DOT/FAA/PM-86/15
NASA CR-177408

Program Engineering
and Maintenance Service
Washington, D.C. 20591

AD-A169 893

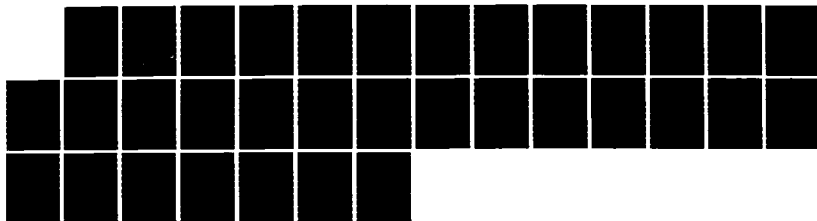# Evaluation of the Usefulness of Various Simulation Technology Options for Terminal Instrument Procedures (TERPS) Enhancement

A.V. Phatak
John A. Sorensen

Analytical Mechanics Associates, Inc.
2483 Old Middlefield Way
Mountain View, California 94035

May 1986

Final Report

JUL 18 1986

DTIC FILE COPY

U.S. Department of Transportation
Federal Aviation Administration

NASA

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

1. Report No. DOT/FAA/PM-86/15 NASA CR-177408	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of the Usefulness of Various Simulation Technology Options for TERPS Enhancement		5. Report Date May 1986
		6. Performing Organization Code
7. Author(s) A. V. Phatak and J. A. Sorensen		8. Performing Organization Report No. AMA Report No. 86-2-II
		10. Work Unit No.
9. Performing Organization Name and Address Analytical Mechanics Associates, Inc. 2483 Old Middlefield Way Mountain View, CA 94035		11. Contract or Grant No. NAS 2-11973
12. Sponsoring Agency Name and Address NASA-Ames Research Center Moffett Field, CA 94035 FAA Technical Field Office P.O. Box 25 Moffett Field, CA 94035		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code
15. Supplementary Notes POINT OF CONTACT: Barry C. Scott - M/S 210-2 FAA/Ames Research Center, Moffett Field, CA 94035 (415) 694-6379 or FTS 464-6379		

16. Abstract

Current approved terminal instrument procedures (TERPS) do not permit the full exploitation of the helicopter's unique flying characteristics. Enhanced TERPS need to be developed for a host of non-standard landing sites and navigation aids. Precision navigation systems such as MLS and GPS open the possibility of curved paths, steep glide slopes, and decelerating helicopter approaches. This study evaluated the feasibility, benefits, and liabilities of using helicopter cockpit simulators in place of flight testing to develop enhanced TERPS criteria for non-standard flight profiles and navigation equipment. Near-term (2-5 year) requirements for conducting simulator studies to verify that they produce suitable data comparable to that obtained from previous flight tests are discussed. The long-term (5-10 year) research and development requirements to provide necessary modeling for continued simulator-based testing to develop enhanced TERPS criteria are also outlined.

17. Key Words (Suggested by Author(s)) TERPS, helicopter flight flight test cockpit simulator operational approach profiles		18. Distribution Statement UNCLASSIFIED - UNLIMITED START CATEGORY 01		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified	21. No. of Pages 30	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161

TABLE OF CONTENTS

SYMBOLS AND ABBREVIATIONS

ARC	Ames Research Center
ATC	Air Traffic Control
CGI	Computer Generated Imagery
DME	Distance Measuring Equipment
DoD	Department of Defense
DOF	Degrees of Freedom
FAA	Federal Aviation Administration
GPIP	Glide Path Intercept Point
GPS	Global Positioning System
HAI	Helicopter Association International
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
JAWS	Joint Airport Weather Study
MLS	Microwave Landing System
NASA	National Aeronautics and Space Administration
Navaids	Navigation Aids
TERPS	Terminal Instrument Procedures
VFR	Visual Flight Rules
VMS	Vertical Motion Simulator
VOR	VHF Omnidirection Range

INTRODUCTION

At the present time, helicopters under instrument meteorological conditions (IMC) must abide by the rules and regulations developed for fixed-wing aircraft. This means that helicopter instrument flight-operations must be restricted to regions where signals from conventional navigation aids (i.e., ground-based systems such as VOR/DME and ILS) are available. In particular, current helicopter IFR terminal area operations, such as take-off and approach to a landing, can be permitted only at airports that have the standard ILS equipment.

These IFR constraints negate, to a considerable degree, the unique advantages of the helicopter as a transportation alternative. What distinguishes a helicopter from an airplane is its ability to hover, vertically climb and descend, and to fly complex curved descending and decelerating (or accelerating) flight profiles. These characteristics make it possible for a helicopter to operate (i.e., take-off and land) out of confined landing sites as small as twice the rotor diameter. However, currently approved terminal instrument procedures (TERPS) do not permit the full exploitation of the helicopter's unique capabilities.

Enhanced TERPS need to be developed for a host of non-standard landing sites and navigation aids (navaids). Possible landing sites include:

a. Airport runway-adjacent-helipads
b. Remote off-shore oil rig platforms
c. Remote overland landing areas
d. Metropolitan building top helipads
e. Mountain pinnacle and other rugged terrain sites.

All, except the airport site listed above, can be safely presumed to be lacking ILS equipment. Furthermore, even if ILS equipment were to be made available at these sites, such equipment may not be used because of environmental and site-specific geometry constraints that preclude flying a standard 3^0 ILS approach profile.

Technological developments over the past decade have led to the introduction of new navigation aids and improved design of on-board avionics which together offer improved navigation performance and broad geographical coverage. These integrated navigation and guidance systems (aided inertial navigation systems) are designed so as to combine optimally one or more (i.e., multiple) navigation signal measurements with on-board velocity and acceleration data to produce best estimates of vehicle position and velocity. The Microwave Landing System (MLS) and the Global Positioning System (GPS) are two examples of new navigation aids for which TERPS need to be developed. In addition, ways in which to combine MLS and/or GPS signals with existing navaids such as VOR/DME, LORAN-C and OMEGA must be considered in the TERPS context.

1

As mentioned above, the use of navaids such as MLS or GPS (by themselves or in combination with other navaids) renders it feasible to estimate absolute vehicle position (e.g., azimuth, elevation and range) with respect to some earth-fixed coordinate system (e.g., helipad-centered). As a result, guidance algorithms can be developed that provide the pilot with the necessary information to fly complex (as opposed to straight-in) horizontal and vertical terminal approach profiles. Guidance can be provided in the form of the standard "angle-only" information (i.e., raw glide-slope and localizer errors with respect to the reference flight path) or by using a 3-cue flight director. More sophisticated methods include pictorial display presentation of own vehicle position and orientation with respect to the outside world.

The introduction of broad precision coverage systems such as MLS and GPS opens a new dimension to TERPS, heretofore missing. This includes the development and evaluation of curved-path and steep glide-slope approach profiles and operational procedures that take full advantage of the helicopter's unique characteristics and the precision capabilities of the navigation and guidance systems. However, since these systems are new, there is no existing complete database which one could use as the basis for developing enhanced TERPS procedures and criteria. Data in the form of airspace requirements, weather minima and pilot acceptability of candidate-approach profiles (i.e., geometry and parameters) must be generated for a variety of test conditions that include various levels of navigation (i.e., on-board receiver/filter), guidance (i.e., raw data/flight-director), flight control augmentation, and display sophistication (i.e., standard instruments versus electronic display formats). These data, along with other pertinent information (such as landing site location, ATC procedures, etc.), must serve as the basis for definition of enhanced TERPS for non-standard situations.

This report describes the findings of: "Evaluation of the Usefulness of Various Simulator Technology Options for TERPS." The specific objectives are to evaluate the merits of simulator-based options in developing TERPS criteria for non-standard helicopter flight profiles and navigation equipment that would be practical in the near-term (i.e., 2-5 years) and long-term (i.e., 10-15 years).

This report is organized into six sections. Current methods used for TERPS evaluation are presented in the next section. This is followed by an evaluation of the simulation technology options for TERPS development and definition. The discussion centers around the feasibility, benefits and liabilities of pursuing the simulator option. The next sections describe the near-term and long-term prospects for simulator-based TERPS evaluation. A summary of the findings is given in the final section.

Appendix A presents a general discussion of visual simulation technology. Appendix B provides data for comparing helicoper flight test costs to cockpit simulator test costs. Appendix C compares other simulator and flight test costs.

2

CURRENT METHODS FOR TERPS EVALUATION

Before embarking on the evaluation of simulation-based options for TERPS enhancement, it is appropriate to understand the existing methodology used by the FAA for developing such instrument procedures and criteria. The overall approach consists of a sequence of four steps which can be described as follows:

Step 1: User Request For Non-standard Instrument Approach

The process of TERPS enhancement usually begins at the "grass roots" level where a particular "user" (user refers to helicopter operators, manufacturers, avionics companies, or professional organizations such as the HAI) requests a non-standard terminal instrument approach procedure to a specific landing site. The procedure is designated as non-standard because of certain operational situations that arise due to one or more of the following factors: (a) non-runway landing site location, (b) new types of navigation aids, (c) complex approach profile geometry, (d) reduced weather minima, (e) unconventional on-board avionics system (i.e., flight control, guidance and display sophistication).

The request is processed by the appropriate FAA agency which must decide whether or not the development of new or enhanced TERPS for this request is warranted. If the decision is affirmative, the next step is initiated.

Step 2: Analyze Existing Database and Define Flight Test Requirements.

If a sufficient database exists that is relevent to the user request, then these data are used either to approve the non-standard terminal instrument approach procedure as requested or to recommend an alternative procedure. In most cases, the available sources of information are not adequate, and additional data must be obtained through flight test in order to generate an enhanced instrument procedure. A flight test plan outlining the objectives, scope, test matrix, data requirements, approach profiles, and pilot procedures must be developed for implementation by the appropriate FAA (e.g., FAA Technical Center) or other government (e.g., NASA or DoD) facility. The latter approach usually involves joint FAA/NASA or FAA/DoD flight-test programs. Examples of such previous joint efforts include the MLS flight-test investigations of non-standard helicopter approach profiles conducted with NASA/ARC during 1979[1] and 1983[2], respectively.

Step 3: Conduct Flight-test Program

The purpose of the flight-test program is to provide the FAA statistical data with which to establish operational system requirements and to develop instrument approach standards and procedures. The data gathered must be sufficient to determine airspace requirements and pilot acceptability of the enhanced instrument approaches.

The flight-test program generally consists of three phases: (1) a pre-flight procedures development phase, (2) an experimental flight investigation phase, and (3) an operational flight evaluation phase.

The purpose of the pre-flight phase is to define a final test plan for flight investigation. This effort is highly labor intensive and may involve some ground-based simulation work if a simulator is available. Specific output of this phase is the definition of each of the components of the test matrix such as (a) the reference approach profile geometry, (b) guidance law and display variables, (c) the weather minima and corresponding decision height specifications, and (d) the pilot's operating procedures.

Thus, for example, in the FAA/NASA MLS test program, this phase involved the selection of the U-turn and S-turn approach profiles at 6° and 9° glide-slopes and the $9^O/12^O$ straight-in approaches. Nominal values for the other parameters of the approach profile geometry such as the approach speeds, decision heights, lengths of the individual rectilinear segments and the radii of the curved segments were also defined. Guidance display sensitivities (i.e., glide-slope/localizer and flight director) were scaled as a function of distance to go from the glide path intercept point.

Having defined a detailed test plan, the purpose of the next phase is to use research or test pilots (e.g., NASA test pilots) to fly the various test procedures to determine if the parameters defined in the pre-flight test phase are acceptable or need modification prior to operational flight evaluation. The net result of this phase is an approved test plan ready for evaluation by the operational pilots.

In the FAA/NASA MLS test program, NASA test pilots made several key recommendations that led to a modification of the nominal test procedures defined during the pre-flight test phase. One heuristic that emerged from these second phase tests was the requirement that there be a 25 to 30 second straight segment between any two curved segments of the approach profile. This prevented vertigo by allowing the pilot to stabilize the aircraft on a straight-and-level flight segment upon exiting a turn and prior to initiating the next turn.

The objective of the final flight-evaluation phase is to determine the operational feasibility of the test procedures developed in the first two phases. These tests use a variety of evaluation pilots. The specific goal is to obtain a statistical database to aid the FAA in establishing Terminal Instrument Procedures (TERPS) for the various non-standard operational scenarios.

Three types of statistical data plots are usually generated by processing the flight test data. They are plots of (1) composite lateral and vertical approach profiles, (2) statistical lateral and vertical approach envelopes (i.e., mean $\pm 2\sigma$), and (3) statistical lateral and vertical flight path tracking errors (i.e., $\pm 2\sigma$). Composite plots of the individual approach

4

profiles are useful in identifying approaches that are representative of the general trend of the data. Thus "outliers" can be removed before statistical processing of the data. The statistical approach envelope plots indicate the amount of airspace required to conduct the approaches, and the statistical flight path error plots show how well the pilots are able to follow their reference flight-paths.

Additional data in the form of answers to a pilot questionnaire are also obtained. The questions are designed to elicit pilot opinion, comment and evaluation of various aspects of the test procedures such as the acceptability of the approach profiles, the recommended speeds, the selected decision heights and the feasibility of IFR operations.

All of the above data types were gathered during the FAA/NASA MLS test program, and made available to the FAA to be used for developing TERPS criteria for curved path and steep glide-slope MLS approaches. This process is on-going at the present time, and additional data for helicopter MLS instrument approaches is being generated through flight tests at the FAA Technical Center.

Step 4: Analyze Database and Establish Enhanced Terps Criteria.

The final step in the current methodology is for the appropriate FAA group (e.g., Aviation Standards Group) to determine if the gathered database is *sufficient for the purpose of* establishing the enhanced TERPS criteria. If the answer is affirmative, their job is to analyze the available data (raw as well as processed) and to arrive at a decision vis-a-vis the formulation of the enhanced TERPS for each non-standard situation under consideration. The final product of this effort is a set of approach plates for each specific landing site and operational factor.

EVALUATION OF SIMULATION-TECHNOLOGY
OPTIONS FOR TERPS

Advances in the state-of-the-art in simulator technology have resulted in their effective use for a variety of aircraft simulation applications, ranging from system development and verification to training, checking and certification of flight crew members. Therefore, it is logical to have similar expectations regarding the usefulness of the simulator-based approach to the development of standards and criteria for enhanced terminal instrument procedures. The following material addresses the merits of taking the simulation-based option. The technical feasibility of substituting the simulator facility for the flight test program is discussed first. This is followed by a survey of the potential benefits and liabilities of using the cockpit simulator for this purpose.

Technical Feasibility

A good way to determine the feasibility of using the simulator in place of flight tests is to examine the various inter-related elements that comprise a successful flight test program. In order for the flight test effort to be duplicated on a cockpit simulator facility, each component of the flight test must be capable of being simulated accurately using hardware and/or software. Technical feasibility, therefore, would depend upon how successful one can be in achieving the desired objective and subjective fidelity of the simulation. The following key elements of the helicopter flight test program must be represented adequately in a piloted cockpit simulation effort:

a. helicopter dynamics;
b. landing navigation aids;
c. on-board avionics systems;
d. approach profile geometry and parameters;
e. environmental disturbances;
f. approach and landing visual scene; and
g. motion cues.

The fidelity with which these elements can be simulated is reviewed in the following paragraphs.

Helicopter Dynamics

A mathematical helicopter model that accurately describes an actual vehicle's characteristics over the full range of flight phases under evaluation must be used in any cockpit simulator investigation. The degree of sophistication required of these models clearly depends upon the portion of the vehicle's flight performance envelope that must be simulated. Typically, the complexity of helicopter models increases rather quickly with the number of components represented. Thus, for example, if only the six rigid body fuselage degrees of freedom are considered, then a 6-DOF linearized model or a

6-DOF quasistatic nonlinear model[3] is needed. However, such models are satisfactory for a very narrow range of steady-state flight conditions; namely, constant airspeed (above the airspeed corresponding to loss of translational lift) and flight path angle flight segments. Six DOF models may be adequate for preliminary fixed-based ground simulator investigations and as such have been used towards this end.

Increasingly, nonlinear and more realistic mathematical models are obtained by allowing for additional components such as the main rotor and the tail rotor. One simple example is a 9-DOF tip-path plane dynamics nonlinear model[4] which includes the usual fuselage 6-DOF plus an additional 3-DOF for the rotor in terms of the blade coning angle and two blade flapping angles, respectively. More complex representations are based on blade element analysis in which total rotor forces and moments are developed from a combination of aerodynamic, mass, and inertia loads acting on each simulated blade segment. Blade element models,[5] validated properly, can be highly accurate in duplicating the subjective and objective characteristics of an actual helicopter.

Based upon the short summary of models above, it is clear that the mathematical tools exist for describing helicopter dynamics with high fidelity over almost the full range of the vehicle's design flight performance envelope. This includes nonsteady flight maneuvers such as accelerating and decelerating flight, turns and rolls. However, it is not sufficient to have the mathematical tools alone; these complex mathematical models must be validated using available flight test data and must be shown to match both the objective (e.g., performance, static/dynamic response, controllability) and subjective (i.e., pilot handling quality evaluations) verification and validation criteria. Furthermore, the models must be capable of operating in near-real time (i.e., cycle frequency greater than at least twice the Nyquist frequency) on the existing computer facilities.

At the present, it takes between two to five years to completely develop, validate and implement in real time a mathematical model for a given helicopter. Furthermore, even if the methodology for modeling is standardized, each helicopter is different in peculiar ways and requires a custom-made effort for model validation. Consequently, this can be a costly and time-consuming effort which may not be necessary or justified for TERPS simulator facilities. Instead, a generic mathematical model representing a typical category of helicopters may be more suitable for TERPS evaluation.

Existing helicopter models are adequate for airspeeds above translational lift (i.e., 45-60 kts) and cannot be used for low altitude flight within ground effects. Therefore, in the near-term period, helicopter maneuvers corresponding to profiles of constant speed ($\geq$ 60 kts) are the only ones that can be investigated. However, in the long-term, rapid developments in computer simulation technology (e.g., parallel processing machines) are expected which should render it feasible to simulate accurately helicopter dynamics over the full flight envelope; in particular, the ability to simulate steep glide-slope deceleration-to-hover approach profiles.

8

Landing Navigation Aids

The landing navigation aids provide the signals that are necessary for a receiver on-board the aircraft to estimate its own position with respect to the outside world. Thus, the MLS azimuth, elevation and DME transmitters provide the raw signal from which aircraft position can be estimated. Similarly, the GPS receivers provide for computation of four range measurements (i.e., from aircraft to each of the four satellites) from which aircraft position can be calculated. These signals must be duplicated as accurately as necessary in any ground-based system. The navigation signals themselves are not perfect and do not provide the true position of the aircraft relative to the earth. The transmitted signal pattern can deviate from the design specifications because of several factors that include the antenna site location and geometry, the surrounding ground elevation including obstacles, and transmitter noise in the form of a varying bias and random fluctuation in the signal. The net result is a received signal that is different or in error from the assumed values. For the simulator results to have any operational significance, the operating and error characteristics of these navigation signals must be suitably represented.

Two types of model may be used--a table-look-up model of the actual measured data or a mathematical model of the error characteristics. However, for most operational situations, the mathematical modeling approach is more than adequate. The table-look-up models require a large amount of data which must be obtained under actual operational conditions. Such data are hard to collect and can be quite expensive and time consuming. For most enhanced TERPS approach profiles, the use of mathematical error models for the navigation signal is recommended. The only times when actual data based table-lookup signal models would be needed are in the simulation of approach profiles on the perimeters of the navigation coverage and in specific geographic locations where severe anomalies are likely to occur because of landing site location (e.g., a cross-radial approach where azimuth signal provides range information and DME signal provides azimuth) or surrounding geography (e.g., multipath error due to hills and obstacles).

On-Board Avionics Systems

On-board avionics systems consist of the navigation, guidance, control and displays needed to successfully fly the desired reference profiles. The on-board navigation system processes the received raw navigation signal provided by the external navigation aid and blends it with other sources of on-board vehicle position information using the appropriate filter configuration (e.g., complementary or Kalman filter) to determine the best estimate of the aircraft state. The guidance system takes this information and provides the pilot the information necessary to follow the reference flight profile (i.e., trajectory and speed versus distance-to-go). This information, in the form of following errors or situation, is presented to the pilot on a display system (e.g., raw angle-only, flight director or electronic situation displays). The purpose of the control system is to provide stability and control augmentation

to the basic helicopter dynamics so as to achieve the desired handling characteristics.

Each of the above airborne systems can be exactly replicated in a ground-based cockpit simulator, including the physical layout of the actual cockpit environment. This is because the systems involve actual hardware and software, and therefore can be acquired and implemented in the simulator.

Approach Profiles

Reference approach profiles are usually defined with reference to an earth-based coordinate system (e.g., helipad-centered Cartesian axes). These are algebraic equations which define the desired position (either Cartesian or spherical) of the aircraft as a function of the along-track distance to go from the glide path intercept point (GPIP). These equations are straightforward to compute and can be implemented on a simulator exactly as in the flight test program.

Environmental Disturbances

As with navigation signals, the environmental disturbances can be simulated using either table-look-up or mathematical models. However, for most TERPS operating conditions, existing mathematical models are adequate. Only for extreme weather conditions such as microburst wind shears is a table-look-up model based upon actually recorded meteorological data (e.g., JAWS project[6]) justified.

Visual Scene and Motion Cues

In a terminal instrument approach, the pilot can see outside the window (technically) only after the decision height is reached. Hence, strictly on a technical basis, the extra-cockpit visual scene need not be reproduced on a simulator except during the final visual flight segment of the approach following decision height. Because of this, all of the enhanced constant speed (≥ 60 kts) TERPS profiles which involve breakout at decision height (e.g., 50/100/150/and 200 ft for $3^0/6^0/9^0/$and 12^0 glide-slope approaches) can be investigated with a minimal visual scene generation system that shows the pilot the extra cockpit view at the moment of transition from IFR to VFR flight. This capability at breakout is necessary in order to provide the crew with a sense of realism that is akin to that experienced in actual flight. With this information at decision height, the crew can make the decision to either go around or continue towards a landing.

However, for simulating the visual segment of the flight following breakout, a high fidelity visual scene generation system is required. This is because the final VFR segment may involve deceleration to a hover using the visual cues. A wide field of view and high resolution scene must be generated so as to provide the near-field cues needed for ground speed and altitude estimation. A survey of the state-of-the-art in computer visual scene generation systems is included in Appendix A.

The motion-drive systems currently available are fully capable of simulating the motion cues experienced by the pilot during any particular approach profile, including the steep glide-slope deceleration to hover procedures. No problems are anticipated regarding the technical feasibility of duplicating the motion sensed by the pilot in actual flight.

Benefits

Many of the benefits of the cockpit simulator cannot be measured directly in terms of cost savings alone. However, these can be important considerations in choosing to use the simulator. Some of these benefits are discussed below.

Controlled Test Conditions

The operating test conditions can be precisely controlled on a simulator. This is because each variable element or parameter in the test plan is known and under the control of the research investigator. Aspects of the operating environment that are beyond human control such as the visibility, atmospheric disturbances and navigation signal error characteristics can be set at any desired value in the simulator. This ability makes it possible to choose any set of operating conditions for a given run and change them in any order for the subsequent sequence of runs. As a result, the experimental test matrix can be designed for maximum statistical robustness. This eliminates the possibility of the pilot learning or anticipating a test condition because of repeated prior exposure to these conditions.

Data Quality and Quantity

The data collection period for a given set of conditions is shorter on a simulator. Hence, for the same period of time, a larger quantity of data for more flight conditions can be generated using the simulator. It is possible to operate around the clock with the simulator because it is not subject to cancellation due to weather, visibility or other traffic conditions.

All the key variables and parameters in the simulation are in the computer and can be recorded as desired. In particular, the true trajectory flown by the pilot is available and does not have to be extracted from noisy tracking data (e.g., ground-based laser trackers). As a result, the quality of the measured simulator data is far superior to that which can be obtained through a flight test program.

Safety

The simulator is much safer to use and makes it possible to investigate new operating test conditions (e.g., instrument deceleration to a hover under zero/zero visibility) that are inherently risky or dangerous. Hence, it is possible to operate on the limits of the flight envelope without the possibility of injury or fatality.

11

Flexibility of Modification

It is easier to modify the simulator because changes do not have to be
certified for flight safety. Consequently, advanced concepts in navigation,
guidance, controls and displays can be investigated without having to be first
approved for safety. Also, redundancy system requirements stipulated for
flight-safety can be deleted with subsequent reduction in system complexity,
reliability and cost.

Cost Considerations

It can be said with confidence that the cost of running a helicopter test
program would be lower on a simulator than it would be with a flight-test
investigation. However, for a "one-shot" test effort alone, the use of a
simulator is not justified. This is because the initial once-only costs of
acquiring a simulator and validating the complete facility for TERPS develop-
ment can be quite expensive. Using an existing helicopter is cheaper because
there is no additional initial development cost for acquiring a mass-produced
vehicle.

However, if the flight test efforts are likely to recur for each new
requirement, as would be true of TERPS enhancement, then the initial acquisi-
tion costs in developing a TERPS simulation facility can be justified if they
are distributed over the life of the new facility. Furthermore, acquisition
costs may be greatly reduced if advantage is taken of existing helicopter
training simulators (which are mass produced at lower cost) by modifying them
for application to TERPS simulation.

The actual costs to run a simulator range from $350 to $1,500 per hour
depending upon the sophistication of the simulator and the number of users.
Flight test costs of helicopters are quoted to range between $2,000 to $10,000
per hour. However, these estimates are hard to quantify and can be easily
misrepresented. The problem lies in stipulating precisely what ingredients
constitute costs. (For example, should they include support personnel costs
in maintaining and running a given facility or test program?)

An attempt is made in Appendix B to compare the costs for helicopter
flight tests against a similar scope simulation effort. The FAA/NASA
helicopter MLS curved path flight tests conducted in 1983 at Crows Landing
Facility are used by way of an example. Appendix C lists other information
obtained comparing simulator and flight test costs.

Liabilities

Use of the simulator can lead to erroneous or unwarranted conclusions.
This can occur either because the simulator facility itself does not
adequately represent the real world or because the simulator is used improp-
erly. Differences between the cockpit simulation and the real world can arise
because of differences between the simulated module and the actual thing, for
one or more key elements. These include, as mentioned before, the helicopter

12

dynamics, the navigation signal characteristics, the visual scene, the cockpit motion, and the atmospheric disturbances.

However, even the acquisition of a fully validated simulator facility may not be sufficient. A simulator, however good it may be, is not an actual aircraft, and abuses or misuses can still occur. These can manifest themselves by the reinforcement of simulator-based flying strategies which differ significantly from what is observed in actual flight (i.e., negative transfer of strategy). Standards and criteria obtained under these conditions, besides being erroneous, can prove to be catastrophic to safety of flight.

These extreme liabilities can be ameliorated by following up any extensive tests on a simulator with verification through a limited flight test effort. This is necessary to ensure that whatever conclusions (e.g., enhanced TERPS standards and criteria for zero/zero visibility conditions) that are obtained by simulator investigations can in fact be duplicated in flight.

This implies that even if a simulator-based approach is used, a flight-vehicle must be available for backup tests and verification purposes. Thus, use of a simulator does not alleviate the need for an actual helicopter for conducting tests.

NEAR-TERM METHODS FOR TERPS EVALUATION

Based upon the discussion in the previous section, it is clear that simulation-based TERPS enhancement in the near term must be limited to an investigation of constant speed approach profiles at airspeeds greater than values corresponding to the loss of translational lift. For most helicopters, loss of translational lift occurs somewhere between 45-60 knots. The primary objectives of the simulation effort must be twofold:

a. The first goal is the verification of the simulation-based approach by repeating a set of experiments already investigated through a flight test program; and

b. The second goal is to study additional test conditions, not previously flown, for subsequent flight-test validation.

As the first experiment, it is recommended that enhanced TERPS for MLS constant-speed steep glideslope approaches be investigated. This is because data and observations from earlier FAA/NASA MLS flight-test programs (conducted in 1979 and 1983) can be used for verification of simulation-based results.

A two-phase simulation study is suggested. The first would be on a fixed-base ground simulator (e.g., NASA/ARC Chair-6), and the second would be on a moving-base simulator (e.g., NASA/ARC VMS). The major difference between the two simulators is in the visual scene generation and motion systems capabilities. The comparison between the two should yield valuable insight into the impact of visual/motion cues on task performance and pilot acceptance ratings. The information learned can be used to develop a systematic screening procedure for deciding the type of simulator (i.e., visual/motion cue requirements) that must be used for any new TERPS evaluation.

The type of helicopter model chosen must be capable of describing the actual vehicle's dynamics for the full range of flight conditions over which the flight tests have been conducted. For the FAA/NASA MLS flight tests, this means a mathematical model that matches the UH-1H characteristics for airspeeds greater than 60 knots and flight path angles as high as 12 degrees. An existing 6-DOF mathematical model for the UH-1H[3] should be adequate for the fixed-base evalution. An improved 9-DOF[4] tip-path-plane UH-1H model may need to be developed and validated for use on the large amplitude motion VMS simulator.

A Gauss-Markov model for the signal characteristics should be adequate for the simulation effort. For the MLS experiments, error characteristics (i.e., bias plus random colored noise) extracted from the actually recorded flight test data could be used to fine tune the signal model. As an option, actual MLS navigation error (i.e., on-board estimate minus true value) time

histories of the azimuth, elevation and range signals may be used to substitute for the navigation system (i.e., ground signal plus airborne complementary navigation filter).

Existing models for the atmospheric disturbances are adequate for near-term TERPS application. An analytical wind shear model of the form recommended in Calspan's revision to MIL-H-8501A[7] is recommended. This model would have to be tuned to match the actual wind shear characteristics recorded during the corresponding flight test program. A Dryden turbulence model should be used during the simulation investigation. Parameters of this model (i.e., signal power and filter time constants) should be adjusted to match as closely as possible actually recorded turbulence data.

The FAA/NASA MLS flight test program investigated a finite number of approach profiles; namely, steep glide-slope curved (i.e., U-turn and S-turn) trajectories, whose geometries and parameters were set by NASA pilots in a very limited number of experimental flight tests. The same was true in the selection of the display sensitivities (i.e., glide-slope/localizer and 3-cue flight director) that were scaled with distance to go from the touchdown point. These and other issues should be more exhaustively investigated in any simulation-based TERPS evaluation of MLS approaches.

LONG-TERM TERPS EVALUATION

There are several parallel technical developments that must take place in the near term to prepare for long-term TERPS evaluation via the cockpit simulator. Helicopter dynamics models must be developed that are good down to hover. This will require using flight tests to collect data and a parameter identification process to determine helicopter stability and control derivatives from the collected data. This requires selecting the degrees of freedom of the model desired, the type of maneuvers required to collect the flight data, the amount and accuracy of the data to be collected, the data processing procedure to extract the derivatives, and the modeling methodology to include these derivatives in the simulator computer.

Navigation models must be developed for the GPS and Loran-C signals, on-board receivers, and airborne recursive filtering. In addition, if there are MLS cross radial errors, these need to be modeled into the current MLS signal models.

Any variations in the airborne guidance signals and flight control augmentation that might be tied to the types of approaches that can be followed need to be examined. If there are several possibilities, each of them needs to be modeled so that the simulator avionics representations accurately model the effect these variations have on flight performance.

A development effort must be initiated to create the desired visual scenes for the CGI system. These scenarios must be compatible with the simulation facility chosen for the evaluation.

A decision must be made on what type of motion simulation is to be used. The VMS currently provides a great deal of capability, but it may be too complicated and expensive for what is required. Several new simulators are being planned for NASA Ames, and one of them may have the necessary motion simulation at a much reduced price.

Different wind models need to be selected to be used during tests of the various scenarios. Wind effects on building tops, mountain sides, and oil rigs can have unusual characteristics, so these conditions need to be explored to establish the extremes needed for TERPS evaluation. New wind models may be required.

A systematic procedure for selecting the maneuvers to try during the simulator testing needs to be established. This includes establishing the geometric parameters that describe (a) curved, constant speed approaches with different glideslopes, (b) decelerating, straight-in approaches with different glideslopes, (c) curved, decelerating approaches with different glideslopes, (d) multiple segment approaches made up of curved arcs, straight lines, descents, deceleration periods, etc., for various approach combinations that may occur in real life, and (e) similar combinations required to establish the TERPS requirements for both takeoff and missed approach/go-around.

The selection of the simulator and the planning of its use needs to be done. This process encompasses each of the above elements. The selection and planning process provides guidelines to direct the other related work, and it ensures that each element is developed consistent with the overall needs for TERPS evaluation.

CONCLUSIONS

It is concluded that cockpit simulator technology can be used to advantage to develop enhanced TERPS criteria for helicopters. Technically, it is feasible to develop or utilize existing mathematical models of all important elements in a simulator system required for realistic simulation of non-standard terminal approaches. There are many benefits of using the simulator approach as opposed to relying strictly on flight tests. These include:

a. better control of test conditions;
b. better data quality and quantity;
c. increased safety;
d. more flexibility in test modification; and
e. decreased operational test costs (by a factor of up to ten).

No conclusive information was obtained on purchase or development costs of obtaining the required simulator configurations.

There can be some liability in using simulators to develop TERPS criteria. However, if care is used in designing flight scenarios and specifying procedural use of the simulator, and if the results are verified by spot check flight tests, these liabilities can be avoided.

It is recommended that in the near term, the NASA Ames flight simulators be used to duplicate helicopter flight tests previously conducted at Crows Landing in 1979 and 1983. These tests would provide useful information to verify that the simulator approach produces similar data to that which would be gained from strictly a flight test approach. It also would give comparative results between a fixed-base simple display simulator (Chair 6) and a sophisticated moving base/CGI display enhanced simulator (VMS). Because the extensive flight test results exist to support such a study, it seems to be an opportunity that should be exploited.

For the far term, a model development program is required to provide necessary software to conduct simulator-based TERPS evaluations. This includes development of models for low-speed helicopter dynamics, non-conventional navigation sources and guidance avionics, CGI data bases, and wind models to support non-conventional landing sites. This model development program is tied to the decision to proceed with use of helicopter simulators for TERPS enhancements.

19

APPENDIX A

VISUAL SIMULATION

The following is a brief discussion of the state of visual simulation for cockpit simulator applications. First, a summary is given of what is currently available in visual simulation, particularly with regard to Computer Generated Imagery (CGI). This is followed by a discussion of what really is required to conduct simulator experiments for establishing TERPS criteria. From this, a proposed experimental set-up that would be suitable for analyzing the approach and takeoff phases of helicopter flight with non-conventional elements is summarized.

Trends

The state of visual simulation technology is one that is under very rapid evolution. The following material was extracted from References 8-16 that follow, and the reader who wants a more complete picture is encouraged to review these references, particularly References 8 and 17.

First of all, simulation offers many advantages over flight test including standardization of testing, elimination of injury and fatality, and increased testing time unhampered by weather conditions and airport traffic. Because simulators permit round-the-clock testing, the Army has calculated that one simulator provides the testing equivalent of 18 real helicopters. Simulators also permit much greater flexibility including night flight, heavy traffic, or stron wind and gust conditions. Although the capital cost of simulators is high, they provide a substantial savings in operating costs. One rule of thumb is that the real aircraft is about 10 times as expensive to fly as the simulator. Thus, there is a solid basis for developing the simulator capability.

An important part of the simulator is the visual scene. In the mid-1950s the flight simulation industry developed computer-controlled television systems, in which a small closed-circuit TV camera moves over a scale landscape (a terrain board) in response to position inputs from the simulator. However, this was limited because the boards could only include a limited area of terrain, were relatively expensive to build, and were limited for simulation of flight close to the earth surface. For this reason, since 1975, model boards have increasingly been replaced by computer-generated imagery systems.

CGI systems continually convert a stored numerical database into a perspective view of a moving terrain and display it in real time on the windows of the test vehicle. CGI is much more flexible than model boards because it permits the use of a variety of different terrains, much larger areas, moving surrounding vehicles, variable time of day, and environmental

21

effects such as haze or fog. Although CGI images tended to be cartoonish, they are becoming more detailed and realistic--a trend supported by rapid advances in computer hardware and software.

The CGI systems on the market are basically of two types: inexpensive systems for passenger-plane or business-aircraft simulators and sophisticated systems that are suited for military mission simulation. Commercial aviation simulators typically offer a narrow field of view and limited resolution. They are intended mainly for takeoff and landing tasks and hence are not required to generate a large gaming area. Commercial-aviation CGI systems that provide night, dusk, and daylight imagery include:

Singer Link-Miles, West Sussex, England	Image III
McDonnell Douglas Electronics, St. Charles, MO	Vital IV
Evans & Sutherland/Rediffusion, Salt Lake City, UT	Novoview SP3T

However, these commercial-aviation systems cannot provide sufficient realism or detail for simulating slow, low altitude helicopter flight. Helicopters operate at a speed and altitude where subtle terrain cues are essential for instantaneous juagment of height, attitude and motion; where rapid visual discrimination of terrain boundaries are required; and where smoke and dust are constant impairments to clear vision. If a visual system cannot provide convincing ground detail at close range, then it will not provide an effective testing mechanism for study of various helicopter missions. Because of this reality, the Army has funded programs to develop a new generation of image generation with the necessary scene realism to display the "leaves on the trees" needed to support helicopter training missions. These new simulator facilities require visual systems that are state-of-the-art high performance machines with the flexibility and future adaptability to meet different operating envelopes and new correlated sensor requirements as well as supporting future out-the-window display technology. Current high-end CGI systems incluae the following:

Evans & Sutherland/Rediffusion	CT5A
General Electric, Daytona Beach, FL	Compuscene IV
Singer/Link, Binghamton, NY	DIG II
Hitachi, Japan	Bestview

For commercial aviation simulators, the trend is to maintain the existing capabilities while reducing the cost. For military and high performance air-craft markets, the trend is to hold the costs constant while providing increasing realism and testing effectiveness. The helicopter TERPS application requires the detailed realism of the latter systems but the operating area of the commercial aviation systems. Thus, such system can be in the medium price range for CGI systems.

Some technical characteristics and trends in CGI development include the following:

1. For dynamic CGI imagery to appear smooth, it must be recalculated and displayed 50-60 times a second.

2. The degree of visual complexity that a CGI system can generate depends on its capacity--the number of edges or polygons it can generate in real time. The E & S CT5A can generate more than 7000 polygons per field. All the objects in a database are made up of polygons and hence have a faceted appearance. To depict curved objects, the display processor employs a linear interpolation technique called shading to convert the faceted model into smoothly shaded surfaces.

3. Scan line processing is rapidly being superseded by a new rendering technique called area processing. This offers major advantages over scan line processing: It can handle a virtually unlimited number of polygons, and it gives better image quality. It also removes stairstepped edges on polygons that are not parallel or perpendicular to the raster lines.

4. Scene management techniques are being used to allocate greater amount of 3-D detail in the immediate foreground, the part of the scene most important to the pilot.

5. Dynamic overload management capability is being used to allow the system to operate close to capacity yet handle temporary overloads gracefully.

6. One way to increase visual realism without expanding the database is to replace hard-edged 2-D textures with edgeless textures such as mottled surfaces, which require fewer calculations. Another way of increasing the image complexity without expanding the database is by using "instancing." This technique reproduces a single 3-D model, such as a tree or rock, repeatedly throughout a scene in the correct scale and perspective.

7. A new approach called fractal surface generation adds irregular detail to an initially simple geometric model to get a crinkled surface that resembles a mountainous terrain. An advantage of fractals is that they can produce highly complex images from a small starting database.

8. A method is being developed to model 3-D objects and terrains by building scenes out of curved 3-D solids such as hyperboloids and ellipsoids. This approach simplifies scene modeling and reduces the number of scene elements that must be stored in the database.

9. Cell texturing maps computer-generated textures onto low-resolution polygonal surfaces to yield greater realism. The textures are blended into the scene with a special filtering technique to avoid hard geometric edges.

10. Computer-generated synthetic imagery (CGSI) stores 2-D surfaces and 3-D object photographs on a rapid-access videodisc and inserts them onto a CGI scene in real time, again for greater realism.

11. Very wide-angle, high-resolution display systems are required to provide the large frontal and downward viewing angles needed to simulate nap-of-the-earth helicopter flight. To fill an entire dome with high-resolution imagery requires many channels and enormous capacity, and the resultant cost may be prohibitive. The key to cost reduction is to take advantage of the fact that the human eye sees sharply over a limited area around the focal point. Thus a number of companies are developing area-of-interest display systems, in which a high-resolution image is presented over a small central area where the pilot is looking at any moment, while a low-resolution background is presented over the peripheral field of view.

12. Non-visual scene information such as altitude above the terrain is being computerized against the visual terrain faces to provide accurate visually correlated radar altimeter and other information for the helicopter.

In summary, the state-of-the-art visual simulations are quickly approaching a near-photographic appearance.

Requirements

Reference 14 gives a good discussion of the requirements for helicopter simulator visual cues. The problem of judgments concerning range, height, and surface orientation using the visual scene in a flight simulator is the central theme of Reference 14. For the landing phase, for fixed wing aircraft, the following are considered to be most important:

1. Size and shape of the runway;
2. Size and shape of familiar objects;
3. Motion parallax;
4. Motion perspective; and
5. Position relative to the horizon.

The helicopter pilot when flying at high speed has the same cues but has the added problem that at slow speed flight or hover, he judges closer distances and has to contend with more vibration which may upset his acuity. Also from simulator investigations, it has been established that image detail, 2-D texture, 3-D texture and visual field of view affect the pilot's judgment.

The main visual cues for height and distance judgments include:

1. Retinal image size;
2. Linear perspective;
3. Interposition;
4. Shades and shadows;
5. Shape;
6. Motion parallax;
7. Motion perspective;
8. Surface or object detail;
9. Aerial perspective;
10. Distance below the horizon;
11. Accommodation;
12. Convergency;
13. Retinal disparity; and
14. Stereoscopic motion.

The first 10 are considered to be monocular information and the last four are binocular. Reference 14 paper addresses the definition and requirements for each of these. A summary of requirements is presented as Table 1.

Practical Considerations

It is not possible to build an image database that would contain all possible scenarios that a helicopter pilot might encounter during the approach, landing, takeoff, and go-around situations. However, a limited number of scenarios can be used to test the use of the helicopter with curved, steep decelerating flight paths, wind gusts and non-conventional navigation aids. These would include the following:

1. A regular helipad in the vicinity of a busy airport;
2. A rooftop helipad on a tall building in a metropolitan area;
3. A helipad on an off-shore oil rig; and
4. A level landing spot in remote mountainous terrain.

These four scenes would be sufficient to begin the comprehensive study of helicopter terminal procedures for different combinations of system elements. They would, no doubt, lead to requirements to test the system with variations in these four basic scenes. However, with the capability of the flexible CGI systems, rapid adaptibility of the systems is possible.

TABLE 1. Requirements for a Practical Visual System

Element	Requirement
Field of View	
Vertical	45 degrees plus chin windows.
Horizontal	Greater than $\pm$ 75 degrees with across cockpit viewing.
Resolution	
Low level flight	6 arc minutes/line pair
Near distance judgments	
Structures	20 feet
Height judgment	Down to 10 feet at slow speeds (less than 60 kt).
Model details	Buildings with windows, masts, pylons, cables, roads, railways, rivers, natural features, including undulation in the terrain, trees, hedges.
Special effects	Weather, wind, and downwash.
Textural information	3-D and 2-D coarse textural information with a mean horizontal spacing of 25 feet, minimum spacing down to 5 feet, minimum fine texture spacing of 1 inch, vertical texture for structures, automatic management of image detail with height and range.

APPENDIX B

COST ESTIMATES OF HELICOPTER MLS CURVED
PATH FLIGHT TEST PROGRAM AND COMPARISON
TO A PROJECTED SIMULATOR-BASED STUDY

The NASA/FAA helicopter MLS curved path flight test program was conducted at the Navy Auxilliary Landing Facility, Crows Landing, California. As discussed earlier, the program consisted of three phases: (1) a preflight procedures development phase, (2) an experimental flight investigation phase, and (3) an operational flight evaluation phase. The following material provides an estimate of the cost (dollars and person-hours) of conducting these flight tests.

1. Research and Development Engineering Support

    2 research engineers (1 senior GS-13 and 1 junior GS-9) for the duration (20 months) of the program.

2. Pilot Flight Hours
    a. Pre-flight Phase: Approximately 10 hours, 1 pilot (simulation)

    b. Experimental Phases: 20 flights, 2 pilots/flight approximately 4 to 6 hours/flight

        Total hours = 20 x 2 x (4-6) = 160-240 hours

    c. Evaluation Phase: 36 flights, 3 pilots (1 safety + 2 guest) per flight, 8 hours/flight

        Total hours = 36 x 3 x 8 = 864 hours

3. Flight-Test Support
    a. Crows Landing Facility: Approximately $1,000/hour
        Experimental Phase: 80 hours (= 20 flights x 4 hours/flight)
        Evaluation Phase: 288 hours (= 36 flights x 8 hours/flight)
            Total Hours: 368 hours

    b. Vehicle Operating Costs: (Fuel and Parts)
        UH-1H: $159/hour
        SH-3: $479/hour
        CH-47: $702/hour

    c. Aircraft Manager/Crew Chief:
        Experimental Phase: 80 hours
        Evaluation Phase: 288 hours
            Total Hours: 368 hours

    d. Contractor Support:
        Experimental Phase: 20 flights x 2 hours/flight = 40 hours
        Evaluation Phase: 36 flights x 2 hours/flight = 72 hours

Excluding item (1) above, which would be the same regardless of whether the investigation involves flight tests or simulation, the overall costs can be summarized as follows:

Crow Landing Costs:
368 hours x $1,000/hour = $368,000

UH-1H Operating Costs:
368 hours x $159 - $58,512

Pilot Support:
1,034 hours (160 + 10 + 864 = 1,034)

Other Engineering Support:
480 hours (368 + 40 + 72 = 480)

In order to estimate what the comparable costs would be for conducting the test program in a simulator, it is best to look at the actual number of approaches flown during the flight-test program. Eighteen evaluation pilots participated. Each pilot flew a total of 12 hooded approaches: Two U-turn and S-turn approaches at 6^0 and 9^0 glide-slopes, and two straight-in approaches at 9^0 and 12^0 flown to either a missed approach or landing. Thirty-six eight-hour flights were flown to accomplish all the 216 (18 x 12) approaches. This corresponds to approximately 1 1/3 hours per approach profile. A comparable approach simulation run should take 10 minutes to complete, which is lower by approximately a factor of eight.

·Based on these calculations, and assuming a $1,500/hour cost of the simulation facility (e.g., NASA/Ames VMS), the comparable cost of repeating the FAA/NASA MLS flight tests on a simulator would be as follows:

Simulator Costs:
46 hours at $1,500/hour = $69,000
(46 hours = 368 hours/8)

Pilot Support:
130 hours (1,034/8)

In summary, even with the cost of a highly sophisticated simulator such as the VMS, the simulator costs would be roughly 20% the cost of actual flight tests.

28

APPENDIX C

COMPARISON OF VARIOUS SIMULATOR VERSUS FLIGHT TEST COSTS

During this study, various sources were checked to compare operational costs of using the cockpit simulator instead of an actual aircraft in flight test. The following values are for airplane simulators and flight tests throughout the country.

NASA Langley - B737
      Simulator : $1,000/hr
      Aircraft : $15,000-$20,000/hr.

Boeing - Simulators for proficiency training
      737   : $190/hr
      747   : $265/hr
      757   : $300/hr
      767   : $300/hr

      Double the above with an instructor.

      Aircraft : $1,000-$15,000/hr of which fuel is $1,000-$2,000/hr.

FAA Southern Region
      Flight costs are 10 to 20 times more expensive than simulator operational costs.

REFERENCES

1. Peach, L. L., Bull, J. S., Anderson, D. J., Dugan, D. C., Ross, V. L., Hunting, A. W., Pate, D. P., and Savage, J. C., "NASA/FAA Flight-Test Investigation of Helicopter Microwave Landing System Approaches," Preprint No. 80-55, American Helicopter Society 36th Annual Forum, Washington, D.C., May 1980.

2. Swenson, H. N., Hamlin, J. R., and Wilson, G. W., "NASA/FAA Helicopter Microwave Landing System Curved Path Flight Test," NASA Technical Memorandum 85933, USAAVSCOM Technical Report 84-A-14, February 1984.

3. Talbot, P. D. and Corliss, L. D., "A Mathematical Force and Moment Model of a UH-1H Helicopter for Flight Dynamics Simulations," NASA TM-73254 (Revised 8/30/78), June 1977.

4. Chen, R. T. N., "A Simplified Rotor System Mathematical Model for Piloted Flight Dynamics Simulation," NASA TM-78575, May 1979.

5. Howlett, J. J., "UH-60A Black Hawk Engineering Simulation Program," Vol. I - Mathematical Model, NASA CR 166309, December 1981.

6. Reeves, P. M., Campbell, G. S., Ganzer, V. M., and Joppa, R. G., "Development and Application of a Non-Gaussian Atmospheric Turbulence Model for Use in Flight Simulators," NASA CR-2451, September 1974.

7. Chalk, C. R., and Radford, R. C., "Mission-Oriented Requirements for Updating MIL-H-8501," Calspan Proposed Structure and Rationale, USAAVSCOM TR-85-A-7, January 1984.

8. Tucker, J. B., "Visual Simulation Takes Flight," High Technology, Vol. 4, No. 12, December 1984, pp. 34-47.

9. Beaver, P., "Super Puma Simulation," Helicopter World, Vol. 4, No. 1, January-March 1985, p. 48.

10. Wingate, J., "Sea King Mk5 Simulator," Defense Helicopter World, Vol. 4, No. 3, September-October 1985, pp. 16-21.

11. Tucker, J. B., "Computer Graphics Achieves New Realism," High Technology Vol. 4, No. 6, June 1984, pp. 40-53.

12 Marsh, G., "Making the Helicopter Simulator Affordable," Defense Helicopter World, 1985, pp. 10-13.

13. Gateau, H., "Flight Tactics & Mission Simulation," Defense Helicopter World, 1985, pp. 48-49.

14. Cross, P., and Roberts, M., "Helicopter Simulator Visual Cueing Requirements and Solutions."

15. Brahney, J. H., "Simulators. Should They Feel Just Like Flying?"
        Aerospace Engineering Vol. 5, No. 9, September 1985, pp. 8-15.

16. Hold, D. J., "Simulators. How Real Does the Visual System Need to Be?"
        Aerospace Engineering, Vol. 5, No. 9, September 1985, pp. 16-22.

17. Kotas, J., "Computer Image Generator (CIG): Realistic Simulation,"
        National Defense, Vol. 70, No. 412, November 1985, pp. 26-31.

END

DTIC

8- 86