}{3} \theta_0 \left(1 + \frac{3}{2} \mu_x^2 \right) - \theta_0 \frac{2\mu_x^2 C}{B + \frac{3}{4}\mu_x^2 D} - \frac{B - \frac{1}{4}\mu_x^2 D}{B + \frac{3}{4}\mu_x^2 D} \lambda \right.$$

$$\left. + \mu_x B_1 \frac{A - \frac{1}{4}\mu_x^2 D}{B + \frac{3}{4}\mu_x^2 D} + \mu_x B_2 \tan \delta_3 \right] \tag{103}$$

where the quantities A, B, C and D are defined in Section A.4.

The rotor longitudinal and lateral forces H and Y will be approximated by considering profile drag effects only. Induced drag effects are small even at low flight speeds. Again considering the blade element, the elemental profile drag is given by

$$dD_o \approx \frac{1}{2} \rho\, ac\, U_T^2\, C_{D_o}\, dr \tag{104}$$

where C_{D_o} = blade airfoil mean drag coefficient

thus

$$H \triangleq \rho \pi R^2 (\Omega R)^2\, C_H \approx \frac{b}{2\pi} \int_0^{2\pi} \int_0^R \frac{dD_o}{dr} \sin \psi\, dr\, d\psi \tag{105}$$

Integrating and multiplying by 1.8 to correct for radial flow,

$$C_H \approx 0.45 \sigma C_{D_o}\, \mu_x \tag{106}$$

Similarly, for motion in the direction of the y_h-axis,

$$Y \triangleq \rho \pi R^2 (\Omega R)^2\, C_Y \tag{107}$$

$$C_Y \approx 0.45 \sigma C_{D_o}\, \mu_y \tag{108}$$

A.3.2 AIRFRAME FORCES

The components of airframe parasite drag are

$$D_x = f_x \cdot \frac{1}{2} \rho \bar{V}_x^2 \tag{109}$$

$$D_y = f_y \cdot \frac{1}{2} \rho \bar{V}_y^2 \tag{110}$$

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$$D_z \approx f_z \cdot \frac{1}{2} \rho (\lambda \Omega R)^2 \tag{111}$$

where $f_{x,y,z}$ = equivalent flat plate areas of airframe, including wings (if any).

On compound helicopters, the wings produce lift L and induced drag D_i. These forces are given by

$$L = \frac{1}{2} \rho (\overline{V}_x^2 + \overline{V}_z^2) S a_w \alpha \tag{112}$$

$$D_i = \left(\frac{L}{b}\right)^2 \frac{2}{\pi e \rho (\overline{V}_x^2 + \overline{V}_y^2)} \tag{113}$$

where S   = wing area

a_w = airframe lift curve slope

α = angle of attack of airframe zero lift line

b = wing span

e = Oswald efficiency factor

A.3.3 PROPULSIVE FORCE

The auxiliary propulsive turbofan on a compound helicopter produces a thrust force P which varies with throttle setting and flight speed. We shall assume that such a turbofan engine maintains constant thermal efficiency, turbine inlet temperature, fan rotational speed, and exhaust static pressure during changes in flight speed at a constant altitude and throttle setting. Then the static thrust can be written as

$$P_o = \eta \dot{m}_o v_o \tag{114}$$

where η = throttle setting

$\dot{m}_o$ = mass flow of engine at rest

v_o = exhaust velocity of engine at rest

For a unit weight of air passing through the fan, an energy balance gives

$$C_P T_1 + C_P(T_2 - T_1) = C_P T_3 + \frac{1}{2} v_o^2 \tag{115}$$

where T_1 = ambient static temperature (absolute)

T_2 = turbine inlet temperature (absolute)

T_3 = engine exhaust temperature (absolute)

For the engine at speed $\overline{V}$ relative to the air mass

$$C_P T_1 + C_P(T_2 - T_1) + \frac{1}{2}\overline{V}^2 = C_P T_3 + \frac{1}{2} v^2 \tag{116}$$

where v = exhaust velocity at speed $\overline{V} = (\overline{V}_x^2 + \overline{V}_z^2)^{1/2}$

thus

$$v^2 = \overline{V}^2 + v_o^2 \tag{117}$$

The thrust of the engine at speed $\overline{V}$ is

$$P = \eta \dot{m}(v - \overline{V}) \tag{118}$$

where $\dot{m}$ = mass flow of engine at $\overline{V}$

Since a turbofan engine is essentially a constant volume pump, $\dot{m}$ remains approximately constant at a fixed throttle setting from rest up to moderate flight speeds at a given altitude. Therefore

$$P \approx \eta \dot{m}_o \left[(\overline{V}^2 + v_o^2)^{1/2} - \overline{V} \right] \tag{119}$$

At a given flight speed and throttle setting, engine thrust is approximately proportional to air density as altitude or ambient temperature varies.

A.3.4 RESULTANT FORCES

The components of the total external forces are desired in the geographic frame for Eqs. (92 - 94). This is accomplished by a vector summation

$$F^n = \begin{bmatrix} F_N \\ F_E \\ F_D \end{bmatrix} = C_h^n \begin{bmatrix} -H \cos \beta_1 - T \sin \beta_1 + D_x \\ -H \sin \beta_1 \sin \beta_2 - Y \cos \beta_2 + T \cos B_1 \sin \beta_2 + D_y \\ -H \sin \beta_1 \cos \beta_2 - Y \sin \beta_2 - T \cos \beta_1 \cos \beta_2 + mg + D_z \end{bmatrix}$$

$$+ K \left\{ C_s^n \begin{bmatrix} -D_i \\ 0 \\ -L \end{bmatrix} + C_b^n \begin{bmatrix} P \cos i \\ 0 \\ P \sin i \end{bmatrix} \right\} \tag{120}$$

where $K = \begin{cases} 0, \text{ for pure helicopter} \\ 1, \text{ for compound helicopter} \end{cases}$

i = inclination of thrust centerline above aircraft longitudinal axis.

A.4   ROTOR BLADE FLAPPING MOTION

Consider the hinged blade shown in Figure 62. The aerodynamic moment about the flapping hinges in undisturbed equilibrium flight is

$$M_A = \frac{1}{2} \rho a c \int_{e_b}^{R} U_T^2 \left(\theta - \frac{U_P}{U_T} \right) (r - e_b) \, dr \tag{121}$$

where $U_T = \Omega r + \mu_x \Omega R \sin \psi$

$U_P = \lambda \Omega R + (r - e_b)\dot{\beta} + \mu_x \Omega R \beta \cos \psi$

$\beta = \beta_o - \beta_1 \cos \psi - \beta_2 \sin \psi$

$\theta = \theta_o + \theta_1 \cos \psi + \theta_2 \sin \psi + \beta \tan \delta_3$

thus
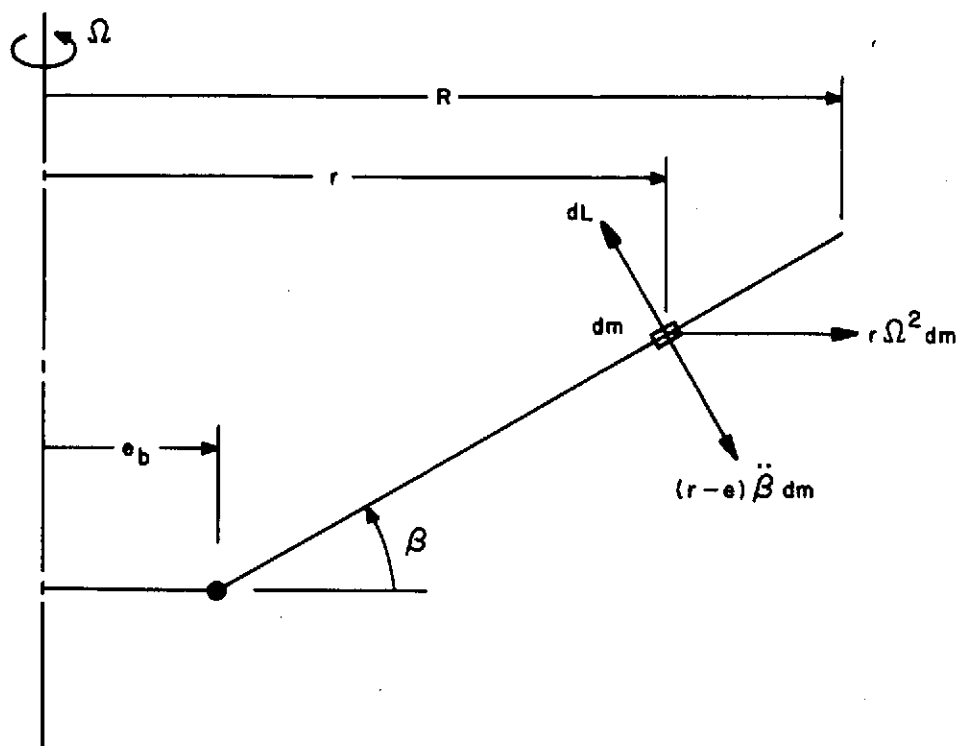
Figure 62. Hinged Rotor Blade Nomenclature.

$$M_A = \frac{1}{2} \rho a c \Omega^2 R^4 \left\{ \left[\theta_o (B + \frac{1}{2} \mu_x^2 D) - \lambda C + C \mu_x \theta_2 + \frac{1}{2} \mu_x E \beta_1 \right] \right.$$

$$+ \left[\theta_1 (B + \frac{1}{4} \mu_x^2 D) + \beta_2 (A + \frac{1}{4} \mu_x^2 D) - \mu_x \theta_o C \right.$$

$$\left. - \beta_1 (B + \frac{1}{4} \mu_x^2) \tan \delta_3 \right] \cos \psi$$

$$+ \left[\theta_2 (B + \frac{3}{4} \mu_x^2 D) - \beta_1 (A - \frac{1}{4} \mu_x^2 D) + 2\mu_x \theta_o C \right.$$

$$\left. \left. - \mu_x \lambda D - \beta_2 (B + \frac{3}{4} \mu_x^2 D) \tan \delta_3 \right] \sin \psi \right\} \tag{122}$$

where $A = \frac{1}{4} - \frac{2}{3} \zeta$

$B = \frac{1}{4} - \frac{1}{3} \zeta$

$C = \frac{1}{3} - \frac{1}{2} \zeta$

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$$D = \frac{1}{2} - \zeta$$

$$E = (\frac{1}{2} - \zeta)\zeta$$

$$\zeta = \frac{e_b}{R}$$

In undisturbed equilibrium flight, the moment of the inertia forces about the flapping hinge is

$$M_I = -\int_{e_b}^{R} \left[(r - e_b)^2 \ddot{\beta} + r(r - e_b)\Omega^2 \beta \right] m(r)\, dr$$

$$= -I_1 \Omega^2 \beta_0 (1 + 3E) \tag{123}$$

neglecting the weak coupling between β_1 and β_2 for small ζ.

where $m(r)$ = blade mass distribution, assumed constant

I_1 = blade moment of inertia about flapping hinge

$$= \int_{e_b}^{R} (r - e_b)^2 m(r)\, dr$$

therefore

$$\beta_0 = \frac{\gamma}{2(1 + 3E)} \left[\theta_0 (B + \frac{1}{2} \mu_x^2 D) - \lambda C + C\mu_x \theta_2 + \frac{1}{2} \mu_x E \beta_1 \right] \tag{124}$$

$$\theta_1 = -\beta_2 \frac{A + \frac{1}{4} \mu_x^2 D}{B + \frac{1}{4} \mu_x^2 D} + \mu_x \beta_0 \frac{C}{B + \frac{1}{4} \mu_x^2 D} + \beta_1 \tan \delta_3 \tag{125}$$

$$\theta_2 = \beta_1 \frac{A - \frac{1}{4} \mu_x^2 D}{B + \frac{3}{4} \mu_x^2 D} - 2\mu_x \theta_o \frac{C}{B + \frac{3}{4} \mu_x^2 D}$$

$$+ \mu_x \lambda \frac{D}{B + \frac{3}{4} \mu_x^2 D} + \beta_2 \tan \delta_3 \qquad\qquad (126)$$

A.5   VEHICLE CHARACTERISTICS

Table 30 presents numerical values for the various vehicle characteristics required by the point-mass dynamic models. These values were derived from data provided by Sikorsky Aircraft for the S-65-40 pure helicopter (Ref. 1) and the S-65-200 compound helicopter (Refs. 2,3) which are described in Section 2.

Table 30. Vehicle Characteristics for Point Mass Rotorcraft Model.

Parameter	Units	Pure Helicopter (S-65 - 40)	Compound Helicopter (S-65 - 200)
m	slug	1300	1950
i	deg	-	-8.5
Ω	rad/sec	19.3	17.7
R	ft	36.0	39.5
σ	-	0.115	0.122
a	1/rad	5.73	5.73
ζ	-	0.058	0.063
C_{D_o}	-	0.012	0.012
f_x	ft^2	46	38
f_y	ft^2	400	700
f_z	ft^2	400	1260
a_w	1/rad	-	4.52
S	ft^2	-	475
b	ft	-	47.5
e	-	-	0.7
$\dot{m}_o$	slug/sec	-	74.4
v_o	ft/sec	-	500
δ_3	deg	0	-30
γ	-	12.3 ρ/ρ_{SL}	13.8 ρ/ρ_{SL}

where ρ/ρ_{SL} is the atmospheric density ratio.

APPENDIX B

GUIDANCE SYSTEM SYNTHESIS

This appendix describes the synthesis of a simple path guidance scheme which produces velocity-correction commands to the rotorcraft flight control system.

B.1   ANALYTICAL DEVELOPMENT

The guidance concept is developed by assuming an unaccelerated nominal flight path which maintains constant ground track (Ψ_i), groundspeed (V_{gi}), and climb angle (γ_i) between defined waypoints (i, i + 1), as shown in Figure 63.
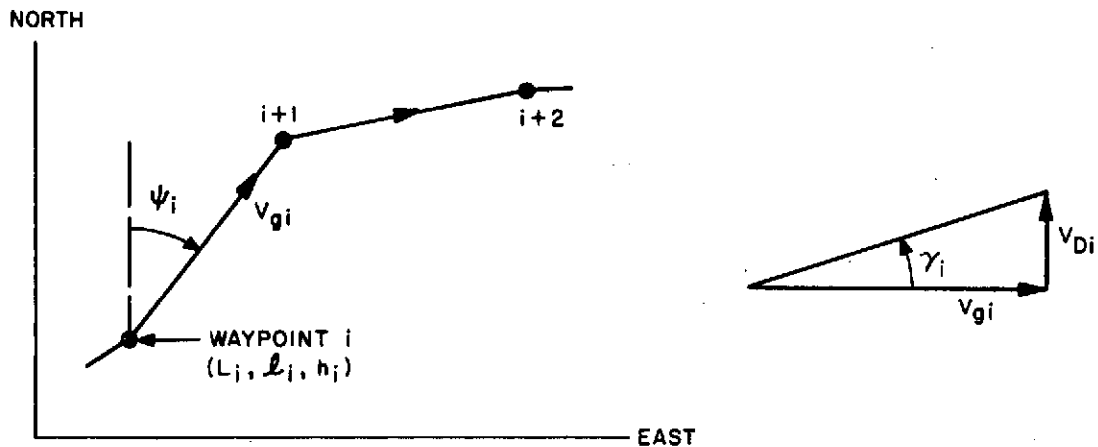
Figure 63. Nominal Flight Path for Guidance Analysis.

The ground track angle between waypoints i and i + 1 is:

$$\tan \Psi_i = \frac{\ell_{i+1} - \ell_i}{\ln\left[\dfrac{\cos L_i \ (1 + \sin L_{i+1})}{\cos L_{i+1} \ (1 + \sin L_i)}\right]} \tag{127}$$

The climb angle is

$$\tan \gamma_i = -V_{Di}/V_{gi} \tag{128}$$

The Northerly and Easterly components of groundpseed are

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$$V_{Ni} = V_{gi} \cos \Psi_i \tag{129}$$

$$V_{Ei} = V_{gi} \sin \Psi_i \tag{130}$$

The equations of motion for this idealized situation are:

$$\dot{L} = \frac{V_N}{r} \tag{131}$$

$$\dot{\ell} = \frac{V_E}{r \cos L} \tag{132}$$

$$\dot{h} = -V_D \tag{133}$$

where $r = r_{earth} + h$.

To obtain a guidance law, we take first-order perturbations from the nominal flight path defined above:

$$\delta \dot{L} = \frac{\delta V_N}{r} - \frac{V_N}{r^2} \delta h \tag{134}$$

$$\delta \dot{\ell} = \frac{\delta V_E}{r \cos L} - \frac{V_E}{r^2 \cos^2 L} (\delta h \cos L - r \sin L \, \delta L) \tag{135}$$

$$\delta \dot{h} = -\delta V_D \tag{136}$$

Writing these equations in state vector form:

$$\underline{\dot{x}} = F \underline{x} + G \underline{u} \tag{137}$$

where

$$\underline{x} = \begin{bmatrix} \delta L \\ \delta \ell \\ \delta h \end{bmatrix} = \text{perturbation state vector} \tag{138}$$

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$$\underline{u} = \begin{bmatrix} \delta V_N \\ \delta V_E \\ \delta V_D \end{bmatrix} = \text{perturbation control vector} \qquad (139)$$

$$F = \begin{bmatrix} 0 & 0 & -V_N/r^2 \\ V_E \tan L/r \cos L & 0 & -V_E/r^2 \cos L \\ 0 & 0 & 0 \end{bmatrix}^* \qquad (140)$$

$$G = \begin{bmatrix} 1/r & 0 & 0 \\ 0 & 1/r \cos L & 0 \\ 0 & 0 & -1 \end{bmatrix} \qquad (141)$$

The * denotes quantities evaluated along the nominal flight path. Since the waypoints will not be separated by large distances, the matrices F and G can be evaluated using the average values of L and r for each:

$$L = \frac{1}{2}(L_i + L_{i+1}) \qquad (142)$$

$$r = r_{earth} + \frac{1}{2}(h_i + h_{i+1}) \qquad (143)$$

Thus we have a stationary system to control between waypoints.

The Quadratic Synthesis technique is used to obtain a steady-state guidance law for each leg of the nominal flight plan. We define a cost function to be minimized

$$J = \lim_{t_f - t_o \Rightarrow \infty} \int_{t_o}^{t_f} (\underline{x}^T A \underline{x} + \underline{u}^T B \underline{u}) \, dt \qquad (144)$$

The matrices A and B determine the relative penalties associated with the perturbations in the state and in the control. Usually, good values for A and B can be obtained from the maximum permissible deviations from the nominal state and control histories; i.e.,

$$A = \begin{bmatrix} \delta L_m^{-2} & 0 & 0 \\ 0 & \delta \ell_m^{-2} & 0 \\ 0 & 0 & \delta h_m^{-2} \end{bmatrix} \qquad (145)$$

$$B = \begin{bmatrix} \delta V_{Nm}^{-2} & 0 & 0 \\ 0 & \delta V_{Em}^{-2} & 0 \\ 0 & 0 & \delta V_{Dm}^{-2} \end{bmatrix} \qquad (146)$$

The minimization of J leads to a linear feedback guidance law of the form

$$\underline{u} = -K \underline{x} \qquad (147)$$

where the feedback gain matrix K is given by

$$K = B^{-1} G^T S \qquad (148)$$

and the symmetric matrix S is the steady-state solution of the Riccati equation

$$\dot{S} = -SF - F^T S + SGB^{-1}G^T S - A = 0 \qquad (149)$$

The steady-state value of S can be found by integrating Eq. 149 backwards in time from $S = 0$ at $t = 0$, until $\dot{S} \simeq 0$.

In expanded form, the feedback guidance law is

$$V_{NC} = V_N^* - K_{N,L}(L - L^*) - K_{N,\ell}(\ell - \ell^*) - K_{N,h}(h - h^*)$$

$$V_{EC} = V_E^* - K_{E,L}(L - L^*) - K_{E,\ell}(\ell - \ell^*) - K_{E,h}(h - h^*) \qquad (150)$$

$$V_{DC} = V_D^* - K_{D,L}(L - L^*) - K_{D,\ell}(\ell - \ell^*) - K_{D,h}(h - h^*)$$

V_N^*, V_E^* and V_D^* are the constant nominal velocity components for a given leg of the flight; L^*, ℓ^* and h^* are the nominal time histories of L, ℓ and h between the two waypoints.

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The guidance scheme can be simplified even further by eliminating the cross-coupling between the vertical and horizontal motions. Both the F_{13} and F_{23} elements in Eq. (140) contain $1/r^2$, which will be quite small. Neglecting these terms, the solution to the Riccati equation becomes:

$$S_{31} = S_{32} = 0$$

$$S_{33} = 1/\delta h_m \ \delta V_{Dm}$$

$$S_{21} = \frac{B_{22} F_{21}}{G_{22}^2} \ \frac{A_{22} + \sqrt{A_2^2 - Y}}{Y}$$

$$S_{11}^2 = \frac{B_{11}}{G_{11}^2} \left(A_{11} + 2 S_{21} F_{21} - \frac{S_{21}^2 \ G_{22}^2}{B_{22}^2} \right)$$

$$S_{22}^2 = \frac{B_{22}}{G_{22}^2} \left(A_{22} - \frac{S_{21}^2 \ G_{11}^2}{B_{11}^2} \right)$$

where

$$Y = A_{22} - \frac{B_{22} \ G_{11}^2}{B_{11} \ G_{22}^2} \left(A_{11} + \frac{B_{22}^2 \ F_{21}^2}{G_{22}^2} \right)$$

This simplifies the feedback gains as follows:

$$K_{N,h} = K_{E,h} = K_{D,L} = K_{D,\ell} = 0$$

$$K_{D,h} = \delta V_{Dm} / \delta h_m$$

In general, the gains $K_{N,L}$, $K_{N,\ell}$, $K_{E,L}$ and $K_{E,\ell}$ will not be zero. However, for flights at constant longitude ($V_E = 0$, $\Rightarrow F_{21} = 0$):

$$S_{21} = 0$$

$$K_{N,\ell} = K_{E,L} = 0$$

$$K_{N,L} = \delta V_{Nm}/\delta L_m$$

$$K_{E,\ell} = \delta V_{Em}/\delta \ell_m$$

Note that the guidance system thus produces the maximum permissible velocity corrections for the maximum allowable state deviations.

B.2   PROGRAM QSYN

QSYN is a digital computer program developed to implement the quadratic synthesis technique described in the previous subsection. It numerically integrates Eq. (149) until a steady-state solution is approximated, and then calculates the perturbation guidance feedback gains given by Eq.(148). The program is written in Fortran IV for the CDC 6600 computer.

QSYN reads the input data shown in Table 31, calls subroutine STATE to calculate the nominal trajectory, calls subroutine HIT to integrate the Riccati equation backwards in time, and prints out the gains. Subroutine HIT uses the Hamming integration technique with a variable step-size for the integration of simultaneous first-order differential equations. It calls subroutine DEV which supplies the derivatives given by Eq. 149. HIT may also call subroutine HINTP, which interpolates for intermediate points. FINIS is a subroutine called by HIT that will stop the integration if the integration time exceeds the input limit ENDD, or if each element of the Riccati matrix S changes by less than .05% during an integration step. Subroutine DEV calls subroutines MXMULT, MXADD, and MXSUB which perform matrix multiplication, addition and subtraction, respectively.

The printout for QSYN consists of the NAM6 namelist input; WAYPTS namelist input; the North, East and Down velocity components - V_N, V_E, V_D; matrices F and G; and the gain matrix K as a function of time.

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Table 31 . Input Data for QSYN.

Card No.	Variable Name		Units	Format	Example
Card 1	Title			8 A10	S65-40: BOS-NYC Boston Tango No. 1
Card 2	DLATM	= Maximum Deviation of Latitude	arc-min	Namelist $NAM6	$NAM6 DLATM = 1.5, DLONM = 1.5,
	DLONM	= Maximum Deviation of Longitude	arc-min		DALTM = 250., DVNM = 20.,
	DALTM	= Maximum Deviation of Altitude	ft		DVEM = 20., DVDM = 500.,
	DVNM	= Maximum Deviation of Northerly Velocity	kt		DEL=-1.0000, BB = .000001,
	DVEM	= Maximum Deviation of Easterly Velocity	kt		DPRIN = -100.00, LPRINT = 2,
	DVDM	= Maximum Deviation of Downward Velocity	ft/min		INTEG = 2, ENDD = 80.00$
	DEL	= Initial Integration Step Size	sec		
	BB	= Accuracy Indicator			
	DPRIN	= Printout Interval	sec		
	LPRINT	$= \begin{cases} 1 \text{ for Printout Every Integration Step} \\ 2 \text{ for Normal Printout} \end{cases}$			
	INTEG	$= \begin{cases} 1 \text{ for Constant Integration Step Size} \\ 2 \text{ for Variable Integration Step Size} \end{cases}$			
	ENDD	= Time Limit for Integration	sec		
Card 3 (One for Each Waypoint)	NWP	= No. of Waypoints in Flight Path (≤ 20)		Namelist $WAYPTS	$WAYPTS NWP = 5, FLATD = 42.0,
	FLATD	= Latitudes of Waypoints (≤ 20)	deg		FLOND = -71.5, ALT = 2000.,
	FLOND	= Longitudes of Waypoints (≤ 20)	deg		VGK = 180.0$
	ALT	= Altitudes of Waypoints (≤ 20)	ft		
	VGK	= Groundspeeds between Waypoints (≤ 19)	kt		
Card 4	End of File Punch				7/8/9

APPENDIX C

SIMULATION PROGRAM 'VALT'

A digital simulation program entitled VALT (VTOL Automatic Landing Technology) has been developed to analyze the rotorcraft navigation system performance and to conduct subsystem sensitivity studies. The program is written in Fortran IV for operation on the LaRC CDC 6400/6600 computer system. Figure 64 presents a general flow diagram of VALT to illustrate the overall organization and logical operation of the simulation. The modular structure is shown by the block diagram in Figure 65, which depicts the interrelationships of the main program and each of the subprograms. The purpose of each of the subroutines and functions shown in Figure 65 is summarized in Table 32. The input structure of VALT is also modularly arranged, using NAMELISTs almost exclusively. A complete summary of the available program inputs is shown in Table 33.

In essence, VALT is actually a double simulation. First, it integrates the equations of motion which simulate the response of the rotorcraft and flight control system to the guidance system commands; and it simulates the actual noisy outputs of the various navigation sensors. This part of VALT is a nonlinear, stochastic process which is intended to provide a reasonably accurate representation of the "real world." The second part of VALT simulates the operations of the onboard navigation and guidance systems. This portion also simulates the rotorcraft motions and navigation measurements, but here models are much simpler, and are linearized about a desired nominal flight path. The models used in this part of the program are purposely kept as simple as possible to minimize the onboard computation requirements.

The principal outputs of the simulation are time histories of the rotorcraft position and velocity, and two sets of error histories. The estimator errors are the differences between the estimated and actual position/velocity, and thus indicate the navigation systems' performance. The second set of errors show the rotorcraft's actual deviations from the nominal position/velocity profiles; these illustrate the overall performance of the entire system, including the navigation, guidance scheme, flight control system, rotorcraft capability, and wind effects.
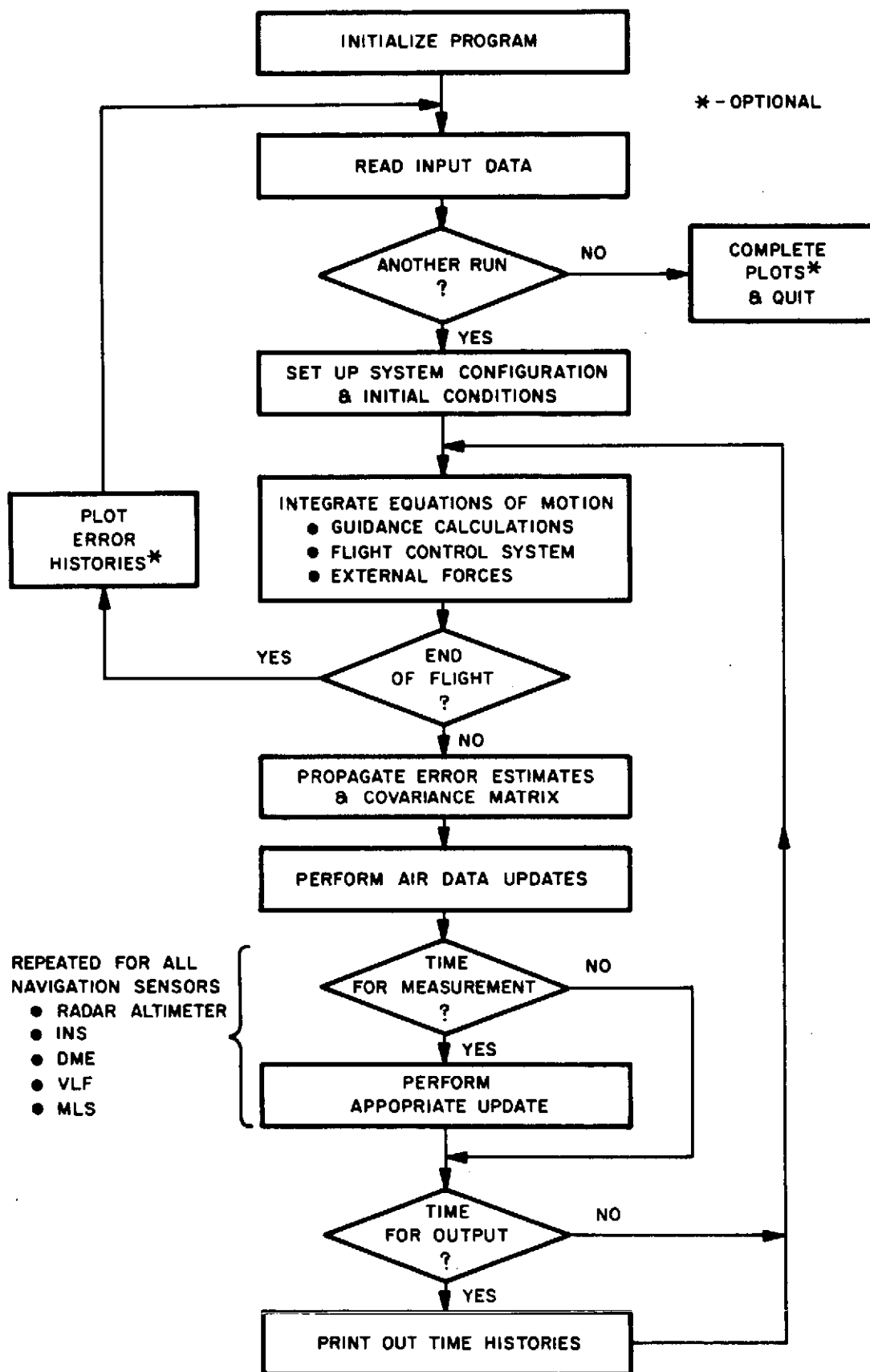
Figure 64. Overall Flow Diagram of Program VALT.
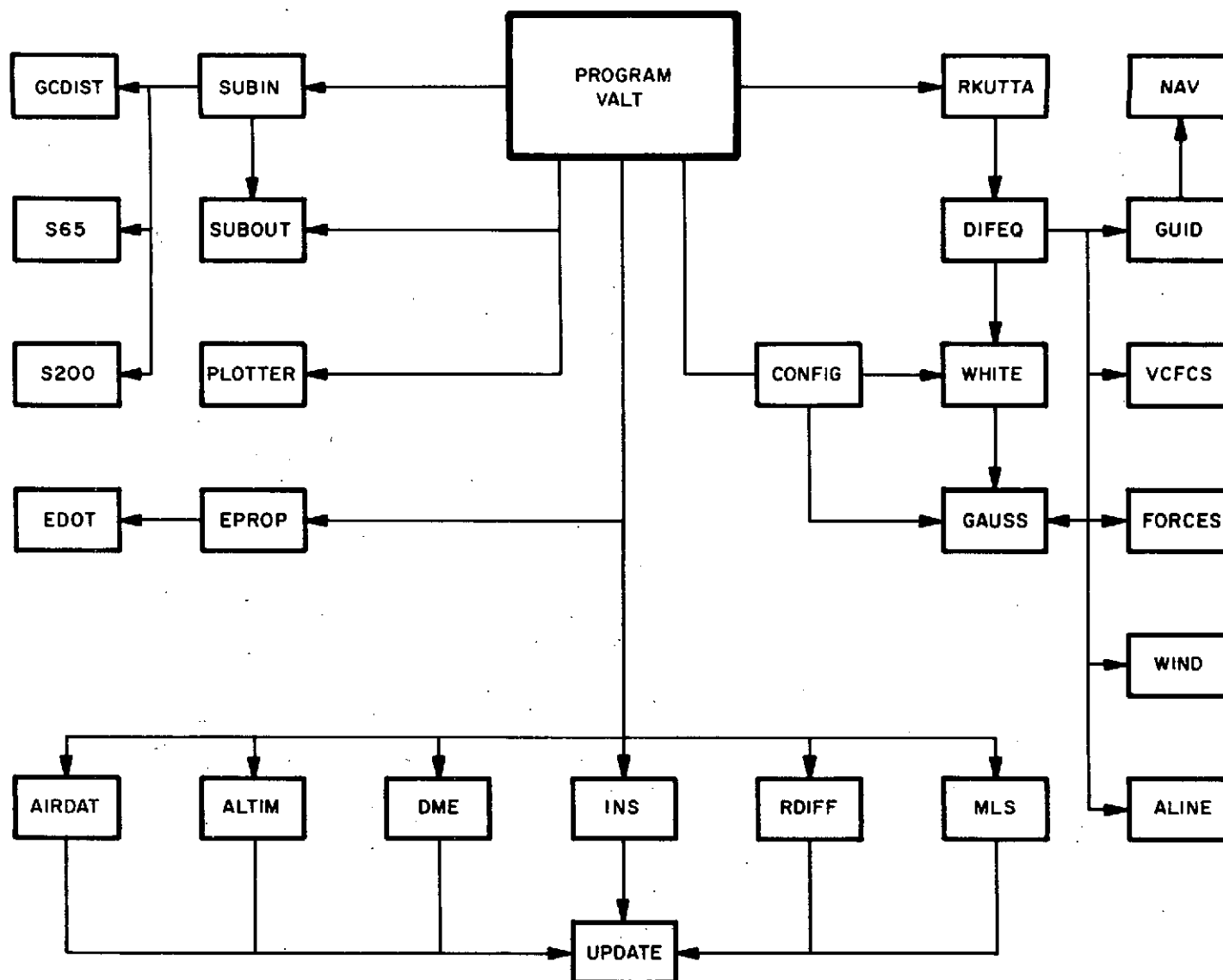
Figure 65. Program VALT Functional Diagram.

Table 32. 'VALT' Program Elements.

1. VALT — main program; controls overall logic.
2. SUBIN — reads and prints input data.
3. SUBOUT — prints page headings and output data; saves plot data.
4. S65 — sets pure helicopter characteristics (S-65-40).
5. S200 — sets compound helicopter characteristics (S-65-200).
6. GCDIST — calculates great circle distance and bearings between two locations.
7. RKUTTA — 4th order Runge-Kutta integration technique.
8. DIFEQ — calculates RHS of differential equations.
9. WIND — calculates steady wind components.
10. NAV — computes estimated position, velocity and measurement errors.
11. GUID — implements guidance system calculations.
12. VCFCS — implements flight control system calculations.
13. FORCES — determines external forces on rotorcraft.
14. PLOTTER — plots error histories.
15. CONFIG — sets initial conditions and noise.
16. WHITE — generates white noise sequences of given strength.
17. GAUSS — generates gaussian random numbers of given mean and σ.
18. ALINE — linear interpolation from tabular data.
19. EPROP — propagates estimator error state vector and covariance matrix.
20. EDOT — calculates derivatives for EPROP.
21. AIRDAT — calculates airspeed and vertical speed measurements.
22. ALTIM — calculates altimeter measurements.
23. INS — calculates INS velocity measurements.
24. DME — calculates DME ranging measurements.
25. RDIFF — calculates range differencing measurements.
26. MLS — calculates MLS azimuth and elevation measurements.
27. UPDATE — calculates filter gains and updates the estimator state and covariance matrix.

Table 33. 'VALT' Inputs.

1. Title (8A10): Run Title

2. $ DATA 1 (namelist): General Control Data

NRUN	— run number.
DT	— integration step size, sec.
DTOUT	— printout interval, sec.
DTPLOT	— plot output interval, sec (no plot if DTPLOT = 0.).
NVEH	— rotorcraft number (65 or 200).
ISEED	— seed for random no. generator.
TENDD	— time limit for simulation, min.

3. $ WINDS (namelist): Wind Data

NW	— no. of points in mean wind profile ($\leq$8).
HW	— altitudes of mean wind profile, ft (1, 2, .. NW).
THW	— directions of mean wind profile, deg (1, 2, .. NW).
VW	— speeds of mean wind profile, kt (1, 2, .. NW).
THWS	— standard deviation of colored wind direction error, deg.
VWS	— standard deviation of colored wind speed error, kt.
ZWS	— standard deviation of colored vertical wind error, ft/min.
THWT	— correlation distance of colored wind direction error, nm.
VWT	— correlation distance of colored wind speed error, nm.
ZWT	— correlation distance of colored vertical wind error, nm.
VWG	— standard deviation of random horizontal wind speed error, kt.
ZWG	— standard deviation of random vertical wind speed error, ft/min.

4. $ INCOND (namelist): Initial Conditions Data

T0	— initial time, min.
LAT0	— initial latitude, deg.
LON0	— initial longitude, deg.
ALT0	— initial altitude, ft.
VG0	— initial groundspeed, kt.
TRK0	— initial ground track, deg.
RC0	— initial rate of climb, ft/min.
PSI0	— initial heading, deg.

5. $ NOM (namelist): Nominal Flight Path Data

NWPTS	– number of waypoints (≤ 10).
WLAT	– latitude of each waypoint, deg (1, 2, ... NWPTS).
WLON	– longitude of each waypoint, deg (1, 2, ... NWPTS).
WALT	– altitude of each waypoint, ft (1, 2, ... NWPTS).
VNOM	– nominal groundspeed on each leg, kt (1, 2, ... NWPTS-1).
PSINOM	– nominal ground track on each leg, deg (1, 2, ... NWPTS-1).
XKNLA	– guidance gain $K_{N,L}$ on each leg, kt/min (1, 2, ... NWPTS-1).
XKNLO	– guidance gain $K_{N,\ell}$ on each leg,, kt/min (1, 2, ... NWPTS-1).
XKNH	– guidance gain $K_{N,h}$ on each leg, kt/ft (1, 2, ... NWPTS-1).
XKELA	– guidance gain $K_{E,L}$ on each leg, kt/min (1, 2, ... NWPTS-1).
XKELO	– guidance gain $K_{E,\ell}$ on each leg, kt/min (1, 2, ... NWPTS-1).
XKEH	– guidance gain $K_{E,h}$ on each leg, kt/ft (1, 2, ... NWPTS-1).
XKDLA	– guidance gain $K_{D,L}$ on each leg, fpm/min (1, 2, NWPTS-1).
XKDLO	– guidance gain $K_{D,\ell}$ on each leg, fpm/min (1,2, NWPTS-1).
XKDH	– guidance gain $K_{D,h}$ on each leg, fpm/ft (1, 2, NWPTS-1).

6. $ ALTDAT (namelist): Altimetry Errors

SIGALT	– σ of scale factor error, %.
RANALT	– σ of random error, ft.
DTALT	– measurement interval, sec.
TALT0	– time to begin meas., min.

7. $ INSDAT (namelist): INS Errors

QWINSN	– strength of driving noise w for north axis, ft^2/sec^3.
QWINSE	– strength of driving noise w for east axis, ft^2/sec^3.
QWINSN	– strength of additive noise n for north axis, ft^2/sec^3.
QNINSE	– strength of additive noise n for east axis, ft^2/sec^3.
DTINS	– meas. interval, sec.
TINS0	– begin meas. time, min.
TINSF	– final meas. time, min.

8. $ DMEDAT (namelist): Range Meas. Errors

    DMELAT   – latitude of station, deg (i = 1, 2, 3, 4).

    DMELON – longitude of station, deg (i = 1, 2, 3, 4).

    DMEALT – altitude of station, ft (i = 1, 2, 3, 4).

    SIGDME – σ of bias error, ft (i = 1, 2, 3, 4).

    RANDME – σ of random error, ft (i = 1, 2, 3, 4).

    DTDME   – meas. interval, sec (i = 1, 2, 3, 4).

    TDME 0 – time to begin meas.,min (i = 1, 2, 3, 4).
    TDMEF   – time to end meas., min (i = 1, 2, 3, 4).

9. $ RDIFDAT (namelist): Range Difference Meas. Errors

    RDLAT   – latitude of station, deg (i = 1, 2, 3, 4).

    RDLON   – longitude of station, deg (i = 1, 2, 3, 4).

    RDALT   – altitude of station, ft (i = 1, 2, 3, 4).

    SIGRD   – σ of correlated error, ft (i = 1,2).

    TAURD   – τ of correlated error, min (i = 1,2).

    RANRD   – σ of random error, ft (i = 1,2).

    DTRDIF   – meas. interval, sec (i = 1, 2).

    TRDIFF   – end meas. time, min (i = 1,2).

10. $ MLSDAT (namelist): MLS Errors

    MLSLAT – latitude of transmitter, deg (i = el, az).

    MLSLON – longitude of transmitter, deg (i = el, az).

    MLSALT – altitude of transmitter, deg (i = el, az).

    SIGMLS – σ of bias error, deg (i = el, az).

    RANMLS – σ of random error, deg (i = el, az).

    DTMLS   – meas. interval, sec (i = el, az).

    TMLS0   – begin meas. time, min (i = el, az).

    TMLSF   – end meas. time, min (i = el, az).

11. $ ESTDAT (namelist): Estimator Data

    Y0   – initial error state estimates – $\hat{y}(t_o)$(i = 1-14).
    P0   – initial uncertainties in $\hat{y}(t_o)$ – 1σ (i = 1-14).
    TAUEST – correlation times of colored noises (i = 1-7).
    SIG   – standard deviations of colored noises (i = 1-7).
    RANALT – random altimeter error, ft.

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DLATE   – latitude of DME stations, deg   (i = 1-4).

DLONE   – longitude of DME stations, deg   (i = 1- 4).

DALTE   – altitude of DME stations, ft   (i = 1-4).

DRANE   – random DME measurement errors, ft   (i = 1-4).

RDLATE   – range difference station latitudes, deg   (i = 1-4).

RDLONE   – range difference station longitudes, deg   (i = 1- 4).

RDRANE   – range difference random measurement errors, ft   (i = 1,2).

RINSE   – random INS errors, kt (i = N, E).

EMLSLA   – MLS transmitter latitude, deg.

EMLSLO   – MLS transmitter longitude, deg.

EMLSAL   – MLS transmitter altitude, ft.

RMLSE   – MLS random measurement error, deg   (i = el, az).

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APPENDIX D

COVERAGE PREDICTION PROGRAM 'COVER'

D.1   DISCUSSION

A digital computer program (COVER) has been developed to predict the airspace coverage of selected navigation, communication, or surveillance systems. The program assists in the selection and evaluation of low altitude inter-city VTOL routes based upon existing or future line-of-sight navaids. The coverage for a given facility is determined by the line-of-sight (LOS) distance from the ground station to the desired flight altitude (Fig. 66), modified by any specified restrictions on the signal coverage. The desired coverage is plotted on a Lambert conformal conic projection, which is scaled to be used as an overlay for standard sectional or world aeronautical charts.
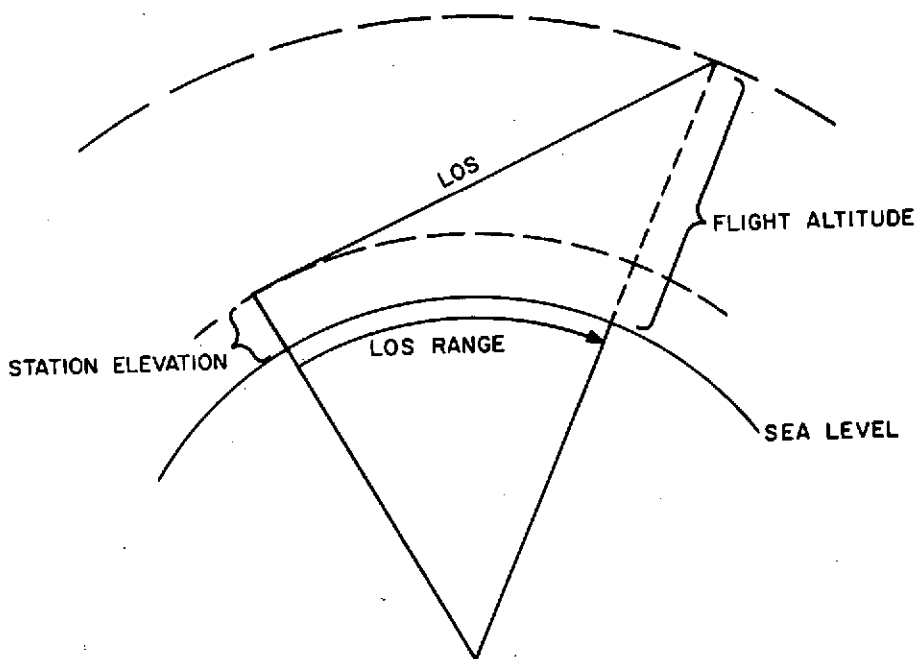

Figure 66. Line-of-Sight Range.

If the Earth were a perfect sphere, the LOS range would be

$$R_{LOS} = 1.0656 \left(\sqrt{h_s} + \sqrt{h_a} \right) \tag{151}$$

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where R_{LOS} = LOS range (nm)

h_s = ground station elevation (ft)

h_a = aircraft flight altitude (ft)

Although it is impractical to model the terrain surrounding the ground facility, it is unlikely there will be no obstructions above sea level. More probably, the average terrain will be near the same elevation as the ground station, although the antenna will undoubtedly be above ground level. For the purposes of predicted navaid coverage, a reasonably conservative model is obtained using the altitude difference between the station and aircraft, i.e.,

$$R_{LOS} \approx 1.0656 \sqrt{h_a - h_s} \tag{152}$$

Eq. (152) is the LOS range used in Program COVER.

The principal motivation in developing COVER was to evaluate the feasibility of the existing VORTAC air navigation system for low-altitude inter-city VTOL routes. However, the program can determine the coverage of specified radar or communication facilities (RCAG s – remote communication, air-ground) which also utilize frequencies which travel LOS.

D.2   PROGRAM COVER USER'S SUMMARY

The purpose of this program is to plot, over a desired geographical area, the coverage of the VORTAC s, radars or RCAG s in that area at a given flight altitude. The program was written in Fortran IV for the CDC 6600 computer and the Calcomp 780 plotter. The program uses four tapes, other than the standard input and output units.

The input data structure for the program is shown in Table 34. "COVER" first reads the Heading Data. The first 72 columns contain a heading which is printed on each page of output. The Plotter Data is read next. If FACTOR = 1. and SF = 500000 (Card 4), the plot is drawn to the same scale as the Sectional Aeronautical Charts and may be used as an overlay. A "FACTOR" smaller than 1. gives a smaller scale. "XMAX" can be determined by predicting the length of each plot in a run; however, "XMAX" is read only once and must equal the total length for all plots in the run.

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"YMAX" will be determined by the width of paper available to the plotter. The width of the paper and the value of "FACTOR" limit the coverage area plotted.

The program then reads Cards 3 and 4 which specify the coverage to be plotted for each case and writes the data on tape 7. This group of cards is followed by an end-of-file card. Next, COVER reads the VORTAC, radar and RCAG data and stores them on tapes 8, 9 and 10, respectively. If all of the VORTAC, radar or RCAG cards are removed from the deck, the end-of-file card that followed each must be left in the deck.

Table 34. Program COVER Input Structure.

Columns	Quantity	Format	Typical Value
	__Card1:__ Heading Data		
2-72	Heading for run	72H	COVERAGE
	__Card 2:__ Plotter Data		
1-10	PROGID (1) = Programmer's name	A10	SMITH
11-20	PROGID (2) = Job number	A10	5560
21-30	PROGID (3) = Plot title	A10	AIRSPACE
31-40	XMAX = Total length of plots in inches in x direction	F10.0	20..
41-50	YMAX = Width of plots in inches in y direction	F10.0	30.
51-60	FACTOR = Multiplicative factor to change size of plotting	F10.0	1.
	__Card 3:__ Coverage Type		
1	CHOICE = 1 If VORTAC coverage is to be plotted for Card 4	I1	1VORTAC
	2 If RADAR coverage is to be plotted for Card 4		2RADAR
	3 If RCAG coverage is to be plotted for Card 4		3RCAG
	__Card 4:__ Map Overlay Data		
1-9	LATA = Lambert conformal conic projection standard parallel (degrees)	F9.4	41.3333
10-18	LATB = "	F9.4	46.6667
19-27	LAT1 = Minimum latitude of coverage (degrees)	F9.2	42.
28-36	LAT2 = Maximum latitude of coverage (degrees)	F9.2	43.
37-45	LON1 = Minimum longitude of coverage (degrees)	F9.2	70.
46-54	LON2 = Maximum longitude of coverage (degrees)	F9.2	73.

Columns	Quantity	Format	Typical Value
	SF = Scale factor	F9.0	500000.
	ALT = Altitude of aircraft for which coverage is desired (feet)	F9.0	2000.

(Cards 3 and 4 must be repeated for each overlay desired)

<u>Card 5:</u>

1	End-of-file card (7/8/9)		

<u>Card 6:</u>   VORTAC Coverage Data

Columns	Quantity	Format	Typical Value
1-3	NAME = Name of VORTAC	A3	CON
11-20	FREQ = Frequency of VORTAC (MHz)	F10.2	112.9
21-30	DLA,XLA,SLA = Latitude of VORTAC in degrees, minutes and seconds	I3,1x,I2, 1x, I2	043-13-11
31-40	DLO,XLO,SLO = Longitude "	"	071-34-33
41-50	ELV = Elevation of VORTAC (feet)	F10.0	719.
51-60	VAR = Variation of magnetic north from true north (degrees)	F10.0	15.
61	TYPE = Type of VORTAC:	R1	L

D	-	DME only
H	-	High altitude VOR
L	-	Low altitude VOR
T	-	Terminal VOR

Columns	Quantity	Format	Typical Value
70-71	NRES = Number of restrictions for VORTAC	I2	2

<u>Card 7:</u>   VORTAC Restriction Data (One required for each restriction of the preceding VORTAC)

Columns	Quantity	Format	Typical Value
1-10	These columns not read but can be used for identification		CON1
11-20	ALFA = Degrees from north to beginning of restriction	F10.2	260.
21-30	BETA = Degrees from north to end of restriction	F10.2	305.

Columns	Quantity	Format	Typical Value
	RMX = Range beyond which restriction is effective (mi)	F10.2	12.
	HMX = Altitude below which restriction is effective (feet)	F10.2	7000.

(Card 6 and its associated Card 7's must be repeated for each VORTAC desired)

Columns	Quantity	Format	Typical Value
1	Card 8:. Mandatory End-of-file punch (7/8/9)		

Card 9: RADAR Coverage Data

Columns	Quantity	Format	Typical Value
1-1	NAME = Name of RADAR	A10	SARATOGANY
11-21	DLA=XLA-SLA = Latitude of RADAR in degrees, minutes and seconds	I3, 1x, I2, 1x, I2	043-00-37
21-30	DLO-XLO-SLO = Longitude "	"	073-40-57
31-40	ELV = Elevation of RADAR (feet)	F10.2	770.
41	TYPE = Type of RADAR: S – Short range M – Long range	R1	S

(Card 9 must be repeated for each radar desired)

Columns	Quantity	Format	Typical Value
1	Card 10: Mandatory End-of-file punch (7/8/9)		

Card 11: RCAG Coverage Data

Columns	Quantity	Format	Typical Value
1-10	NAME = Name of RCAG	A10	HAMPTON
11-20	DLA-XLA-SLA = Latitude of RCAG in degrees, minutes and seconds	I3, 1x, I2, 1x, I2	040-55-08
21-30	DLO-XLO-SLO = Longitude "	"	072-19-02
31-40	ELV = Elevation of RCAG (feet)	F10.2	1000.
41	TYPE = R for RCAG	R1	R

(Card 11 must be repeated for each RCAG desired)

Columns	Quantity	Format	Typical Value
1	Card 12: EOF on EOR card (7/8/9 or 6/7/8/9)		

APPENDIX E

EVALUATION FLIGHT SUMMARIES

Date	Flight Time (hr)	Flight Designation	Remarks
9/26/73	1.5	C	Pilot Checkout.
10/9, 10, 11/73	10.4	I	Introduction to low altitude RNAV; systems checkout. Round trip: Boston/NASA LaRC.
10/23/73	2.6	1	Data recording procedures checkout. Preliminary Zulu route evaluation VORTAC coverage checks.
11/6/73	4.4	4	Low altitude RNAV route checks. VORTAC coverage checks. Round trip: Boston/NYC for NYA-1.
11/6/73	2	NYA-1	VOR/ILS connectors: JFK/LGA. VOR coverage check over Hudson River. Descending spirals (2).
11/7/73	2.8	3	VORTAC coverage and accuracy checks.
11/8/73	2.0	2	Boston Tango Connector evaluations. Heliport site checks. Surveillance checks. ATC and CTOL interactions.
11/12, 13/73	3.6	5	Low altitude simulated IFR practice. Coverage checks on two arcs of HFD VORTAC.
11/14/73	4.1	9	Hooded flight on Zulu routes. Round trip: Boston/NYC for NYA-2.
11/14/73	~2	NYA-2	Half ILS (2). Hi-lobe approach (3). Wall Street approaches (3). Spirals (4). VOR coverage check over Hudson River.
11/19/73	3.6	6	LOS evaluations: climbs and descents. 6 different radials.
11/20/73	2.2	7	Boston Tango Connectors; reverse direction. Alternate heliport site check. Surveillance check. ATC and CTOL interactions.

Date	Flight Time (hr)	Flight Designation	Remarks
1/5, 6, 12, 13/74	10.7	8	Summary flight, roundtrip: Boston/LaRC. Zulu routes Boston/NYC/WDC. Coverage checks and accuracies.
1/25/74	~3	NYA-3	MLS Approaches: 5 @ 4.5° glide slope. 3 @ 6° glide slope. MLS coverage checks. Spiral descents and transition to stabilized MLS approach: 3 @ 4.5° glide slope. 1 @ 6° glide slope.