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STUDY OF FLIGHT MANAGEMENT REQUIREMENTS DURING SST LOW VISIBILITY APPROACH AND LANDING OPERATIONS

FINAL SUMMARY REPORT

June 1968

Prepared by:

Walter B. Gartner

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Prepared under Contract No. NAS2-4406 by

SERENDIPITY ASSOCIATES

Los Altos, California

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FOREWORD

This report summarizes a study of potential problems in supporting the performance of flight management tasks in SST low visibility approach and landing operations. More extensive documentation of the study is available for limited distribution in references 3, 4, and 5. The intent of this report is to provide an overview of the analytic procedures employed, summary statements of the flight management support problems distinguished in this analysis, and a brief outline of a simulation research study recommended as an initial attack on these problems.

The study reported in this document was directed toward the identification of specific research issues for consideration as candidate projects for investigation in piloted flight simulation facilities at the NASA Ames Research Center. It was conducted under NASA contract NAS 2-4406. The effort was greatly enhanced through the interest and support of the Technical Monitor, Mr. Charles C. Kubokawa of the Man-Machine Integration Branch of the Biotechnology Division at Ames.

INTRODUCTION

One of the principal conclusions of a recent analysis of system concepts and operational problems in the development of an all weather landing capability for advanced SST's (ref. 1) was that the main impediments to the introduction of all weather landing involved operational procedures rather than individual technical problems. The role of the pilot in managing the aircraft was cited as a major source of controversy and it was concluded that methods of using the crew to monitor performance of the automatic equipment and a definition of crew procedures for various failure situations are critical problems which remain to be worked out for low visibility approach and landing operations. A clear statement of the importance of resolving the many outstanding issues with respect to the pilot's role in all weather landing operations is given by Beck in the con-conclusion to a comprehensive overview of crew factor problems in achieving Category II operational goals (ref. 2):

> Beginning with the initiation of a Category II approach, the success of each segment of the flight, as it progresses toward the touchdown and rollout, depends on a compatible pilot/aircraft relationship that can react properly to and take cognizance of each of the multitudinous factors that will be involved in making this approach consistent, reliable, of high quality, and above all operationally safe. In October, 1965 the All-Weather Study Group of the International Federation of Air Line Pilots made the following statement: "It is the Study Group's view that, in the very low minima envisaged, it is no longer possible to compromise and make exceptions to accommodate unique circumstances. The operation is too critical for that. Standardization now becomes essential. If ALL requirements cannot be met, the operation should not take place."

What are some of these outstanding issues and how are they to be resolved? In the study summarized in this document, an attempt was made to explicate some of the more significant problems areas by focusing on the flight management task requirements imposed upon the pilot-in-command during low visibility approach and landing operations. The aim of this study was to translate some of these issues into research questions for investigation in piloted flight simulation facilities available at the NASA Ames Research Center.

NASA research efforts in support of the national supersonic transport program have been directed toward a number of critical development areas. One area of concern is the nature and kind of crew tasks performed in a supersonic transport and the determination of crew workload and subsystem and/or flight deck design requirements. As a direct outgrowth of earlier studies by Serendipity Associates in this area, certain kinds of crew tasks may be identified as being crucial to the safe and economical utilization of the SST. Increasing demands on previously effective human performance dictate increasing applications of mechanical and/or electronic devices to replace or augment man's performance capabilities. Questions regarding the necessary and desirable extent of such applications have always represented lively issues in system development efforts and it is now fashionable to search for "optimal integrations" of man and machine capabilities. Considerable effort has been applied to accomplishing this objective and for certain perceptual and psychomotor tasks such efforts have often been successful. However, in more and more system contexts, excessive demands are increasingly being referred to more exlusively cognitive tasks, often characterized as involving "judgment" or "decision making", and while there is no shortage of attempts to replace or support human performance in this sort of task, successes here have not been notable.

In the context of potential crew roles in SST flight operations, then, a subset of system functions generally referred to as "Flight Management" can be defined, emphasizing such responsibilities as assessing the overall flight situation, judging the significance of particular events, and exercising final authority with respect to how the system is operated, i.e., what actions are taken and when. This type of task is characterized by a man-machine interaction that is primarily cognitive in nature. That is, the relationship of the crew to the aircraft, the ongoing flight situation, and the flight environment is one of information gathering, integration and decision making, rather than one of direct control. In some cases this type of task is a relatively simple one; for example, the flight engineer may monitor a set of subsystem displays in order to detect possible malfunction indications. His response in terms of direct control of any aircraft component is limited to that elicited by a malfunction indication and corresponding remedial control actions specified in established operational procedures. At its most complex, flight management is typified by the kind of crew behavior seen during the approach and landing phase of a flight. In this case, the pilot-in-command is required to scan a wide variety of displays, and respond with indirect or direct control actions. The general concern of the present study was to determine how well this kind of crew activity is supported in projected SST design concepts and operating procedures.

In the first phase of the study, the principal components and design features of the landing system envisioned for the SST were delineated and the distinguishing characteristics of flight management functions were discussed. This material was presented in Volume 1 (ref. 3) together with assumptions regarding crew roles and mechanication concepts for satisfying flight management task requirements during a projected SST approach and landing sequence.

The second phase of the study was directed toward an identification of potential problems in supporting SST command pilots in carrying out flight management responsibilities. The central concern of this phase of the study was to identify potential problems in the performance of flight management tasks during low visibility SST approach and landing operations, considering the projected SST landing system design concepts and operational procedures. The general procedure for identifying these problems entailed an analysis of the cognitive task loading or information processing demands imposed on the pilot-in-command. In the course of this analysis, consideration was also given to more specific crew acceptance and human engineering problems which could be referred to particular aspects of the Captain's role or to system design concepts and features. The results of this analysis are presented, in Volume II of the study (ref. 4), as a discussion of selected flight management tasks which were found to impose unrealistic information processing demands on the Captain or to be especially vulnerable to such factors as time constraints on task performance or limitations in the quality of available information.

In the analysis, the identification of anticipated difficulties, uncertainties, and lack of clear structure in the information processing descriptions of component diagnostic and action decision tasks provided a direct basis for distinguishing inadequately supported flight management activities. Insofar as possible, the specific SST landing system design features, operational procedures, and/or environmental conditions which were suspected to be sources of flight management difficulties were identified in the discussion of potential problems. In the final phase of the study, some of these problems were developed into specific simulation research objectives and submitted to the NASA Ames Research Center for consideration as candidate SST simulation projects.

From the outset, the present study has been directed toward the identification of specific research objectives within this problem area which can be met using the jet transport simulation capabilities at Ames. Accordingly, the final phase of the study was concerned with the selection of problem statements for further empirical study using Ames simulation facilities and with the preparation of detailed recommendations for a simulation study. Volume III of the study (ref. 5) presents the general approach adopted for an investigation of selected flight management problems in the piloted flight simulator and provides a detailed plan for carrying out initial studies.

The complete documentation of the study in the references just cited was intended to support Ames personnel in the set-up and execution of the recommended simulation study. Detailed discussions of the analysis of flight management requirements, the subsequent delineation of potential problem areas, and the materials developed in the simulation study plan were prepared for use within the Center and are not considered to be of interest to the general reader. The purpose of this report is to provide an overview of the analytic procedure employed, to summarize the potential problems in supporting flight management which were distinguished in this analysis, and to provide a summary statement of the simulation study recommended as an initial attack on this problem area. Interested readers may request the more detailed documentation of the study by contacting the NASA Technical Monitor.

OVERVIEW OF THE ANALYTIC PROCEDURE

A fundamental assumption underlying the analysis is that the development of effective means for supporting the performance of flight management tasks must be based upon a clear appreciation of the information processing demands of component cognitive processes. The general intent of the analytic procedure was to identify potential difficulties in crew information processing in such a way as to provide a direct basis for specifying the SST design features crew factors, environmental conditions, operating procedures, etc., which appear to be the source of these difficulties. Products of the analysis should thus serve to identify a number of potential simulation research objectives concerned with an empirical assessment of the hypothesized difficulties and/or with developing and testing solution concepts.

Analysis of Flight Management Task Requirements

Flight management requirements outlined in reference 3 provided the point of departure for the analysis. The general character of flight management functions and their relationship to other SST flight operations control functions is schematized in Figure 1. Note especially that operations control objectives are most directly achieved through the performance of Flight Control and, to a lesser extent, Subsystem Control functions. Flight management functions may thus be construed as "additive", since operations control objectives could be achieved in their absence. The rationale for including flight management functions is to increase the probability of achieving specified objectives and/or of satisfying specified constraints as regards safety, reliability, efficiency, passenger comfort, economy, etc. The general character of flight management functions is further indicated in this schematic in that they are concerned with generating "commands and/or control instructions",

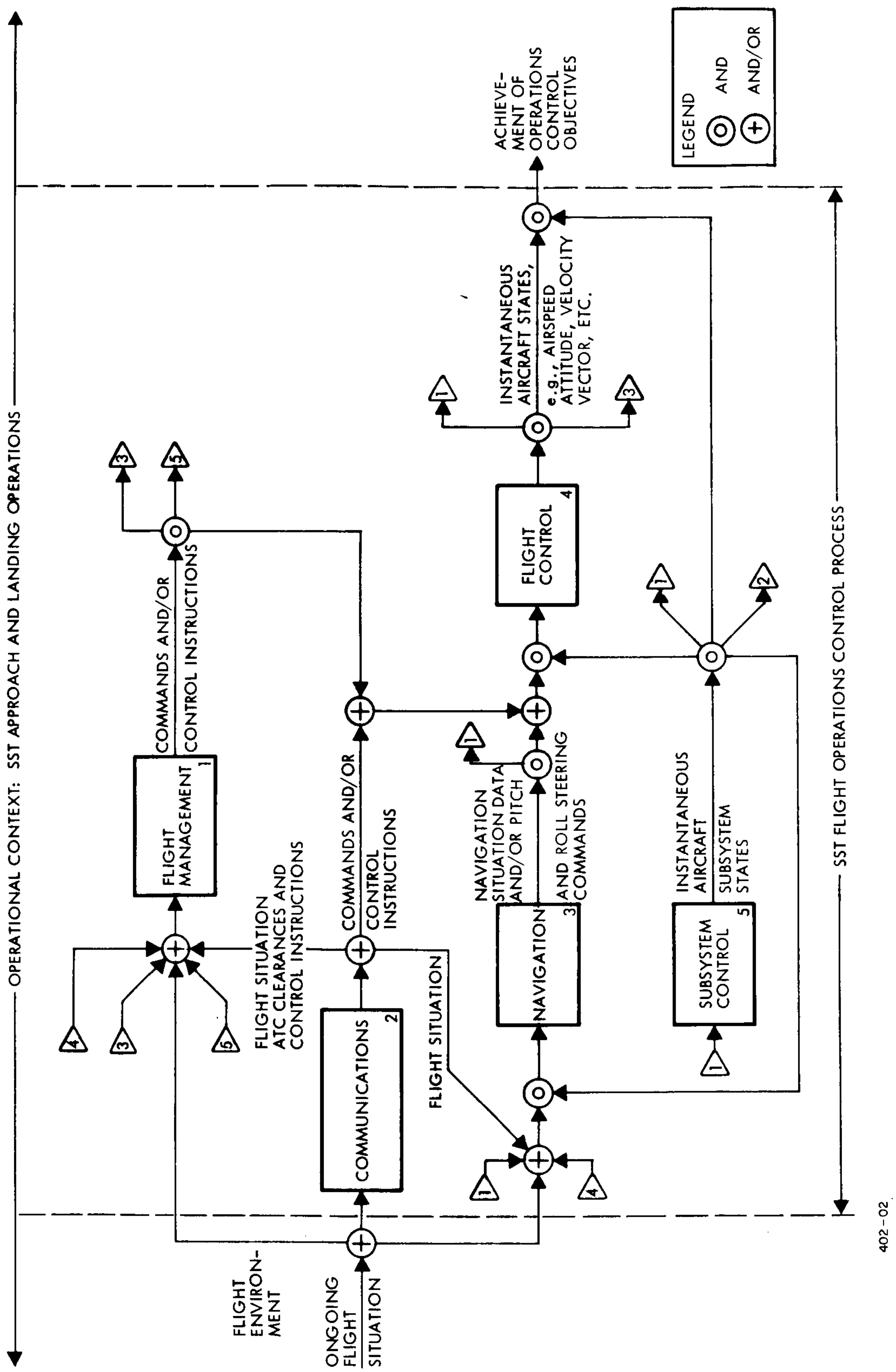

Figure 1. General character of flight management functions as they relate to other SST flight operations control functions.

which can be applied to adjust or direct the implementation of the other operations control functions, and that these outputs are derived from ongoing flight situation data as well as data reflecting aircraft and subsystem states.

Specific flight management requirements are defined in terms of "input" information states, representing actual and/or assigned "values" for aircraft and subsystem states, flight situation parameters, etc., and of "output" information states, representing control actions required, if any, to direct and/or adjust these "values" in accordance with flight management operating criteria. By definition, then, flight management covers all requirements for assessing or diagnosing flight situations, aircraft performance, subsystem operation, and conditions in the flight environment and for formulating and resolving action decision problems which may arise out of these assessments. These requirements may be satisfied by "fully automated" equipment systems or by unaided crew members -- but under more realistic system mechanization concepts they are likely to require a more or less complex integration of crew members (in particular, the pilot-in-command) and equipment (e.g., built-in system performance monitoring and warning systems).

Seven basic flight management functions were distinguished to provide the framework for the derivation of specific crew task requirements during the SST approach and landing sequence. The principal diagnostic and action decision components of each of these functions are outlined below.

Assess and/or Diagnose Flight Progress

The progress of a designated SST flight, from the time it arrives at the altitude or position specified by its clearance for initiating a let-down into the terminal area until it is rolling on the runway at its assigned destination airport, is defined by a closely controlled flight path in both vertical and horizontal dimensions and in respect to arrival times at key control points. Strict adherence to track keeping limits, altitude constraints and airspeed restrictions is a routine matter for scheduled air carrier operations throughout the flight profile, but these demands must be met with the highest degree of precision during approach and landing operations. There is an ongoing flight management requirement to carefully follow the actual condition of the flight with respect to such demands and constraints, to stay far enough ahead of what the airplane is doing to anticipate control requirements, and to apply corrective actions, if necessary, soon enough to preclude significant deviations from the assigned approach and/or clearance instructions.

The key inputs to this function during approach and landing are the assigned enroute course to the terminal entry point, the assigned instrument approach plan, initial and amended letdown, approach and landing clearances, special terminal area maneuvering instructions such as radar vectors and holding requests, ETA's and low approach initiation time assignments, and data reflecting present aircraft position, ATA's at control points, velocity vectors, and flight path projections. Component diagnostic activities are primarily concerned with the continuous determination of present aircraft status on such critical flight path control parameters as cross-track error, along-track error, relative height and rate of descent, flight path alignment with the runway, and time of arrival at critical control points. Assessments of present status against clearance instructions, established approach and landing procedures, safety-of-flight and regulatory considerations, etc., are also ongoing.

Assess and/or Diagnose Aircraft Performance

The major emphasis in the performance of this flight management function is on ensuring that critical flight maneuvers required during approach and landing are executed in accordance with operating techniques appropriate to the handling qualities and performance characteristics of the SST and with constraints derived from such considerations as situation-specific terrain features or weather phenomena (e. g., wind shear), pilot acceptance of maneuvering demands and aircraft response, economic penalties, noise control in the vicinity of the airport, and passenger comfort. Critical flight maneuvers include vertical flight path control during penetration, localizer capture, glide slope capture and stabilization, the landing maneuver from flare initiation to touchdown, and, when necessary, the go-around maneuver.

Basic flight control parameters such as airspeed, vertical speed, attitude and attitude rates, absolute altitude, and velocity vectors are assessed in this function and, again, considerable importance is attached to "staying ahead of the aircraft", i.e., anticipating tendencies for movement in the direction of out-of-tolerance conditions. In addition, the timing of certain control actions (e.g., flare initiation), the response characteristics of the aircraft, and such intangibles as the "feel" of the instantaneous flight situation are carefully appraised. More specific flight management requirements of this type were identified with reference to particular maneuvers and/or flight path control objectives rather than isolated aircraft performance parameters.

Assess and/or Diagnose Operational Conditions

For approach and landing operations under Category II conditions, the focus of this flight management activity is on the accurate prediction of Runway Visual Range (RVR) at the presecribed decision height and on the the severely time-constrained assessment of the adequacy of extra cockpit visual references as the aircraft approaches and attains that point in the landing sequence. There is a concurrent requirement to detect and appraise such other critical conditions as crosswinds, wind shear (velocity gradients), turbulence, and other weather phenomena which may combine to degrade or distort the information available through external visual reference. These assessments are all related to the "see-to-land" requirement inherent in the Category II situation.

Although significant weather phenomena are the principal concerns of this activity, flight management attention must also be directed toward other conditions and events in the flight and ground environments which are essential to the safety and success of the approach and landing. These include spatial and kinematic relationships with other air traffic, terrain features and structures (e.g., towers) affecting navigation tolerances, the operating status and characteristics of available ground navigation and guidance facilities, the availability and status of various landing aids at the destination airport, runway conditions, and so on. Component diagnostic and assessment activities might thus be concerned with a wide range of environmental factors and with determining their impact on the ongoing flight situation and the realization of flight control objectives.

Assess and/or Diagnose Aircraft Subsystem Operation

This general flight management function covers all requirements during approach and landing for determining the on-line configuration and operating mode of airborne equipment systems and components and for monitoring or assessing their performance. Critical equipment components of the landing system, such as the flight director system, the automatic flight control system, flight control and navigation instrumentation and computing equipment, are the chief concern of this function, but attention to other aircraft systems (e.g., electrical, fuel, hydraulic, etc.) is an ongoing requirement and must also be considered.

Provisions for testing the readiness of landing system components, for detecting and isolating malfunctions, for reconfiguring on-line units to preclude interruptions or degradations in operational capability, for generating warning and advisory signals, and for monitoring the occurrence of critical equipment operating states are all examples of overall system features concerned with this management function. Again, the general requirements are to "stay ahead of the airplane" by detecting trends toward out-of-tolerance equipment operation as soon as possible and to achieve required reliability and "fail safe/fail operational" goals when operating limits are exceeded.

Resolve Flight Progress Decisions

Action decision problems in the operational situation are expected to arise out of the performance of one or more of the foregoing assessment/diagnostic functions. With respect to flight progress, these decisions have to do, generally, with the successive determination of whether or not the flight should proceed with the approach as planned and finally with a commitment to initiate the terminal landing maneuver. Decisions to deviate from the established flight plan, to request clearance changes, to abort the approach, to execute a go-around or missed approach procedure indicate the possible outcome of this management function.

A basic element of the approach adopted in the present study is that the formulation and resoltuion of such decision problems is a major variable in the implementation of flight management functions and that this variable should not be prematurely fixed by the adoption of analytically derived models of operational decision problems. The consideration of crew information processing in the development and resolution of decision problems was an important part of the analysis of cognitive task loading in the second phase of the study.

Resolve Non-Routine and Emergency Action Decisions

The general characterization of the preceding function is also applicable here. Decision problems distinguished here have to do with selecting or adopting a particular course of action after it has been determined that a non-routine or emergency condition exists. For the most part, these decision problems will arise out of the assessments or diagnoses of aircraft subsystem operation outlined above. Corrective actions will include decisions to reconfigure on-line systems, modify operating modes, switch-over to backup systems, initiate emergency procedures, request assistance, etc.

It is reasonable to assume that the criticality, safety, and economic considerations associated with decisions of this type will call for a considerable amount of preplanning for such contingencies and for specifying as completely as possible, in advance, the decisions to be taken. In the subsequent analysis of this general flight management function, decision problems which can be clearly anticipated and resolved in accordance with well defined rules or operating policy were screened out where it could reasonably be assumed that these procedures would govern crew performance. Emphasis was thus given to the more complex decision problems or those seen as difficult to resolve in the time available or with the amount and quality of data which is expected to be available to the system.

Record Flight History and Subsystem Status Data

This general function covers all requirements for recording flight path data, selected aircraft performance and configuration parameters, company and FAA specified flight logs, flight deck voice communications, and any special aircraft subsystem performance (e.g., fuel consumption) or operating status data considered useful for maintenance analysis. These data are recorded primarily for post-flight or accident analyses and are not routinely used for in-flight functions. For this reason and the fact that automatic devices requiring little or no crew participation are used for most of the recording functions, no significant crew factor problems were envisioned for this flight management activity. The function was included to assure comprehensiveness and consideration of its relationship to other flight management functions, such as the ongoing concern for recording fuel "how-goes-it" data and the possible use of subsystem performance data recorded enroute in management problems during approach and landing.

The Baseline SST Low Visibility Landing System

The subsequent determination of specific crew task requirements in carrying out these flight management functions was based on the system design features, capabilities, and mechanization concepts adopted to define a baseline low visibility landing system for the SST. Initial development of this baseline system was by necessity largely eclectic, being based upon various sources of varying relability and authority. As data was obtained relative to what was planned or proposed by Boeing for the SST, it seemed more useful to follow their projects whenever possible. Of course, Boeing is also anticipating the desires of the airlines and the requirements and constraints established by the FAA. The specifications developed by Boeing in their Phase III SST proposal ". . . reflects extensive coordination with United States and non-United States airlines and the FAA." (ref. 6).

The baseline system adopted in this study should not be viewed as the system which will be aboard the B-2707. It should be understood as a composite system concept, heavily influenced by available SST proposal data and recent developments in the area of all weather landing systems. A graphic description of the baseline Low Visibility Landing System (LVLS) is given in Figure 2. It should be re-emphasized here that the components which make up the baseline SST LVLS reporesent the state of our knowledge at the time of the study. A number of developmental systems and components, such as the Advanced Instrument Landing System (AILS), head-up displays, "self-contained" systems employing airborne infrared sensor techniques, electronic (CRT) displays, and runway imaging systems were examined in the present study but considered inappropriate for inclusion in the baseline LVLS concept.

Emphasis was placed on defining a system with minimum Category IIIa capability as the initial reference for study. Concepts and techniques under consideration in developmental systems could then be examined as possible

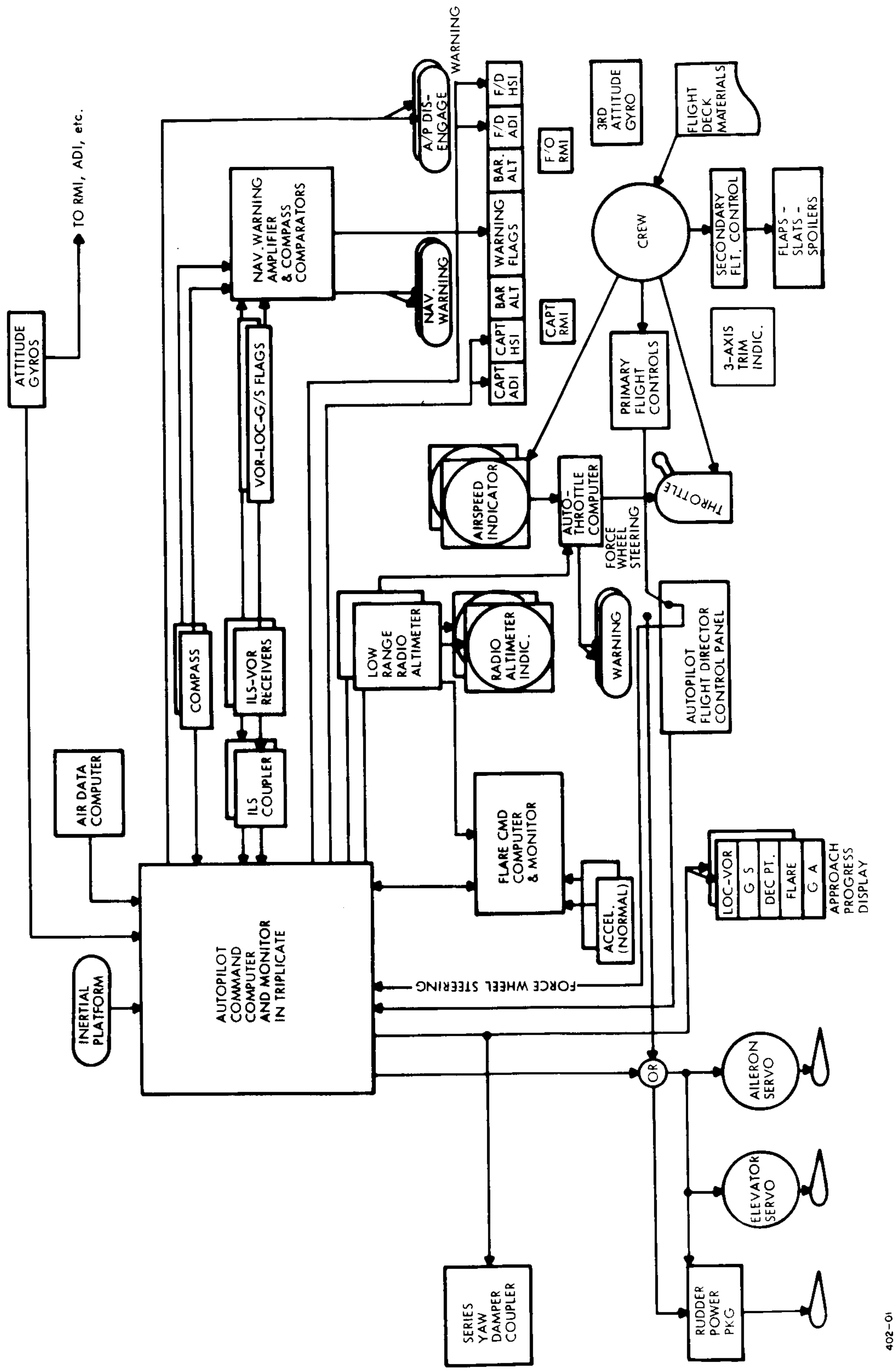

Figure 2. Baseline SST LVLS and associated equipment.

solutions to flight management problem areas disclosed in the present study. While Figure 2 identifies the equipment components chosen to represent the baseline SST LVLS, then, it does not include all of the landing system capabilities which might have been included.

Analysis of Cognitive Task Loading

The first step in the analysis of cognitive task loading was to adopt a generalized information processing schema as a cognitive process model of crew performance in flight management activities. In this schema (see Figure 3), the crew is understood to be in contact with the objects, events, processes, etc., which define the ongoing SST flight situation through either direct perceptual contact or a display system, i.e., all of the visual and auditory displays available to him in the projected SST operational situation. For the purposes of this analysis, it is useful to distinguish three components of the crew information processing task associated with flight management. Of these, the central component, identified in Figure 3 as Diagnosis, was considered to be the key to the subsequent identification and appreciation of information processing task demands.

As indicated, the diagnostic component must generate the "awareness" of certain states of the ongoing SST flight situation which, in turn, initiate the flight management decisions related to the major action alternatives available to the Captain during the approach and landing sequence. Such states are referred to in the information processing schema as "Diagnostic Categories" and in general they are to be understood as perceived or inferred states of the aircraft, its subsystems, or the operating environment which indicate that the SST operations control functions being managed are exceeding flight management tolerance or are tending in that direction.

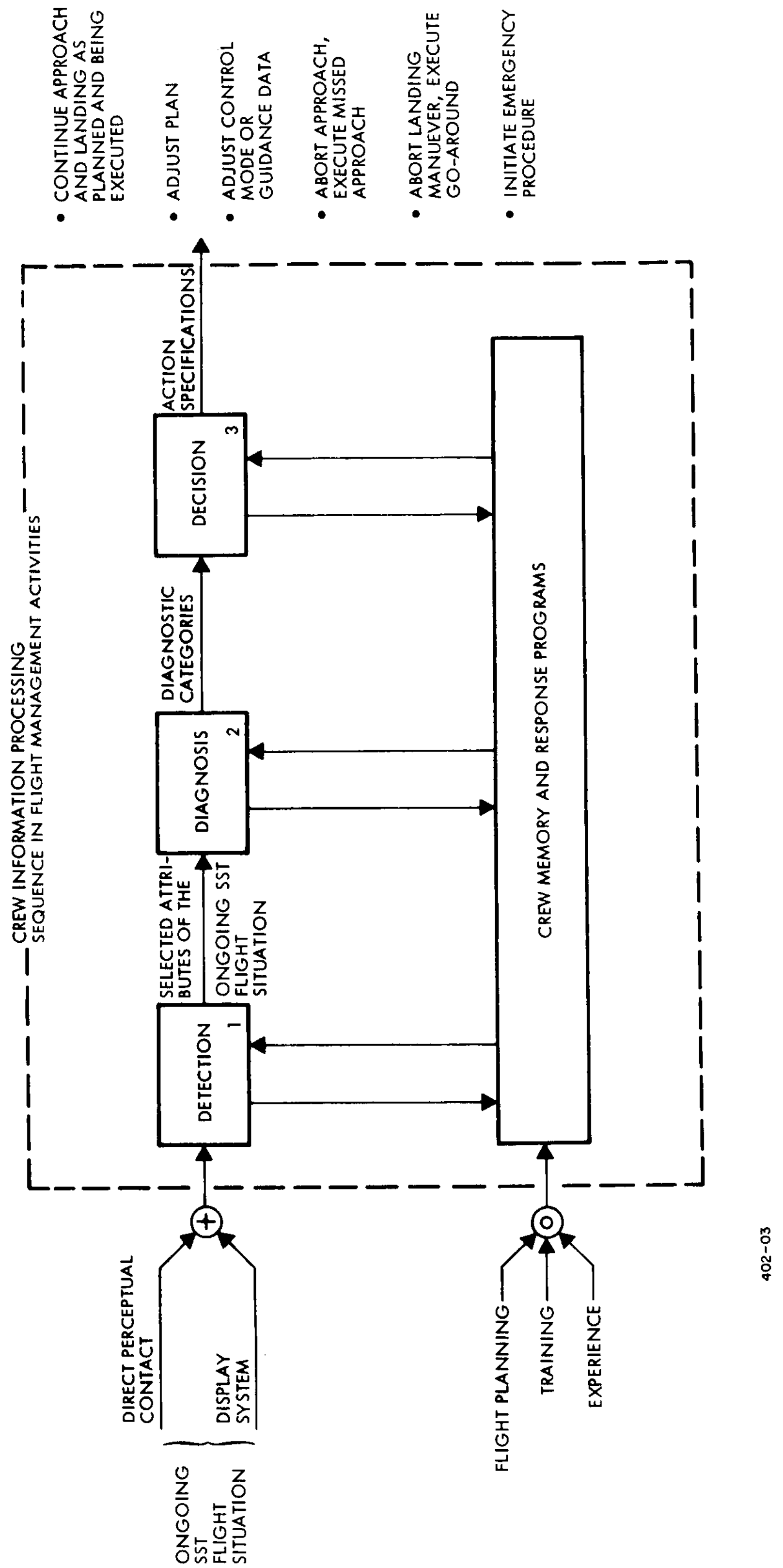

Figure 3. Schematic overview of key cognitive processes in SST flight management activities.

The term "Diagnostic" is used here in the most general sense of resolving any uncertainties which may arise with respect to the identity, character, or significance of selected aspects of the ongoing flight situation. For example, a determination that the speed or rate-of-sink of the aircraft is "excessive" or "increasing too rapidly" would entail diagnostic activity. In the schema adopted, diagnostic activity is understood as a form of "categorizing" of the objects and events which define the flight situation, based on certain defining or criterial attributes, and the outputs of this activity are thus referred to as diagnostic categories.

The key role of diagnostic activities in initiating subsequent action decisions has already been mentioned and it can now be seen that the identifications of diagnostic categories is also the key to establishing requirements for the data input or "Detection" function. Diagnostic categorizations are defined by "criterial values" on designated parameters (attributes) of the ongoing flight situation; relevant inputs to the diagnostic functions are thus derived from a consideration of the parameters and values actually used by the Captain or those he "should" use in exercising "good judgment". The "Detection" function can be understood, then, as a directed monitoring or scanning (data sampling) of the actual flight environment, when direct perceptual contact is possible, and/or of the flight instruments, communications channels, flight deck reference material, etc. which comprise the projected SST crew information environment (display system).

In applying this schema to projected SST flight management requirements, each of the component assessments and decision problems were examined in order to determine the judgments involved, the flight management consequences associated with negative assessments, the immediate bases for the judgments in terms of the information expected to be available to the SST Captain, and the information processing considered necessary to arrive at the judgments. The cognitive process schema just outlined was used to guide this analysis in that judgments were identified by distinguishing the diagnostic categories assumed to underly the major flight management decisions. Information processing demands on the Captain could then be identified by considering the defining or criterial attributes of the flight situation which were expected to determine these categorizations and by an examination of how this information could be derived in the projected SST system.

As the analysis proceeded, potential problems in supporting the Captain in the performance of flight management tasks were noted whenever the following conditions were found to apply to the projected SST operational situation:

1. Significant conditions and events, which must be assessed within very short time spans, are not directly represented in the SST display system.

2. Displays are available from which significant conditions and events can be inferred, but the information processing involved would take too long, be subject to unacceptable error probabilities due to inaccuracies in source data or the low reliability of processing steps, and/or be subject to distortion or bias due to the stress of task conditions.

3. Criterial information, required to assess the significance or character of available information on actual aircraft and environmental states, is not expected to be available.

4. Criterial information is available but not with necessary precision or in the appropriate form for direct application to the assessment task.

5. Concurrent flight management or other operations control tasks may be degraded or attention to them may compromise performance of the primary task.

6. Low or negative pilot acceptance of an information source or task condition can be anticipated.

IDENTIFICATION OF POTENTIAL PROBLEMS IN SUPPORTING THE PERFORMANCE OF FLIGHT MANAGEMENT TASKS

Suspect flight management tasks, i.e., those found to impose unrealistic information processing demands on the Captain or to be especially vulnerable to the effects of time constraints or limitations in the quality of available information, identified in the foregoing analysis are outlined below. Operational procedures or situations which might reduce pilot acceptance of the landing system were also considered in the analysis. For convenience, the problems cited are related to five major flight management activities and are introduced, generally, in the order in which these activities would occur in the approach and landing sequence. An abbreviated discussion of the component flight management task requirements and assumptions regarding the manner in which the task will be performed in the SST is given for each of these activities. Potential problems and a brief recap of the supporting argument are then stated. Reference 4 and additional references given in this section should be consulted by the interested reader for a more complete explication of the problem areas.

Potential Problems in Judging the Success of the Approach

The general concern of this flight management activity is the ongoing judgment of the success of the approach to pre-established minimum altitudes where the landing commitment decision is finally taken. For Category II operations, the minimum approach altitude is 100 feet above the touchdown zone on the established glide path. At this point a missed approach must be initiated if the approach is judged unsuccessful or when certain ground and/or airborne equipment operating requirements cannot be satisfied. For Category III operations, no formal minimum approach altitude has yet been established but it can be assumed that a decision height based on minimum altitude requirements for executing a go-around will be determined. The key requirements to be satisfied in achieving a successful approach are taken as those dealing with the aircraft's position and tracking velocities relative to the entended touchdown area on the runway as the descent to the established decision height proceeds. Discussions of these requirements are frequently expressed in terms of an "approach gate" or "window", defined by lateral and vertical flight path displacement limits, from which a "soft" landing (i.e., a touchdown rate-of-descent of about two feet per second) can be achieved within a tightly defined touchdown area without exceeding autopilot authority limits or imposing excessive demands on pilot skills in manually controlling the aircraft.

Assessing Relative Altitude as the Aircraft Approaches the Authorized Decision Height.

Relative altitude is the present elevation of the aircraft relative to the elevation of the intended touchdown area on the runway. The appraisal of approach success must be completed before the wheels of the aircraft reach a specified relative altitude, i.e., the decision height. As the aircraft approaches the decision height, then, the Captain must monitor and assess relative altitude to ensure that the aircraft does not proceed below the decision height unless the approach is judged successful.

In the projected SST landing system, relative altitude is not directly represented. Dual low-range radio altimeter systems will be available and it is assumed that relative altitude judgments must be derived from several radio altitude displays. Scalar indications of radio altitude, resolvable to about five feet, will be continuously available below 300 feet. Based on information given in approach charts, an index on the radio altimeter can be set to correspond to the relative altitude at the decision height. Below 200 feet, radio altitude is displayed qualitatively on the Attitude Director Indicator (ADI) using a "rising runway" symbol. In addition, arrival at a pilot-selected radio altitude is indicated by both a legend light component of the approach progress display and an auditory signal. Conventional readouts of barometric altitude will also be available and could be used to cross-check or supplement radio altitude information.

The principal difficulty in this assessment is that the absolute altitude indications available from the radio altimeter systems can differ significantly from relative altitude due to irregularities in terrain features along the approach path. As Litchford reported several years ago (ref. 7):

> The pilot wants to know his height above his touchdown, which is some 3300 feet in front of him if he is indeed at 100 feet. But the terrain leading to the approaches of many of our major airports is usually very irregular, and this is becoming more common as runways are extended out over tidal waters and ravines to provide sufficient length for landing jets.

The use of a pre-set relative altitude on the radio altimeter will provide a discrete indication of arrival at the decision height, but false indications are possible when the approach terrain is higher than the runway elevation. The use of currently operational barometric altimeters to supplement or cross-check radio altitude displays does not seem promising. Their use under Category II conditions is considered "basically unsafe" by the ALPA All-Weather Flying Committee (ref. 2) and in FAA tests of various methods for determining the 100 foot point on the glide slope, barometric altimeters were found to be the least accurate technique.

Assessing Flight Path Alignment with the Runway

As indicated earlier, one of the key requirements to be satisfied in a successful approach is that the aircraft's position and velocity vectors at the decision height are such that a "soft" landing within a well-defined touchdown area on the runway can be accomplished without exceeding autopilot authority and/or pilot-defined maneuvering limits. Most analyses of tolerable lateral offset limits suggest that lateral flight path alignment at the 100-foot decision height should be within 50 feet of the runway centerline extended and that velocity vectors (flight path projections) should be parallel or converging with respect to this reference line. Approaching the decision height, the Captain must judge flight path alignment to be within these limits or to be correcting so as to arrive within these limits by the time the decision height is reached.

In the projected landing system, flight path alignment with the runway centerline is not directly represented. The principal basis for judging flight path alignment is assumed to be the expanded localizer deviation indicator. Boeing design goals for localizer tracking during the final approach are to maintain the aircraft within ±20 microamps of the localizer beam, an indicated deviation of about one-quarter dot (ref. 8). As the aircraft closes to the decision height, visual cues will "fade in" and may also be used by the Captain to judge flight path alignment and tracking tendencies. The First Officer will continue to monitor the localizer deviation indicator and report excessive cross-track error and/or divergent tracking tendencies when the aircraft arrives at the decision height.

There are three unresolved issues associated with supporting this flight management requirement:

1. Firm criteria for judging excessive cross-track error at the decision height have not been established for the SST. From

FAA Advisory Circular 120-20 (ref. 9) absolute limits on the horizontal dimensions of the approach gate, at 100 feet, may be set at ±75 feet from the runway centerline (i. e., tracking within the lateral confines of the runway extended, with a standard runway width of 150 feet assumed). However, somewhat stricter limits must be placed on lateral displacement limits when the pilot's ability to correct for a lateral offset condition is considered. British studies of the ability of airline pilots to execute the "sidestep" maneuver, as reported in reference 1, indicate that lateral offsets in excess of a 20% localizer scale deflection (approximately 75 feet and consistent with the FAA limit) were clearly outside the range of acceptable conditions for manual landing success. Limits on this range of acceptable offsets, begin, however, with localizer scale deflections of about 14% or approximately 50 feet from the runway centerline.

The pertinent implications of the foregoing are that an offset limit of ±50 feet may be a more appropriate criterial value for judging excessive cross-track error than the FAA standard of ±75 feet, and, perhaps more important, that criterial values should be based on a determination of offset distances from which pilots can comfortably perform lateral correction maneuvers in the SST. The data just cited were obtained using aircraft representative of conventional subsonic jet transports and should be derived again for the SST. Other analyses (ref. 1) have indicated that an uncorrected landing maneuver, committed on the basis of an indicated 20% localizer deviation, could miss the runway completely and that one committed with only a 10% deviation can result in a touchdown dangerously close to the edge of the runway.

The problem here, then, is that there is currently considerable uncertainty with respect to the degree of lateral offset which should be judged "excessive" by the SST Captain. It is suggested that criterial values for this assessment be established on the basis of demonstrated pilot ability and willingness to manually execute a lateral correction from the decision height.

2. The ILS localizer deviation information used as the primary basis for this assessment, together with basic flight situation instruments such as the heading indicator which may also be used, may not enable pilots to judge cross-track error and tracking tendencies to the required accuracies. An early indication of this potential problem emerged in Phase II of the joint FAA-USAF Pilot Factors Study of control-display concepts applicable to flying the SST under low visibility conditions (ref. 10), as suggested by the following excerpt from the discussion of results (underlining added):

> Control of the Cross-Track Component. The lateral requirements for routine operation inside the middle marker demand more than keeping the aircraft within the center half of the runway. The lateral velocity vector of the aircraft becomes increasingly important to the success of the approach under 200 ft. For a constant approach speed the lateral velocity vector of the aircraft determines the direction and speed that it moves with respect to the runway centerline. As a consequence the cross-track component of the aircraft's lateral velocity vector must be maintained within tolerances about zero so that the aircraft will be moving parallel to the runway centerline upon breakout or, in the case of a touchdown on instruments, straight down the runway for roll-out. Certainly, there are trade-offs involved between displacement and the cross-track rate component. But in any event, there is no question but that both parameters must be controlled for successful operation inside the middle marker.

> Localizer deviation showed that the standard flight director displays presented control information which was adequate with respect to lateral displacement inside the middle marker. However, the standard flight director configuration apparently did not provide the proper type of information to the pilot for maintaining the cross-track component of the aircraft's lateral velocity vector within tolerances. Indicative of this inadequacy was the finding that 12% of the coupled touchdowns, 16% of the semi-automatic touchdowns, and 32% of the manual touchdowns had a cross-track component of a magnitude that precluded a safe roll-out. A number of times, the hooded subject pilots expressed surprise upon a quick take-over at touchdown that such a cross-track component existed. Everything "looked good" on the panel.

In the projected SST landing system, the integration of an expanded scale localizer deviation indicator into the ADI may improve the pilot's ability to estimate offset distance and cross-track velocities, but this possibility should be confirmed. Even with such display improvements, however, difficulties in assessing actual lateral offset and tracking tendencies remain due to localizer beam characteristics and the information processing required to translate indicated localizer deflections to offset distances in feet. In order to determine actual offset distance, the Captain would require relative transmitter distance information, which will not be available, and would have to recall a complex conversion table for translating qualitative beam deviation indications into microamp displacements and then into offset distance in feet. It is, of course, unreasonable to assume that such data processing will occur. It is likely that deviation indications on the order of one-quarter dot or less will be accepted as providing adequate runway alignment until, under Category II conditions, track alignment and tracking can be confirmed by external visual reference.

3. It is questionable whether pilots can accurately estimate lateral offset and tracking vectors using external visual cues. This question is applicable to an approach under Category II conditions

wherein the Captain attempts to assess flight path alignment and tracking relative to the runway by reference to visual cues emerging in the extremely limited time period just prior to arrival at the decision height. It should be noted that the approach success judgment can be made solely on the basis of instrument reference and visual confirmation may not be necessary. However, it will be recalled that the Captain is assumed to be "head up" at this point in the approach in order to assess the adequacy of external visual reference for the landing and it is further assumed that the compelling character of even fragmentary visual cues is such that they will influence his final judgment regarding flight path alignment. The potential problem here is that information available from these visual cues may prove to be a highly unreliable basis for judging flight path alignment, and, further, that the severe time constraints on resolving the judgment, together with psychological factors which can be expected to bias the judgment in favor of a positive assessment, will increase the already high error probability in this component of the approach success decision.

From British studies of low visibility conditions (ref. 11), it can be concluded that there is a high probability of achieving visual contact and a 500-foot visual segment prior to reaching the 100-foot decision height, with contact occurring in most instances (70%) at altitudes between 200 and 300 feet. These data suggest that the total elapsed time from the first "fade in" of visual cues to arrival at the Category II decision height will be on the order of 10 to 15 seconds, assuming a nominal rate of descent of about 12 feet per second. During this time interval, which must be reduced to allow the pilot to transition from near-field to far-field viewing conditions and to acquire and recognize usable visual cues, the Captain must also assess his vertical situation and the adequacy of visual conditions for completing the landing maneuver under manual control. It is anticipated, then, that pilots may experience considerable difficulty in extracting timely and accurate indicators of flight path alignment from visual cues expected to be available in Category II conditions.

Assessing Vertical Flight Path Alignment

The second major component of the approach success judgment is the determination that the aircraft's relative altitude (see above), vertical flight path angle, airspeed, and rate of descent are within appropriate limits for effecting a landing within the "touchdown zone". The touchdown zone is defined by the FAA (ref. 9) as the first 3000 feet of runway, beginning at the threshold, and in specifying Category II operating requirements this agency requires that a missed approach be initiated when a touchdown cannot be accomplished within this area. Somewhat more stringent constraints on the desired touchdown point have been suggested by other interested agencies. The Air Transport Association, in a proposed Advisory Circular to the FAA on Automatic Landing System Standards, dated 14 December 1966, calls for longitudinal touchdown dispersion limits of -300 feet to +1000 feet from a line on the runway which is the intersection of the linear extension of the glide slope with the runway. As an indication of preferred touchdown areas in current operations, the mean touchdown point of 1510 feet obtained in an FAA study of hundreds of jet landings by experienced pilots under visual conditions may be cited (ref. 12).

In the projected SST landing system, the principal basis for making this judgment will be the glide slope deviation indicator and the direct readouts of airspeed, radio altitude, and vertical speed. Problems associated with the use of radio altitude displays for determining relative altitude have already been discussed. No direct representation of vertical flight path angle is available and no problems are anticipated in monitoring airspeed and vertical speed. The potential problem associated with the use of these instruments to assess the vertical situation approaching the decision height is that the information provided may not allow the Captain to determine that his touchdown will occur within acceptable limits. In an analysis of touchdown dispersion outlined by Osder (ref. 1), it was shown that touchdowns can occur well beyond the 3000-foot touchdown zone even when the instruments accurately reflect the fact that the aircraft is precisely on the glide slope, maintaining appropriate airspeed and vertical velocity, and at the appropriate relative altitude as the aircraft arrives at the decision height.

This basic problem is well documented in the literature on proposed Category II landing systems employing existing ILS installations and it is generally conceded that lower minima touchdowns will occur at a considerable distance down range of the glide slope intersection point. Lower minima flareout trajectories start tangent to the glide slope and thereafter always remain above it. Data reported by Litchford (ref. 7) indicates that glide slope intersection points range from about 700 feet to more than 1500 feet past the runway threshold. When it is recalled that flare initiation will occur at 75 feet in the SST, rather than the 50 feet used in Osder's analysis, the present concern for the Captain's ability to assure a touchdown within the touchdown zone can be appreciated. Pilots, of course, are concerned about stopping distances and prefer to touchdown much closer to the runway threshold, especially under low visibility conditions. In Category I conditions, this has been accomplished by performing a "duck under" maneuver as soon as adequate visual reference is achieved and prior to initiating the flare. As many writers have pointed out (refs. 1 , 2 , and 7), this maneuver cannot be tolerated under Category II conditions due to the rapid increase in sink rate that would occur close to the ground.

Potential Problems in Resolving the Landing Commitment Decision

In the present analysis, it is convenient to distinguish the landing commitment decision from the low approach commitment decision and assessment of approach success which were considered earlier. For operations in marginal weather conditions, the notion of proceeding with an approach to a pre-established decision point prior to finally committing the aircraft to the landing maneuver is deeply ingrained in pilots. The pilot's requirement to approach only as close to the ground as his confidence in the system warrants and "have a look" before committing himself to the landing is, of course, explicitly provided for in the Category II situation. And, although no specific "decision height" has been established, the Category IIIa situation (700 feet RVR) is widely regarded as a "see-to-land" condition at least with respect to last-second assessments of flight path alignment and touchdown attitude.

With the exception of full Category III conditions, then, considerable emphasis is given to a final assessment of the flight situation by reference to external visual cues in resolving the landing commitment decision. Under Category II conditions, and assuming a positive assessment of the approach, the decision to land is taken only when external visual reference is considered adequate for executing a safe and comfortable landing maneuver under manual control. Under Category IIIa conditions, the landing commitment decision prior to initiating the landing maneuver is necessarily made by instrument reference and is thus indistinguishable from the approach success judgment. However, as visual cues emerge during the landing maneuver, they are expected to become a compelling influence on the ultimate decision to continue the maneuver or abort the landing and execute a go-around (as opposed to a missed approach) even when controlled runway contact cannot be averted.

Problems associated with resolving the landing commitment decision are all related to the task of assessing the adequacy of external visual reference for assuming manual control and completing the landing maneuver. Three of these problems were distinguished in the analysis, as outlined below.

1. In specifying operating limitations for Category II operations, the FAA (ref. 9) clearly requires that a missed approach be initiated when ". . . the pilot, upon reaching the authorized decision height, has not established adequate visual reference . . ." Thus, there is a formal requirement for the Captain to make this determination, but as yet no further specification of what a pilot must or should see at the decision height to assure adequate visual reference has been developed, i.e., there are no criteria to guide the Captain in making this assessment.

   There is, of course, a considerable amount of opinion on this issue and some of it is supported by data. British studies of vertical flight path control by visual reference (ref.13) suggest the often quoted requirement for seeing both the runway threshold and a flight path aiming point beyong the threshold. Unfortunately, when reported RVR is 1200 feet, it is unlikely that the pilot will be able to see his aiming point and there is some uncertainty regarding his ability to see the threshold. On a glide slope of three degrees with an RVR of 1200 feet, it has been estimated that the pilot's eye would have to be as low as 70 feet in order to see as far as the point on the ground to which his aircraft is heading. And, with respect to the threshold, the ALPA All-Weather Flying Committee is convinced, according to Beck (ref. 14), that if 1200 feet RVR is being reported on the ground a pilot should be able to see the final segment of the approach lights and the green threshold lights. Based on observations in the fog chamber at Berkeley, however, they concluded that unless the pilot has been "head up" for some time prior to arrival at the decision height, completely adjusted to long range vision, and accurately directing his line of sight toward the runway threshold, he will not see the green threshold lights.

The problem of developing criterial information for assessing the adequacy of external visual reference for the landing is complicated by the fact that a satisfactory determination of the visual cues used in controlling the landing maneuver, even under VFR conditions, has never been accomplished.

2. It has been widely reported on the basis of flight tests under low visibility conditions that when slant visual range is less than about 1600 feet, visual cues used to assess the flight situation often "fade in" rather than emerging suddenly and clearly as they might in the "break out" phenomena associated with higher minima operations and on training flights when a hood is removed at minimum altitudes. Studies of weather phenomena producing Category II visibility conditions indicate that a number of potentially misleading visual effects may be encountered and there is serious concern for the impact of these effects on human judgment, particularly with respect to assessing the vertical flight situation.

In some instances the pilot will be able to see only a limited, roughly conical-shaped region in front of him. This situation is often cited as the basis for the observed tendency of pilots, under Category I conditions, to execute the "duck under" maneuver cited earlier. The fact that the pilot will continue on the glide slope to lower altitudes under Category II conditions before acquiring visual cues will intensify this problem, since an even greater discrepancy can be expected between what the pilot sees and what he expects to see on the basis of extensive past experience in approaching the runway under higher minima conditions. Assuming present glide slope intersections with the runway, an on-glide slope approach will result in a vertical flight path which crosses the runway threshold at about 50 feet. VFR approach paths typically cross the threshold at about 20 feet as a result of the pilot's effort to touchdown within the first 1000 feet of the runway. On "breaking out" or "fading in" to visual conditions from an on-glide slope approach, then, the Captain could find himself up to twice as high as he normally approaches under better visibility conditions. In view of the marked differences that can occur in the geometric relationships of the pilot's visual field as a function of relative eye position and line of sight, considerable disagreement may be expected in this situation between what the Captain "sees" and his perceptual expectancies.

3. As the aircraft approaches the decision height, the Captain must continue to assess the flight path and velocity vectors against approach success criteria and at the same time evaluate the external visual field for controlling the landing maneuver. Both of these assessments must be resolved before the aircraft leaves the "decision region". This segment of the approach is defined by the FAA as ". . . the region between the middle marker and the 100-foot point where the pilot must decide to either continue his approach or execute a go-around." In the present analysis, the position is taken that ultimate responsibility for the performance of these and other flight

management tasks can only be assumed by the pilot-in-command. This position has been expressed by Beck (ref. 14) as follows:

> When the airplane starts down the glide slope, the next assumption must be that the Captain will manage the approach, that any allocation of crew duties will be such that there will be no abrogation of the prerogative of command, and that he, this Captain, will make the decision as to whether the approach is to be continued or a go-around executed.

Potential problems in retaining full command prerogatives are in large measure dependent upon the procedures adopted by the Captain in obtaining the necessary information for this decision. Freed of the demands of continuous manual flight path control by the automatic pilot, the Captain may elect to divide his attention between the flight instruments and external visual reference as soon as fragmentary visual cues become available. The penalty for this procedure is the well-documented information gap of two or more seconds which is estimated to occur whenever the pilot transfers his sight from instruments to the external visual field. The time required to fully transition from instruments to visual reference can vary from a fraction of a second to intervals of 8 to 12 seconds (ref. 15) and even if this transition were completed, cross-checking of flight instruments would still be necessary for assessing approach success.

Information gaps of this sort are clearly unacceptable during the critical time period while the aircraft is in the decision region and crew procedures have been adopted to assure continuous monitoring and delegation of control authority. Since these procedures require the Captain to rely on the First Officer to perform critical assessments of aircraft performance and/or the flight situation, their adoption can be expected to entail some "abrogation of the prerogative of command" and thus potential acceptance problems.

Potential Problems in Assessing the Initiation and Execution of the Landing Maneuver

The landing maneuver begins with the initiation of the flare. The objectives of this maneuver are to maintain flight path alignment with the runway, reduce sink rate to about two feet per second at touchdown, maintain wings level and establish a landing pitch attitude of approximately seven degrees, and to contact the runway within the touchdown zone with the longitudinal velocity vector aligned with the runway centerline. The overall flight management requirements associated with this activity is to assess whether these control objectives are or will be met and thereby decide whether to take corrective action, and/or continue with the landing or abort the maneuver. The analysis of system performance during the initiation and execution of the landing maneuver revealed the potential inadequacies in supporting flight management.

Assessing Flight Path Alignment During a Category IIIa Landing Maneuver

The flight management task requirement here is to determine that the aircraft is tracking so as to touchdown near the runway centerline and the judgment involved is similar to the earlier discussion of assessing flight path alignment at the Category II decision height. The following discussion questions the pilot's ability to reliably assess runway alignment on the basis of either visual cues or flight instruments during the landing. Under Category IIIa conditions, aircraft performance monitoring will continue to require reference to cockpit instrumentation, though visual cues will be appearing outside. As already indicated, such cues are extremely compelling as they appear to directly represent the aircraft position relative to the ground. Any disparity between perceptual expectancies and observed visual patterns is likely to induce anxiety and possibly, disorientation. Fog, smoke, and haze tend to make objects appear to be farther away, and severely limit or eliminate rate of motion cues (ref. 16). In addition, a crab angle may be established or increased after one of the pilots begins to look outside and this could also produce an unexpected visual pattern. Crab angle changes as great as 17 degrees were experienced in Caravelle flight tests between glide slope capture and 100 feet (ref. 17).

The detection of rate and direction of movement under low visibility is also questionable. To do so accurately requires that the pilot observe one bank of lights approximately normal to his view and then see another bank a short time later (ref. 2). For example, touchdown zone lights in successive parallel banks would be seen as horizontally displaced if the aircraft has a cross-track velocity. The time duration between the first and second sightings and the degree of displacement provides the rate cues. The flight management problem here is due to the possible ambiguity between emerging visual cues which are largely devoid of rate information, and, the situation represented by instrument indications. The Captain may be reluctant to accept the First Officer's assessment based upon instruments but will be unable to verify them using the marginal visual information which is expected to be available.

Assessing the Flare

The purpose of the flare is to reduce the rate of descent from a nominal 12 feet per second to about two feet per second. This is accomplished in the SST by reducing power and increasing pitch smoothly by one or two degrees.

The optimum flare path is not directly represented. It has been shown that variability in glide slope impact points at different airports (ref. 6) will not allow the pilot and/or auto coupler to execute the same approach and flare even though the same glide slope angle is employed. The external view will vary accordingly and compromise the ability of the pilot to assess the landing maneuver on the basis of external cues. In addition, the absence of pitch cues under low visibility does not allow the Captain to assess whether the flare is progressing properly. In this connection, studies indicate that: (1) when flying into gradually thicknening fog the pilot looking out feels he is climbing and may compensate by descending too low, and (2) a slight bank may cause the pilot to think he is higher than he is (ref. 18).

Under Category IIIa conditions, visual cues are considered inadequate to assess pitch attitude changes during the flare. The pilot apparently needs to see both an initial aiming point and the touchdown point in order to assess the flare on the basis of visual cues. The only means by which the pilot can anticipate the flare using instruments is to monitor the radio altimeter reading as it approaches 75 feet. At that altitude the approach progress annunciator illuminates "green" and the flare is programmed to begin. An additional problem here is that lag in aircraft response may momentarily create doubt and anxiety that the flare actually has been initiated. Auto throttles will begin to retard and sink rate should reduce after a few seconds and assure the pilot that the aircraft is executing the flare. But a few seconds may be too late to recover. At Toulouse, after some 500 automatic landings, a failure occurred in the auto flare and even though the pilot took control he could not avoid an extremely hard contact (ref. 17).

In assessing the flare, then, the head down pilot may have difficulty detecting the small change in pitch (one or two degrees) associated with flare initiation. At the same time, the head up pilot may feel that this pitch change is excessive due to concomitant though unrelated changes in visual conditions, e.g., flying into a dense patch of fog. Thus the problem of resolving information discrepancy without adequate support is again introduced.

Assessing the Adequacy of Visual Cues for Manual Control of Rollout

When the aircraft touches down on the main landing gear, the flight deck will be 20 to 30 feet high and another five second will elapse prior to nosewheel touchdown. Uncorrected crab or lateral velocity may cause the aircraft to veer upon touchdown and the pilot must be ready to apply a correction and keep the aircraft tracking along the runway centerline. The flight management task requirement here is to assess the visibility conditions sometime prior to or at the point of touchdown as to their adequacy for rollout guidance. The Captain must determine that visibility is adequate for rollout control soon enough to safely abort the landing if it is not.

The Captain will have received RVR information prior to this point in the approach but the ultimate criterion for what constitutes adequate visual conditions is obtained by looking out the windscreen. A reported RVR of 700 feet is no assurance to the Captain that visual cues are adequate for a safe rollout since the existance of dense fog patches could result in a temporary disappearance of visual cues and loss of control even though reported RVR is equal to or greater than 700 feet. Exactly what RVR value relfects visual conditions which are adequate for rollout guidance is apparently unresolved. Fog chamber studies indicate that 1200 feet RVR is adequate to control rollout with 50 foot spacing of 5000 candlepower centerline lights (ref. 2). But for lower minimums there is still some question. In discussing rollout and taxi guidance requirements, B. L. E. U. (ref. 19) has concluded that:

> As runway visual range drops below 250 yards the visual guidance provided by runway markings by day and center-line lighting by night becomes insufficient for the pilot to perform safe visual rollout.

Assessing the Touchdown

The problem associated with this assessment is that the Captain may not be able to accurately and reliably estimate his touchdown point soon enough to execute a safe go-around if this assessment is negative. Under Category II minimums the Captain should be able to visually assess that the landing will be within the touchdown zone prior to arrival over the threshold. However, with an RVR of 700 feet and the aircraft using up runway at a rate of 200 feet per second, the pilot has only a few seconds to determine where his touchdown will occur. An accurate determination of touchdown point under Category III conditions may not be possible urtil contact with the runway is unavoidable. In the Category II situation, the Captain will assume manual control of the aircraft at the decision height and proceed by visual reference. Under Category IIIa conditions he will be looking out prior to touchdown. On the basis of aircraft instrumentation reflecting aircraft performance or subsystem operation, then, the First Officer may conclude that a go-around should be initiated. Depending upon pre-arranged procedures, the First Officer would either announce any out-of-tolerance condition to the Captain or he might immediately initiate a go-around. Time constraints would probably not allow the Captain to receive the information, confirm it and then take whatever action he deems appropriate, e.g., continue, take manual control or execute a go-around. However, the Captain may be reluctant to permit the First Officer to make the go-around decision.

Once go-around has been initiated, execution of the maneuver under automatic control must be assessed using flight instruments. The first few seconds of the operation would be monitored by the First Officer, since the Captain would have to readjust to instrument viewing conditions. If the First Officer believes the maneuver is not being performed properly he might override the autopilot using control wheel steering. It is considered doubtful that Captains will accept this exercise of control prerogative by the First Officer under such circumstances.

Potential Problems in Assessing the Initiation and Execution of the Go-around or Landing Abort Maneuver

The go-around maneuver is a safety valve operation. It is initiated anytime during the approach and landing that the assessments being performed by the Captain indicate that safety would be compromised were he to continue with the landing. In the proposed SST landing system, when the go-around button is depressed and throttles are manually advanced, the autopilot will follow a pitch control program designed to minimize altitude loss and establish a safe climb angle. Considerable controversy appears in discussions of the missed approach maneuver. The issues around which the controversy revolves include the minimum altitude at which a go-around can be safely initiated and the Captain's acceptance of procedures under which the First Officer would make the go-around decision or where control authority is delegated to the First Officer.

With respect to the first issue, NASA simulation studies show altitude losses up to 70 feet on go-around in jet transport aircraft (ref. 20). Boeing estimates for the SST show a maximum loss of 45 feet on go-around (ref. 21). On the other hand, flight experience with the Lear Siegler/SUD system in the Caravelle (ref. 17) indicates ". . . that a safe go-around can be made from any altitude – even down to touchdown." The issue here is that the minimum altitude at which a go-around can be safely executed in the SST has yet to be established. Computations based upon approach speed, aircraft configuration and gross weight must be performed to establish a minimum go-around decision height.

Regarding the second issue, it is considered questionable whether Captains will accept any operational procedure that precludes their being able to immediately assess execution of the go-around using flight instruments or that requires them to rely upon a decision to go-around made by the First Officer.

Potential Problems in Assessing Equipment Operating Status and Resolving Override, Reconfiguration and/or Disengagement Decisions

No requirement is more heavily stressed in current efforts to develop an effective low visibility landing system than the demand for ultra-reliable equipment operation in all subsystems which are essential to the success and safety of the landing. To satisfy safety and legal requirements, the Captain must have continuous assurance that certain system components are operating properly and that possible failures will not have catastrophic consequences. Despite the considerable attention given to this issue, the role of the pilot in fault detection and isolation and in resolving decisions regarding override control and/or disengagement of automatic systems is still largely unresolved.

The requirement for automatic fault detection and isolation capability is widely recognized, though much concern remains in regard to the possible interference of such systems with the operation of the systems being monitored and to the possibilities for nuisance warnings or false alarms. The extent to which these systems should be tied-in to an automatic switch-over to redundant control systems and provisions required for various degrees of pilot intervention are more controversial issues. Even in the United Kingdom's position, however, where no reliance is placed on pilot capabilities for fault detection or corrective action in achieving "failure survival" goals below the minimum decision altitude, an active monitoring role for the pilot is still acknowledged (ref. 22).

There are two principal unresolved issues in supporting the Captain in assessing equipment operating status and determining what action to take when malfunctions occur. The first questions the Captain's ability to detect significant conditions and events within the severe time constraints imposed on this task, even when sophisticated monitoring techniques and warning display systems are assumed to be available. His ability to select and implement an effective corrective action without incurring excessive risks is questioned in the second issue.

Assessing Equipment Operating Status

The proposed SST landing system can be characterized as a "fail operational" system. The principal component, the Automatic Flight Control System (AFCS), is comprised of an autopilot equipped with three integrated autopilot/flight director pitch-roll computers, an autothrottle, a continuously operating Stability Augmentation System (SAS), and an angle-of-attck warning and control system (ref. 21). A triple redundant, fail-operational capability is thus provided for initial autopilot failures with a fail-passive capability for a second failure. Dual redundancy is employed in the autothrottle system to provide only a fail-passive capability. A complete display of AFCS operating status is also proposed. When the first failure occurs, status lights associated with mode selector control for each autopilot axis will indicate trouble in either the servos or the electronics for the designated channel. In addition, the pilot will be informed of this condition by a warning annunciator and the flashing of a master warning indicator on a system warning annunciator panel. An improved flight director system and flight instrument monitoring system is also expected to be available in the SST.

The problem here is that even with the considerable effort being made to improve the timeliness and comprehensiveness of critical fault detection and to promptly and clearly display the results of this monitoring to the pilot, the number of parameters which must be monitored and the information processing required to assess the significance of indicated conditions may combine to overload the Captain. Human operators have been shown to be versatile and effective monitors but only where the number of parameters to be monitored are few and if the monitoring task is of short duration. The severe compression of time available for detection, interpretation and assessment of indicated conditions as the approach and landing proceeds, and the comparatively greater demands of concurrent flight progress and aircraft performance monitoring must also be considered. Detection probabilities for critical system malfunctions under these conditions should be determined empirically.

Resolving Override Control, Reconfiguration and Disengagement Decisions

Various combinations of visibility conditions, equipment operating states, and the actual time of occurrence of significant state changes (e. g., malfunctions) can interact to produce a complex set of action alternatives which must be considered by the Captain in attempting to satisfy safety-of-flight and legal constraints. It is reasonable to assume that as operational experience in low visibility operations is gained and crew training programs are developed and refined, clear and simple decision rules can be formulated to reduce the many contingencies and complexities in action alternatives available to the Captain to a manageable operational procedure.

The problem here stems from the fact that a nearly instantaneous response to a potentially complex set of circumstances will be demanded of the Captain. His ability to match the right action alternative to the situation encountered should be examined. Certain combinations of weather conditions and system operating status may occur only very rarely in actual operations, but it is important to determine the Captain's response capability for low probability events to establish boundaries, if any, on the pilot's ability to intervene.

Unresolved issues in this problem area include time limits on exercising override control options (e. g., through control wheel steering), time required to confirm indicated failures and reconfigure the system (e. g., select alternate systems or operating modes), absolute altitude limits on assuming manual control, and time required for pilots to enter various control loops and to stabilize out-of-tolerance control parameters.

For Category III operations, it is important to determine the risks involved in attempting to assume manual control and complete the landing and touchdown solely by instrument reference. Data on these issues would provide Captains with criteria for deciding when and how to enter various control loops.

RECOMMENDATIONS FOR A SIMULATOR STUDY OF SELECTED FLIGHT MANAGEMENT SUPPORT PROBLEMS

Insofar as support for flight management activities is concerned, each of the problem areas outlined in the foregoing section represents a possible inadequacy in the SST landing system design features and/or operational procedures assumed as the reference system in the analysis. To the extent that comparable system design features and procedures are also characteristic of low visibility landing systems under development or currently being certified for other jet transports, including operational subsonic aircraft, these problem statements are also applicable outside of the SST context. Despite active and increasingly extensive research and development programs in support of low visibility landing systems, the issues raised in these problem statements remain largely unresolved.

In the third phase of the present study, an ongoing simulation research program designed to provide an empirical assessment of suspect system design features and procedures and, subsequently, to develop and test solution concepts for empirically verified problem areas was recommended. The long term objectives of this program would be to obtain empirical confirmation or disconfirmation of each of the problem statements, to isolate the specific system design features and/or procedures which appear to be the source of these problems, and to identify and test desired changes and/or new developments in system design and operating techniques.

As an initial effort in setting up this program, a piloted flight simulator study of selected problem statements was recommended. The limited scope and objectives of this initial study will allow for the gradual development of the simulation equipment capability and techniques which are peculiar to the assessment of flight management task performance and, at the same time, provide data on the selected issues. Both of these products are needed to guide the design and implementation of subsequent studies. A summary statement of the selected problems, initial study objectives, and the recommended plan for the conduct of the study is given in this section.

Problems Selected for Initial Study

Two major considerations influenced the selection of problem areas for initial investigation in the recommended simulation program. First, it was decided that problems peculiar to Category II operating conditions, and preferably those applicable to current subsonic jet transport operations as well as to the SST, were to be considered early in the program. A number of system configurations have already been certified for Category II operations and data on potential operating problems, if any, should be made available as soon as possible if it can be expected to affect the development and use of these systems. Further, these developments can be expected to be a significant factor in the subsequent derivation of Catetory III system design concepts and operating criteria which are not yet formally specified.

The second consideration is that it is desirable, for initial investigations, to select problems which can be examined without imposing extensive demands on simulation equipment capability. At the time of this writing, full capability for simulating all SST crew stations and all of the flight deck instrumentation, external visual effects, environmental conditions, etc., which may affect flight management were not available in Ames simulation facilities. This is understandable, since comprehensive requirements for simulation studies in this area have not previously been defined. Beginning with the recommended initial studies, however, the additional capabilities required can be built up as they are needed and this development can be guided by experiences gained with the more austere facilities.

These general constraints were satisfied by selecting potential flight management problems associated with judging approach success as the focus of initial study efforts. In the baseline low visibility landing system, suspect components of this flight management activity are performed, primarily, by reference to conventional flight instruments. Representation of SST-peculiar aircraft dynamics and flight deck design concepts in the simulation is, of course, desirable, but is not considered essential to the derivation of useful data in the simulation study. The results of the initial study could therefore be applicable to Category II operations and to appropriately equipped subsonic jet transports as well as to the baseline SST system. At the same time, minimum demands would be imposed on the simulation facility, since no complex display of extra-cockpit visual cues is required and no advanced display concepts need be represented in initial simulation sequences.

The general objective of the initial study will be to exercise subject-pilots in the performance of approach assessment tasks, under nominal Category II operating conditions, and to determine how well they are supported in the performance of these tasks by the SST information availability and display characteristics assumed for the baseline low visibility landing system. Suspect approach assessment tasks include the assessment of relative altitude, flight path alignment with the runway, and vertical flight path alignment as the aircraft approaches the Category II decision height. Summary statements of related problems were given on pages 24, 26 , and 31 of this report. The initial study is also designed to explore some of the factors which are expected to affect the performance of approach success judgments and to determine the effects of these factors on the accuracy, reliability, and/or timeliness of component assessment tasks. A more complete discussion of the objectives of the initial study and the approach to be taken is given below.

Study Objectives and General Plan of Attack

The principal objective of the recommended simulation study is to determine the accuracy, timeliness, and reliability of component judgments of approach success during a dynamic simulation of the Category II approach and landing sequence. During these simulated flight sequences, it will be of critical importance to control the subject-pilot's orientation toward task performance, the information available to him for assessing the ongoing flight situation, and manner in which this information is displayed. The general intent of these controls is to ensure that the information processing demands of the experimental task do not differ in any significant way from those envisioned for the actual tasks in the baseline SST landing system. To the extent that this key control requirement can be satisfied in the simulation sequence, data obtained on the subject's performance of assigned flight management tasks can be used to confirm or disconfirm the selected problem statements and thus forecast difficulties, if any, in supporting flight management task performance in the projected baseline system.

In order to exploit this basic experimental situation to obtain additional data, the study will also be designed to examine the effects of alternative crew procedures and control task loadings on flight management task performance and to examine landing performance from various flight path offset conditions at the decision height. Variations in crew procedures can be distinguished by citing differences in the pre-arranged assignment of specific monitoring and/or control duties to the Captain and First Officer. It is reasonable to assume that flight management performance would be differentially affected by such variations, since the immediate bases for making the approach success judgments, in terms of information available and display modes, will not be the same when alternative crew procedures are adopted. Alternative flight control modes, i.e., fully automatic, split-axis control, and fully manual, will be examined to disclose the effects, if any, of differences in task loading on the Captain. When manual control is assumed for one or more axes, the Captain can be expected to have less time and attention to apply to flight management tasks, per se.

The basic design of the study, then, can be understood as a test of the extent to which the information environment projected for the baseline SST landing system may be expected to support the Captain in his assessment of approach success. For the most part, this information environment is comprised of flight deck instruments and auditory display channels (e. g., aural warning signals and radio voice communications), and study results would thus apply primarily to the selection or development of these landing system components. But the information environment also includes such information sources as flight planning and in-flight referenc materials (e. g., clearances, approach charts, flight data sheets, etc.), the air and ground environment, and even learned procedures and perceptual expectancies. The influence of these additional information sources on flight management task performance must also be considered in the simulation study.

It should be clear that the study is not intended, in any sense, to evaluate the quality of individual pilot-subject's judgmental or decision making abilities. Indeed, the recommended experimental plan gives explicit consideration to controlling the effects of individual differences in subject skills in this area. Moreover, subject-pilots will be asked to provide critical evaluations of the information and display characteristics available to them in the simulation, in much the same way that expert opinion judgments and preference data are obtained in aircraft handling qualities investigations. The subject's primary role, of course, will be to carry out the assigned approach management and landing control tasks in accordance with the orientation given. Subject selection and orientation to the experimental task will be directed toward achieving behavior in the simulator that is representative of the behavior of SST command pilots in an actual operational situation.

The structure of the recommended study is schematized in Figure 4 Each run in the simulator will represent the execution of an approach and landing sequence beginning with the aircraft at approximately ten nautical miles from the runway, stabilized on the assigned localizer course, and maintaining an assigned initial approach altitude. This sequence ends with the aircraft on the runway declerating to a nominal turn-off speed or with the subject-pilot's decision to reject the approach and initiate a go-around. During this simulated flight sequence, subjects will perform specified flight management tasks, responding to simulated information inputs representing the ongoing flight situation as they would be available to command pilots in the projected SST operational environment. The intent here is to impose the same information processing demands on subjects in the simulation as those associated with the performance of specified tasks in the operational situation. For this reason, both the information provided and the display characteristics (i.e., presentation mode, type of display, and, in some instances, display-referent relationships) must match their assumed counterparts in the baseline SST system.

On each run, data on subject performance will be recorded as indicated by the subject outputs shown in Figure 4. At the same time, data will be recorded on the "actual" position and behavior of the aircraft as represented in the simulation sequence and, where appropriate, on the corresponding display of flight situation parameters which, presumably, will serve as the immediate basis for subject judgments. These data, together with the results of subjective data obtained from subject following their participation in the simulation exercise, will then be available for analysis and interpretation as appropriate to the objectives of the study.

Notice that simulated information inputs, subject task assignments, and the data taken will be held constant on all simulated runs. Controlled variations in the flight path actually followed (e.g., ILS deviation, actual lateral and vertical offset position at the decision height, etc.) and

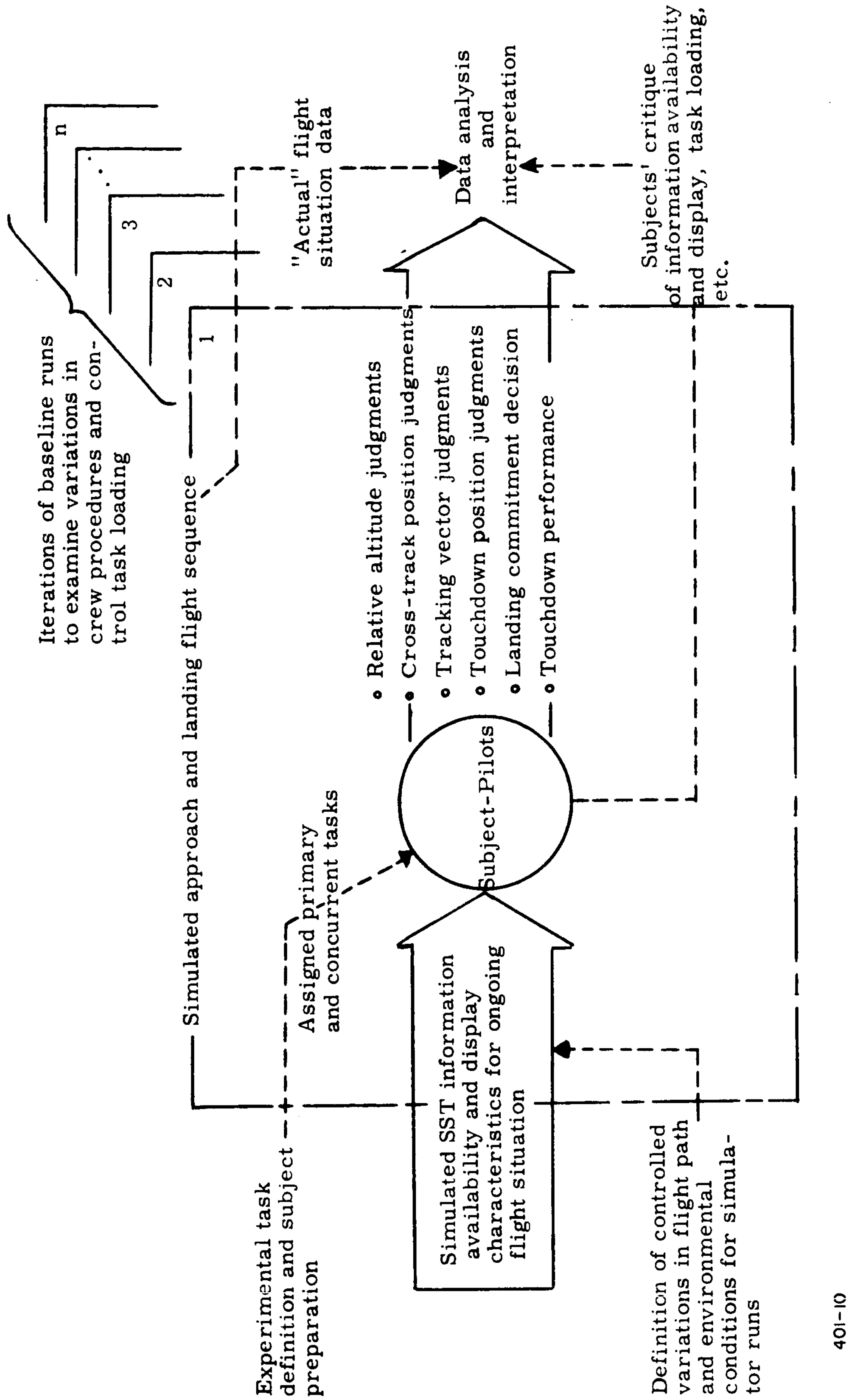

Figure 4. Schematic representation of the overall structure of the recommended simulation study.

environmental conditions (e. g., terrain profiles approaching the decision height, wind conditions, break-out height, etc.) will be represented in the information inputs in order to include a number of different flight situations for subjects to respond to. A systematic assignment of these variable conditions to simulation runs will be worked out to ensure an appropriate sampling of conditions of interest.

Baseline runs will be conducted with a fully-coupled automatic flight control mode simulated and, somewhat arbitrarily, adopting a crew procedure wherein the Captain exercises complete control of the approach to the decision height. As the aircraft approaches the decision height, the Captain has the option of looking up to assess the adequacy of external visual reference at any time. Based on this assessment and, at his discretion, on the additional cross-checking of flight instruments, he would then resolve the landing commitment decision and either abort the approach or assume manual control to complete the landing maneuver. As indicated in Figure 3, iterations of the baseline scheme will be carried-out to examine the effects of alternative flight control modes and crew procedures. The structure of the study, as schematized, will be essentially unchanged in these iterations, but in each of the iterations a different combination of control mode and crew procedure would govern the subject's task orientation and the simulation of the flight sequence.

Each element of the study schematized in Figure 3 was considered in more detail in an experimental plan outlined in reference 5. The intent of the foregoing discussion is to provide an overview of the structure of the recommended study and the general sense of conducting the study in this way. This study concept was used to guide the development of the plan and will in turn guide the subsequent specification of means for the actual set-up and conduct of the study.

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