

N71-38683

**DISPLAY REQUIREMENTS AND CONCEPTS
FOR SPACE SHUTTLE RECOVERY AND LANDING**

**CASE FILE
COPY**

Walter B. Gartner
Larry L. Jenney

July 1971

Prepared under Contract NASW-1987 by

**BioTechnology, Incorporated
3027 Rosemary Lane
Falls Church, Virginia**

for

**Headquarters
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

67371

**DISPLAY REQUIREMENTS AND CONCEPTS
FOR SPACE SHUTTLE RECOVERY AND LANDING**

Walter B. Gartner
Larry L. Jenney

July 1971

Distribution of this report is provided in the interest of information exchange.
Responsibility for the contents resides in the authors and organization that
prepare it.

Prepared under Contract NASW-1987 by

**BioTechnology, Incorporated
3027 Rosemary Lane
Falls Church, Virginia**

for

**Headquarters
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance and guidance provided by Dr. Walton L. Jones and Mr. Joseph N. Pecoraro of the NASA Office of Life Sciences who acted as technical monitors of this study. Valuable support was also given by Capt. William Winter, BioMedical Divison, NASA Flight Research Center, and by Mr. Milton O. Thompson, Mr. William H. Dana, and Mr. John Manke who offered helpful insights gained through their experience in the X-15 and Lifting Body research and flight test programs conducted at the NASA Flight Research Center.

SUMMARY

Space shuttle design requirements are based on an operational concept which approaches that of commercial aviation. The orbiter and booster vehicles will be capable of maneuvering flight upon reentry into the atmosphere and of landing on runways no longer than 10,000 feet in visibility conditions down to current FAA Category II minima. Further, the space shuttle is expected to operate with a high degree of autonomy, without reliance on ground support for mission planning, control, guidance and navigation functions. At the heart of the space shuttle system will be a sophisticated and flexible confederation of computers and data processing equipment which will permit both fully automatic operation and optional manual control modes.

In view of these operational requirements, there is a need for examination of the role of the crew and the performance demands which will be placed on them. The nature of the crew's participation in system operation must be carefully defined, and the displays which will support the crew's assigned functions must be designed in such a way that full advantage is taken of both human and computer capacities to process information and to control complex activity.

This study addresses itself to the terminal portions of the space shuttle mission — recovery and landing operations. The objectives are:

1. To identify display requirements for the descent, approach, and landing sequence;
2. To review advanced display technology and assess its applicability to space shuttle operations;
3. To outline display concepts for consideration in simulator studies and flight tests.

The report begins with a review of space shuttle mission requirements, placing emphasis on those related to orbiter recovery and landing. Following this is statement of vehicle control requirements and an outline of generalized flight profiles and control schemes in VFR and IFR conditions. These constitute an operational model which is used to derive specific information requirements for recovery and landing displays. The next step is a review of advanced display concepts and technology which could be brought to bear in the design of displays to support the space shuttle crew in their roles of managing, monitoring, and controlling recovery and landing. This two-part analysis of operational requirements on one hand and display technology on the other forms the basis for suggested display concepts and an illustration of their application in automatic and manually controlled flight under VFR and IFR conditions. The report concludes with recommendations for further display design and development activities.

TABLE OF CONTENTS

	<u>Page</u>
SUMMARY	iii
CHAPTER 1 – INTRODUCTION	1
Background	1
Study Objectives	2
General SSV Mission Profile	3
System Functions and Crew Roles	5
CHAPTER 2 – OPERATIONAL CONTEXT	9
Overview of Recovery Sequence	9
Guidance and Control Concepts	13
VFR Approach Sequence	14
IFR Approach Sequence	18
CHAPTER 3 – INFORMATION REQUIREMENTS FOR RECOVERY AND LANDING DISPLAYS	23
Operational Model and Pilot Functions	24
Analysis of Pilot Functions	26
Information Utilization by Flight Segment	29
Identification of Display Referents	30
Minimum Display Requirements	31
CHAPTER 4 – ADVANCED DISPLAY CONCEPTS AND TECHNOLOGY	35
Current Trends in Aircraft Displays	35
Survey of Advanced Display Technology	40
Flight Displays	40
Navigation Displays	45
Multi-Function Displays	47
Other Devices and Techniques	50
CHAPTER 5 – DISPLAY CONCEPTS	53
Selected Display Support Functions	53
Integrated Orientation Display Concept	56
Integrated Director-Monitor Display Concept	58

TABLE OF CONTENTS (Continued)

	<u>Page</u>
CHAPTER 6 – SUMMARY AND CONCLUSIONS	67
Summary of Conclusions	68
Recommended Studies	70
REFERENCES	73

LIST OF TABLES

<u>Table</u>	<u>Page</u>
I Orbiter Touchdown Requirements	14
II Analysis of Pilot Functions	27
III Information Utilization by Flight Segment	29
IV Display Referents	31
V Minimum Information Requirements for Vertical Situation Display	32
VI Minimum Information Requirements for Horizontal Situation Display	33

LIST OF FIGURES

Figure	Page
1 General SSV Mission Profile	4
2 General System Diagram	7
3 Generalized Orbiter Recovery Sequence	10
4 Derivation of Reference Profiles for the VFR Approach Sequence	15
5 Reference Profile – Final Approach and Landing Segments	17
6 Derivation of Reference Profiles for the IFR Approach Sequence	19
7 Typical Electronic Attitude Director Indicators	41
8 EADI with Independent Landing Monitor	43
9 Typical Head-Up Displays	44
10 Moving Map Horizontal Situation Display	46
11 CRT Horizontal Situation Display	48
12 Multi-Function Display	49
13 Electro-Mechanical ADI	51
14 Integrated Orientation Display – Descent Mode	57
15 Integrated Orientation Display – Approach Mode	59
16 Integrated Director-Monitor Display – Descent Mode	61
17 Integrated Director-Monitor Display – Approach Mode	62
18 Integrated Director-Monitor Display – Flare Guidance Elements	64

CHAPTER 1

INTRODUCTION

Background

The development of a space shuttle system has assumed a position of priority in the planning and activities of the National Aeronautics and Space Administration. One reason for this is the emerging requirement for frequent transportation of personnel and materials into Earth orbit. A second reason is economy, the importance of which is evident in a recent statement by Mathews (1970), who listed space shuttle program objectives as follows:

- to reduce space transportation operating costs by an order of magnitude below operating costs of current systems,
- to provide a highly versatile payload capability to support a variety of space missions,
- to approach a commercial airline-type environment and operating concept,
- to provide a versatile system which is capable of multimission and multiagency usage, and
- to extend the technology of manned space transportation systems.

The preceding list indicates other characteristics of the space shuttle vehicle (SSV) which differentiate it from the earlier Mercury, Gemini, and Apollo vehicles. Payload capability will be different. A shirtsleeve environment will be afforded the crew and passengers. New technologies will be brought to bear. Finally, the vehicle will be capable of controlled flight both in the vacuum of space and in the atmosphere of Earth. As a result of these changes, the demands placed on the capabilities of the space shuttle crew will be different from those in earlier spacecraft. The human element and its role in the operation of the shuttle therefore must be reassessed if one is to insure successful performance of this system.

For the present study, which deals with orbiter recovery operations, the salient characteristics of the vehicle are the requirements for aerodynamic maneuver after reentry into the Earth's atmosphere and for approach and landing much like a commercial airliner. The design reference mission for the Phase B program definition studies now in progress is a logistics resupply of a space station or base (NASA, 1970a). The vehicle design goals for the baseline mission are as follows:

1. An all-azimuth launch capability, within a 60-second launch window, from sites located at the Eastern and Western Test Ranges or an inland site.
2. A 50 by 100 nm reference injection orbit with at least 1500 ft/sec of ΔV capability in excess of that required to attain injection orbit.
3. A circular 270 nm design reference orbit, with a 55° inclination.

4. A mission duration of at least 7 days and up to 30 days with the weight of additional expendables charged to payload.
5. A launch capability from a standby status within 2 hours, nominally at the next acceptable in-plane opportunity.
6. A cross range capability of approximately 200 nm (low cross range configuration) or up to 1500 nm (high cross range configuration).
7. An automatic landing capability which will allow recovery operations under FAA Category II visibility conditions, with an option for pilot-controlled approach and landing.
8. The capability to land horizontally on runways no longer than 10,000 ft.
9. Landing visibility comparable to that of high-performance aircraft.
10. A one-time, go-around capability for both booster and orbiter vehicles.
11. The specification of a two-man flight crew for the orbiter, with the vehicle flyable by a single crewman in an emergency.
12. Provision for redundant full-mission capability (minimum-requirement, minimum-performance backup systems are not acceptable).
13. Design for maximum onboard flight control, guidance, and navigation.
14. Use of advanced, electronically generated displays wherever practical.

Of these operational requirements, nearly two-thirds (Items 6-14) pertain to the recovery, approach and landing portion of the mission. In essence, the orbiter must meet the goals of a spacecraft in transferring personnel and cargo to orbit and back, but under the serious constraint of completing its return to Earth as an aircraft. In addition, the design requirements call for the orbiter to operate without major support from the ground.

Study Objectives

The capability for launch into orbital flight, rendezvous and docking with other spacecraft, reentry into the Earth's atmosphere, and landing more or less as a conventional aircraft makes the space shuttle a unique vehicle. It will be somewhat hybrid in character, possessing many of the characteristics of a spacecraft while retaining much of the flavor of an aircraft. The unusual capabilities of the orbiter, particularly as it passes through the transonic range and enters the terminal landing area, have drawn attention to the possible need for new display systems for the pilot. At the moment, there is considerable difference of opinion as to the kinds of display systems which will be required. Intensive work will be required in order to resolve these differences and to specify the optimum system.

This study, which was undertaken as a first step in the development of a display system to support crew performance in recovery and landing operations, has three major objectives:

1. To identify display requirements for the descent, approach, and landing sequence;
2. To review advanced display technology and assess its applicability to SSV operations;
3. To outline initial display concepts for consideration in later simulator studies and flight tests.

This study is based on an analysis of system performance requirements and anticipated crew roles in both VFR and IFR conditions. The underlying assumptions are that the orbiter will operate with a great degree of autonomy during recovery and landing and that onboard flight control and guidance activities will be supported by a highly sophisticated and flexible computer complex capable of carrying out most functions automatically. However, it is also assumed that the capability for pilot override and intervention must exist to assure safety of flight and fully redundant manual control. The essential features of the recovery and landing phase of the SSV mission and a basic system description are presented in the concluding sections of this chapter.

General SSV Mission Profile

Several vehicle configurations have been considered in the SSV design studies. Until recently, a full reusable two-stage configuration employing straight fixed wings on both the booster and orbiter was favored because of its reentry, approach and landing characteristics. However, in this configuration the orbiter has limited cross range capability (approximately 230 nm). Therefore, the current trend is toward a delta-wing orbiter vehicle, which offers about 1100 nm cross ranging and an increased payload. A delta-wing configuration has been assumed for the purpose of this study.

The mission profile shown in Figure 1 depicts a generalized delta-wing vehicle. Minor modifications might be required to make it applicable to the configuration which is ultimately selected, but this probably would not have a substantial effect on the display requirements analysis presented in this study.

For the sake of completeness, Figure 1 shows the entire mission sequence from lift off to touchdown. Since only orbiter operations in the terminal portion of the mission are of interest in this study, no discussion of the ascent, staging, and orbital phases is necessary.

During reentry, the orbiter vehicle will assume a relatively high angle of attack ($25^{\circ} - 45^{\circ}$). This attitude will be highly constrained throughout the descent to approximately 100,000 feet so as to control heat loading and total dynamic pressure. At 100,000 feet the velocity will have decreased to approximately 3000 feet per second (Mach 3.0), and the vehicle will then establish an equilibrium glide path angle of about 10° for the return to the landing site.

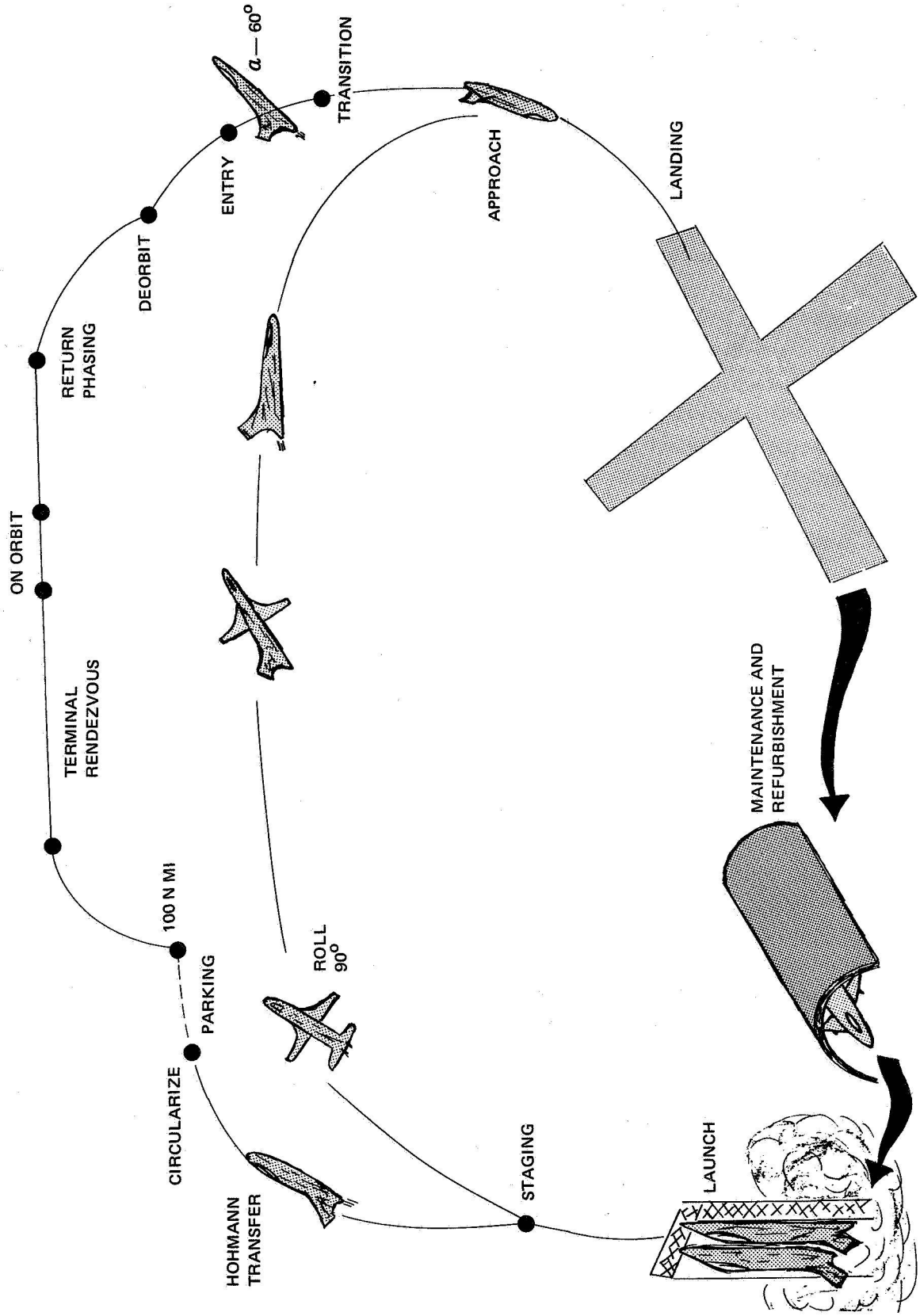


Figure 1. General SSV Mission Profile

The approach and landing phase following reentry is expected to consist of a maneuvering descent (energy dissipation) segment integrated with the initial approach to the landing site, a comparatively steep ($10^{\circ} - 12^{\circ}$) final approach, and a one- or two-step flare maneuver for landing. Nominal touchdown speed is expected to be about 180 knots, which is comparable to that for the X-15 and lifting body aircraft but somewhat greater than the speeds characteristic of jet transports. Rate of descent at touchdown will be on the order of 3 feet per second, providing a soft landing. A more detailed analysis of the recovery and landing sequence is presented in Chapter 2 of this report.

System Functions and Crew Roles

The SSV design concept places emphasis on reusability, autonomy, and fail-operational automation of mission-critical functions. Each of these has a major influence of the specification of crew roles and performance requirements. Reusability is reflected in design features which permit the booster and orbiter vehicles to return to designated recovery sites and land with minimal requirements for refurbishment and relaunch preparation. Autonomy derives from design features which enable the SSV to operate with considerably greater independence from active ground support than current space vehicles. Automation concepts are embodied in the extensive onboard computer control and checkout of vehicle subsystems and in the use of an integrated avionics system for guidance, navigation and flight control functions.

Five classes of system functions can be distinguished:

1. Flight Management
2. Guidance and Navigation
3. Flight Control
4. Subsystem Control (including environmental control and life support)
5. Communication.

The first three of these are of central concern in recovery, approach, and landing. The analysis of these functions to determine the crew roles and performance requirements is a major objective of this study, and a further examination will be made in Chapter 3.

A general schematic diagram of system functions and the central computer/crew interface is presented in Figure 2. At the core of this system is a central computer complex which will be programmed to perform the following centralized functions:

1. Vehicle subsystem configuration
2. Onboard checkout
3. Performance monitoring and display

4. Data management
5. Onboard mission planning
6. Guidance, navigation and flight control
7. Data processing for crew controls and displays

Design guidelines for the orbiter have called for operational capability for both manual and automatic control modes, especially for guidance, navigation and flight control functions. It may also be expected that the crew's ability to intervene and exercise override control as an option or in nonroutine situations will be fully exploited, but many problems with respect to control authority are expected to arise. In any event, it is clear that crew participation can be more accurately characterized as careful monitoring of and communication with computers than as manipulation of control devices.

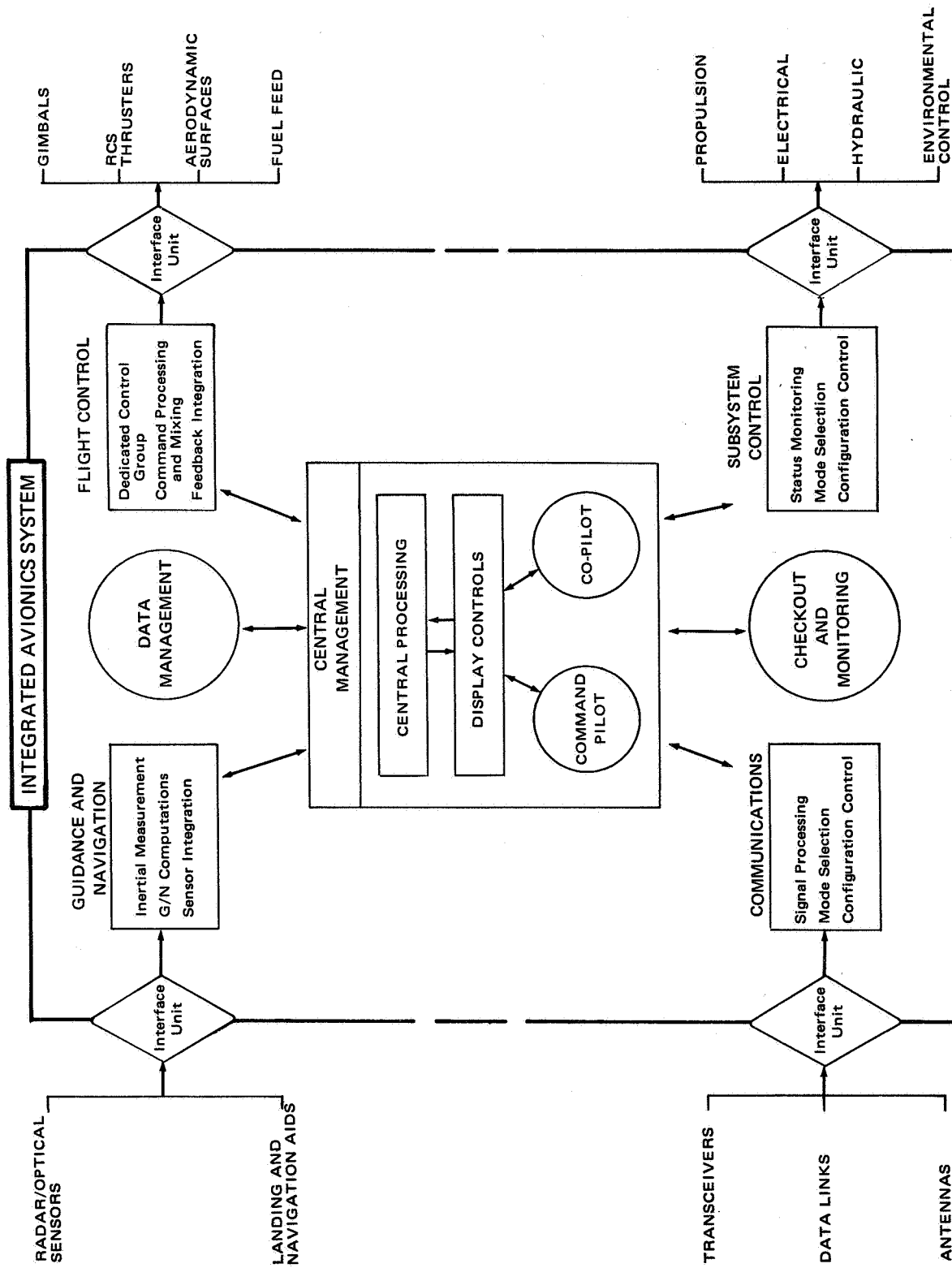


Figure 2. General System Design

CHAPTER 2

OPERATIONAL CONTEXT

The identification of display requirements in this study is based in part on projected guidance and control concepts for approach and landing operations. At this stage of the SSV development program, these concepts have not been fully defined, and the final mechanization of onboard flight control functions has not been established. For study purposes, however, an outline of the general structure of the recovery sequence and a tentative statement of vehicle control requirements and techniques are necessary as a framework for distinguishing pilot tasks and information requirements. In this chapter, the principal considerations affecting recovery operations are identified and a reference profile is defined in order to provide this framework.

The chapter begins with an overview of the recovery sequence from the end of reentry to touchdown. For each phase of this flight sequence, the general flight control objectives and constraints are stated, and operational factors affecting onboard guidance and control functions are identified. Following this is a brief discussion of the guidance and control system concepts which are currently under consideration. These preliminary concepts form the basis for definition of a reference profile which is used in the present study as the framework for establishing pilot task requirements and information needs.

Overview of the Recovery Sequence

A generalized orbiter recovery sequence is schematized in Figure 3. Key events and vehicle states are used to distinguish four flight segments which will serve to structure the discussion of flight control requirements and techniques. Initial conditions for the recovery sequence are a nominal altitude of 100,000 feet, a forward velocity of approximately 3,000 feet per second, and a downrange position of about 60 nautical miles from the selected landing site. As indicated in the schematic, the goal of subsequent terminal area maneuvering and vertical flight path control is to produce a soft touchdown on a 10,000-foot runway, satisfying prescribed position, velocity, rate of descent, and attitude constraints.

Implicit in this general characterization of approach technique is the assumption that the vehicle is operating without power. One of the major design alternatives provides for the use of air breathing turbojet engines which could be ignited during recovery to provide a brief power assist for the approach or to enable a go-around in the event of a missed approach. The addition of a limited-duration powered flight capability has the advantage of allowing wider margins for error in flight path control on the approach and would provide an energy reserve to be called upon in addition to lift/drag modulation in case of mismanagement of the approach or in case of off-nominal guidance and control system performance. However, this advantage must be set against the penalties of weight and complexity which come with the incorporation of jet engines and a fuel supply. The issue is unresolved at this point.

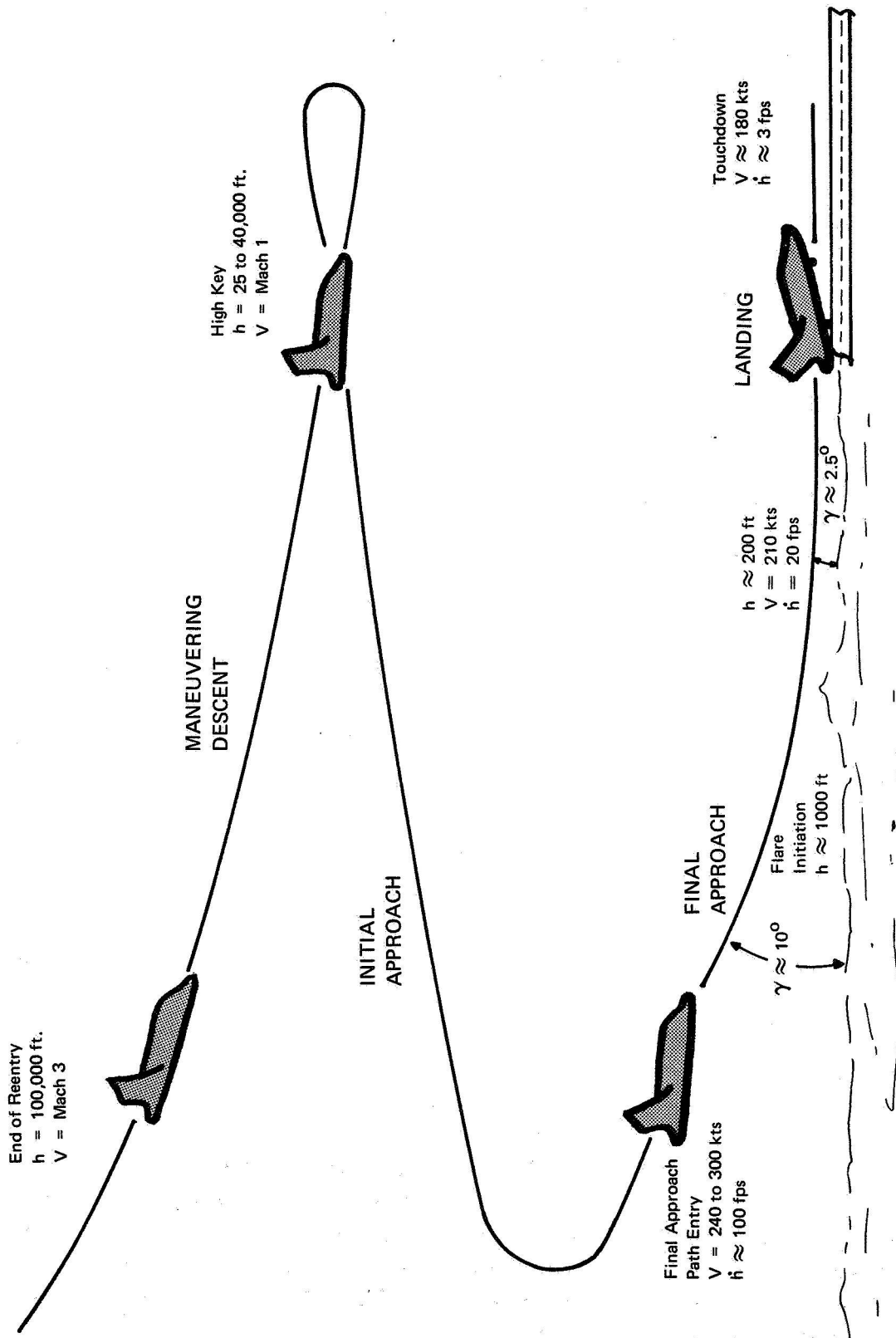


Figure 3. Generalized Orbiter Recovery Sequence

No position on this matter is taken in this report. However, the subsequent analysis of display requirements is based on the assumption that the recovery sequence will be accomplished unpowered. This assumption assures the validity of the statement of requirements regardless of whether or not engines are incorporated in the SSV. That is, even if powered flight capability is provided, it will still be necessary to consider the contingency of engine malfunction. Assuming unpowered flight as a baseline thus covers the more inclusive set of conditions. The argument for establishing unpowered operation as the nominal condition has been cogently stated in a recent symposium at the NASA Flight Research Center (Thompson, 1970):

We are not proposing that you eliminate landing engines or a go-around capability. If you, as designers, program managers and users, decide that you can afford landing engines or need them for any other purpose, you should certainly include them. Even our experienced pilots would not reject the engines if they were flying the shuttle; however, they would refuse to rely upon them to make a successful approach and landing. The shuttle, whether it has landing engines or not, must be maneuvered, unpowered, to the point near the destination because the engines cannot be started until the vehicle is subsonic and only limited fuel will be available. To us it seems ridiculous to maneuver to a position where power must be relied upon to reach the runway. Instead, we would maneuver to a high key position to begin an unpowered approach. Then, regardless of whether the engines could be deployed, started, and kept operating, a successful approach and landing could be made.

Established touchdown constraints and the handling qualities and performance characteristics of the unpowered orbiter vehicle will govern the final selection of flight control techniques. Considerable revision and refinement of these techniques can be expected to occur as operational experience accumulates. The generalized recovery sequence depicted in Figure 3 is compatible with the various terminal area guidance and control schemes now under study by NASA. However, it must be understood that the nominal values cited for key profile-defining flight parameters (i.e., velocities, altitudes, distances, etc.) may be adjusted by later specifications of orbiter flight characteristics and operational procedure.

During the Maneuvering Descent flight segment, guidance and control functions will be governed by an energy management strategy designed to position the vehicle at a selected runway offset point with sufficient energy for completing final runway alignment maneuvering. This offset point will be referred to as a "high key" position. Its height and location relative to the intended touchdown point will be based on expected visibility and wind conditions at the landing site and on the selected final approach control technique. The high key position may be selected to accommodate either a traditional circling approach down to the desired entry onto the final approach path (FAP) or a long straight-in approach to the FAP entry point.

In either case, the Initial Approach will be planned with the primary objective of dissipating excessive energy, in the form of either altitude or airspeed, and establishing a final approach glide path from which a smooth and consistent flare and landing maneuver can be flown to achieve desired touchdown objectives. Operation of the vehicle on the front side of the lift/drag (L/D) curve to provide sufficient excess energy for good controllability margins is preferred throughout the approach, as indicated by the following comments from pilots in the lifting body flight test program (Dana and Gentry, 1970):

We want to position the vehicle on a flight path or dive angle to intercept a preflare aim point on the ground. This task is minimized by using a relatively steep approach (10° to 25°) . . . Our whole pattern, then, is just a means of establishing ourselves on this flight path. Because we generally fly well on the front side of the L/D curve, we never plan to be, and seldom are, short of energy. We modulate this energy to arrive on our desired flight path either by slowing or accelerating, or we can remain at approximately the same speed, and use speed brakes to alter our flight path as required.

The latter portion of this statement describes the energy management techniques which are available during unpowered flight. These include flight path maneuvering, adjustment of airspeed and/or angle of attack, and the judicious timing of speed brake deflections. Once the vehicle is stabilized on the selected final approach, only minor adjustments should be required to maintain the desired flight path toward the pre-flare aim point and to compensate for wind effects.

The relatively steep nominal glide path angle shown in Figure 3 for the Final Approach segment and the high approach airspeeds anticipated will make it necessary for the pre-flare aim point to be set some distance back from the intended touchdown point on the runway. In lifting body operations, using indicated airspeeds of 270 to 300 knots on final, this point is set approximately 1.5 miles from the runway. The location of this point for orbiter operations will be a critical factor in determining the outcome of the unpowered approach and will be based on the control technique adopted for the flare maneuver and on the deceleration characteristics of the vehicle at its landing weight and configuration. In some final approach guidance schemes currently under consideration, the pre-flare aim point may be located more than 3.5 miles from the runway.

At a preselected height about the runway, a flare maneuver is initiated in order to decrease the rate of descent and to establish a shallow decelerating glide path toward the intended touchdown point on the runway. The nominal situation represented in Figure 3 entails transition from the initial 10° approach path to a conventional 2.5° glide slope angle at a height of about 1000 feet. Flare initiation height may be expected to vary with the adjustment of the pre-flare aim point closer to or further from the runway.

To accommodate variations in flare technique, the initiation of the landing flight segment is somewhat arbitrarily established at a height of 200 feet above the runway. In the present study it is assumed that adequate visual reference will be available at this altitude for controlling and/or monitoring the landing maneuver. This maneuver will consist of a final alignment of the flight path with the runway and precise control of touchdown position, speed and rate of descent. Attitude adjustments may be required just prior to touchdown to assure vehicle alignment with the runway and to preclude tail and/or wing structure contact.

Guidance and Control Concepts

A full elaboration of terminal area guidance and control schemes currently under development for application to recovery operations is beyond the scope of this report. At FRC, exploratory studies and flight evaluations of approach and landing techniques have been conducted (Koch, 1970; Hoag, 1970), and the feasibility of unpowered recovery operations executed by the pilot with minimum dependence on ground facilities has been demonstrated. At ARC, analytic and simulator studies of various automated recovery system concepts developed by Sperry Flight Systems Division and Bell Aerospace Corporation are in progress (Showman, 1971). Automated guidance and control schemes are also being developed and evaluated at MSC (Moore, 1971), and a number of promising techniques are emerging. The interested reader is referred to the sources cited for the details of these guidance and control schemes.

To serve the needs of the present study, a reference flight profile incorporating the essential features of these guidance and control concepts was defined. It is presented here, in broad outline, to document the assumptions underlying the subsequent analysis of display requirements. One of the guiding assumptions for this analysis is that the integrated avionics system ultimately adopted for the orbiter, including crew displays, will allow for considerable flexibility in the planning and execution of recovery operations. Accordingly, the reference profile is not specific to any one terminal area guidance scheme, and it can accommodate a wide range of approach control techniques.

The reference flight profile is defined, ultimately, in terms of the desired vehicle state at touchdown, which may be considered the goals of the recovery and landing sequence. These terminal conditions, which were derived from an analysis of touchdown and rollout requirements for the NAR 161C orbiter configuration (Clark, 1971), are summarized in Table 1.

Working backward from the touchdown requirements, it is possible to define successively earlier key parameters, each governing a segment of the flight profile. From low to high altitude, they are:

1. the location of the pre-flare aim point,
2. flare initiation height and airspeed,
3. the final approach path entry height and airspeed,

4. the location of the high key position,
5. the vertical flight path angle adopted for high altitude energy management.

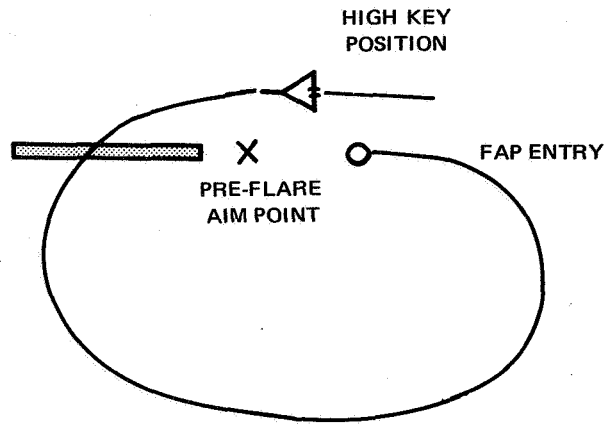
TABLE I
Orbiter Touchdown Requirements

Parameter	Nominal Value	Limits
Forward Velocity	304 fps (~180 kts)	225 fps (tail contact) 375 fps (rollout limit without chute)
Vertical Velocity	-3 fps	-1.5 fps (minimum) -8 fps (gear structural limit)
Position down Runway	1800 ft	250 ft (minimum) 3750 ft (rollout limit without chute)

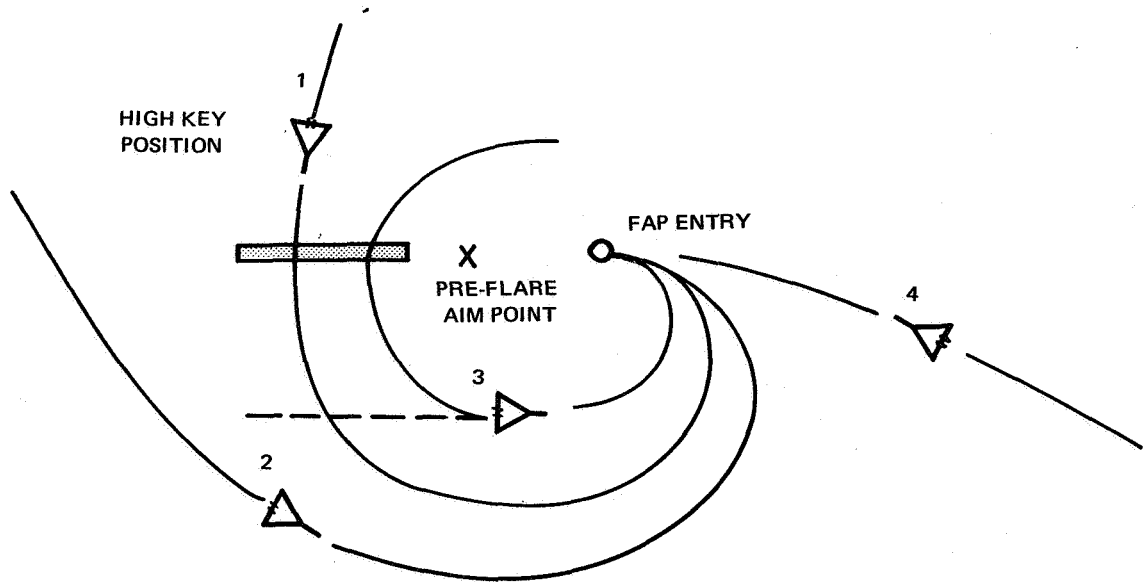
To facilitate the analysis of minimum display requirements, a baseline reference profile was defined for recovery operations under unrestricted visual conditions (VFR) and then modified as necessary to satisfy the constraints of operations under degraded visibility conditions (IFR). Operational goals for the orbiter vehicle include approach and landing under FAA Category II visibility conditions (down to 1200 feet runway visual range). However, operation to such low minima imposes special problems, and it is difficult to state meaningful requirements without a clear specification of the guidance and control system to be employed. Since the SSV development program has not yet reached a stage where the Category II guidance and control system can be so defined, the IFR reference profile used in this study is based on the assumption that full visual reference will be available at an altitude of 200 feet, which corresponds roughly to Category I conditions.

VFR Approach Sequence

The distinguishing feature of the VFR profile is that a high key position is selected to optimize visual contact with the intended touchdown point on the runway, thereby allowing the pilot to execute an accurate and consistent initial approach maneuver primarily by external visual reference. A typical high key position for unpowered X-15 recovery operations is located near the approach end of the runway and offset laterally, as shown in Figure 4a. Nominal altitude and airspeed status at this high key eliminates any uncertainty with respect to reaching the runway, and a carefully controlled circling descent to a selected final approach path (FAP) entry point is carried out to establish the desired conditions for the final approach to the pre-flare aim point (PAP).



a. A Typical VFR Circling Approach



b. Circling Approach Patterns from Alternate High Key Positions and Energy States

Figure 4. Derivation of Reference Profiles for the VFR Approach Sequence

This technique can be generalized for the approach sequence in VFR conditions by generating a more inclusive set of spiralling initial approach profiles based on the aerodynamic characteristics of the vehicle and its turning capabilities at various airspeeds and bank attitudes. The common end point for all of these profiles is the selected FAP entry point. A set of potential left-turn approach profiles is schematized in Figure 4b. A set of mirror image profiles can be generated for a right-turn approach to the FAP entry.

Note that alternative high key positions may be selected to accommodate variations in altitude and/or airspeed, as dictated by the flight plan adopted for a particular recovery sequence or by constraints imposed on high altitude energy management. High key position 4 in Figure 4b, which is almost a straight-in approach to the FAP entry point, may be seen as a special case of the circling approach for low energy situations. The nominal situation adopted for the reference profile is represented by high key position 1.

In the VFR approach sequence, then, the aim of guidance and control activities during Maneuvering Descent would be to arrive at the pre-selected high key position with sufficient energy to complete the planned initial approach circuit. For the nominal situation this energy state is provided by an airspeed of about Mach 1 at an altitude of 35,000 feet. In the reference profile, the initial approach is flown at a constant indicated airspeed, with bank attitude modulation to arrive at the FAP entry point at the desired height above the runway.

The desired FAP entry point and altitude will be determined by the location of the pre-flare aim point and the vertical flight path control technique adopted for the final approach and flare maneuver. A three-phase final approach sequence was adopted for the reference profile and is illustrated in Figure 5. This profile, derived in part from a study of power-off landing techniques at ARC (Bray, 1960), is characterized as follows:

Phase I represents a straight-in approach to the landing area in a steep glide at a relatively high indicated airspeed. The flight path is defined by the angle of descent (matching the vehicle lift-drag ratio at the selected airspeed) and the preselected geographical reference point short of the runway, at which the aircraft is aimed. Availability of speed brakes is assumed during this portion of the pattern where their high-speed effectiveness can be used for precise speed control, thereby reducing the precision required in establishing the initial flight-path angle. Phase II, the pull-out or flare, is initiated at a predetermined altitude (h) and is performed at a constant value of normal acceleration, which is maintained until the flight path of the vehicle is aimed at the touchdown point. Phase III is the final approach along a shallow flight path, nominally 3° , to the preselected point. The speed programmed for the end of Phase I depends on the deceleration characteristics of the aircraft in Phases II and III. Accordingly, during Phases II and III, configuration changes affecting the lift-drag ratio of the airplane, such as dive brake, flap, and gear extension, must be rigidly programmed with speed.

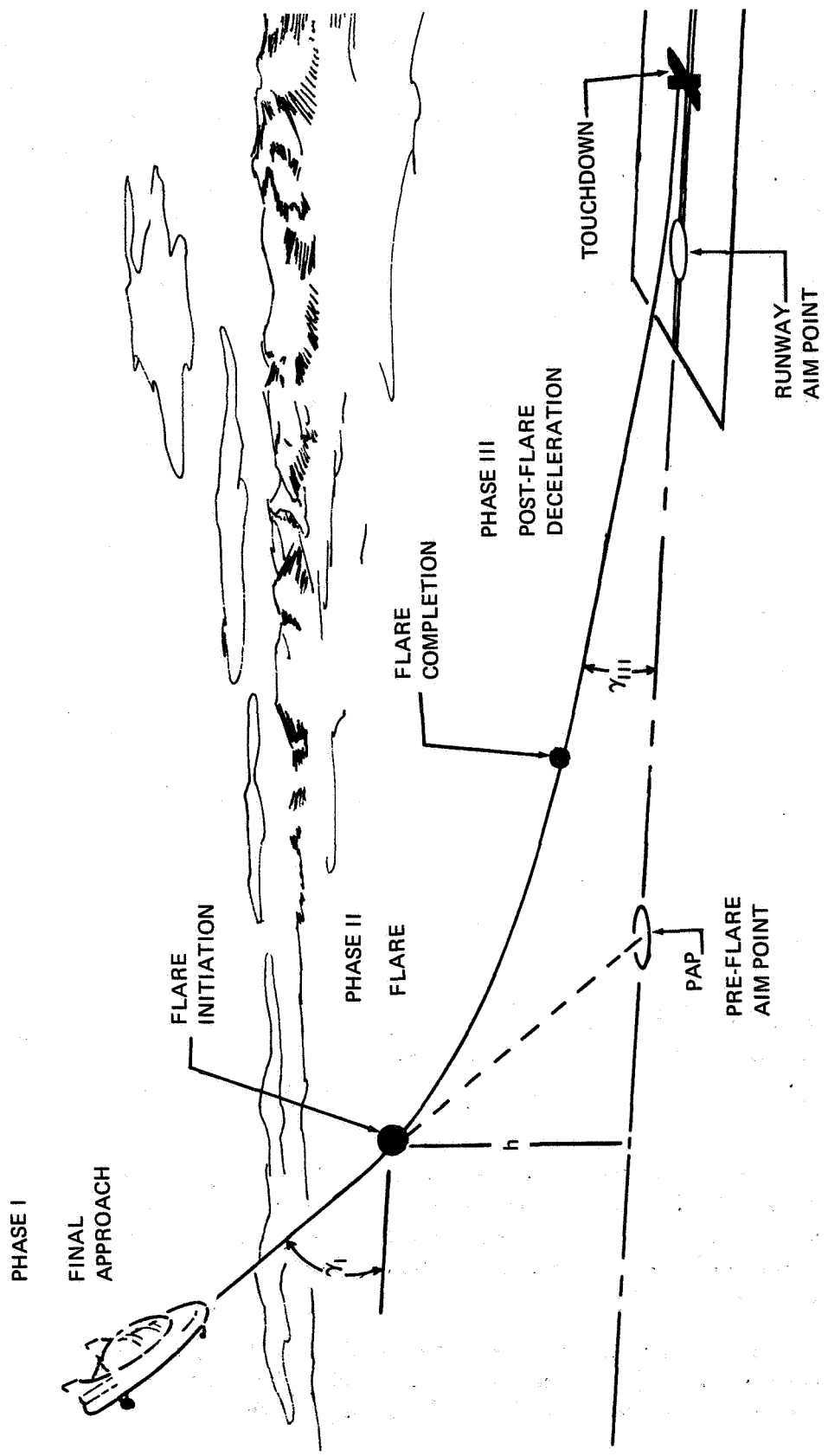


Figure 5. Reference Profile – Final Approach and Landing Segments

Nominal values for the final approach speed and corresponding flight path angle (γ_I) will be derived from L/D data for the orbiter vehicle. Currently they are estimated to be approximately 250 knots and 10° , respectively. Post-flare airspeed and deceleration characteristics, also a function of vehicle L/D, will determine the appropriate offset distance for the pre-flare aim point. Some adjustment of this point may also be necessary to compensate for wind effects. Nominal offset distances will be on the order of 3 nautical miles. The post-flare flight path angle (γ_{III}) is nominally set at the conventional 2.5 to 3° , which means that a final flare would be incorporated in the landing maneuver at the end of Phase III.

IFR Approach Sequence

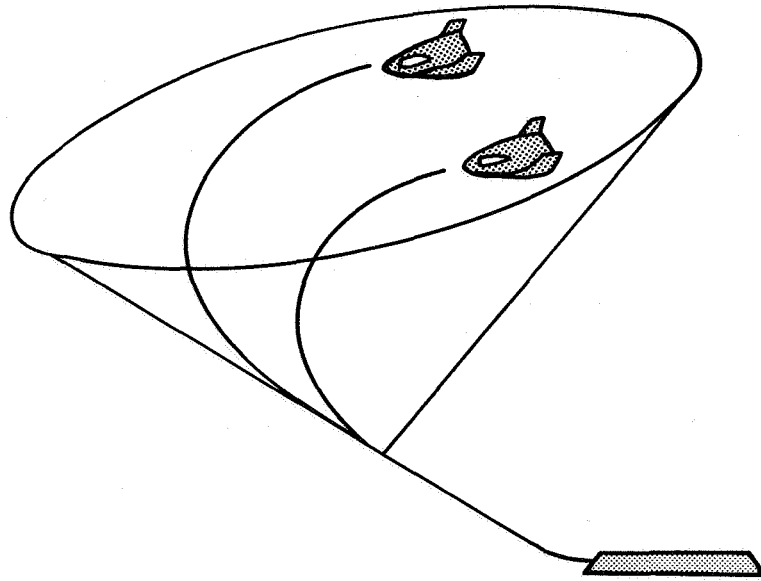
Pilots often comment that IFR approach procedures and techniques should be compatible with those employed under VFR conditions. This principle is seen as especially pertinent to unpowered orbiter recovery operations. Therefore, it has been adopted in the development of the reference profile for the degraded visibility situation. For the most part, the approach sequence just described for VFR operations is applicable to the IFR condition. There are some minor differences derived primarily from final approach guidance requirements and the corresponding modification of control technique.

A circular approach guidance scheme developed at FRC represents the most direct translation of the techniques adopted for the VFR approach sequence to the IFR situation. The general features of this scheme are illustrated in Figure 6 and have been characterized by Schofield (1970) as follows:

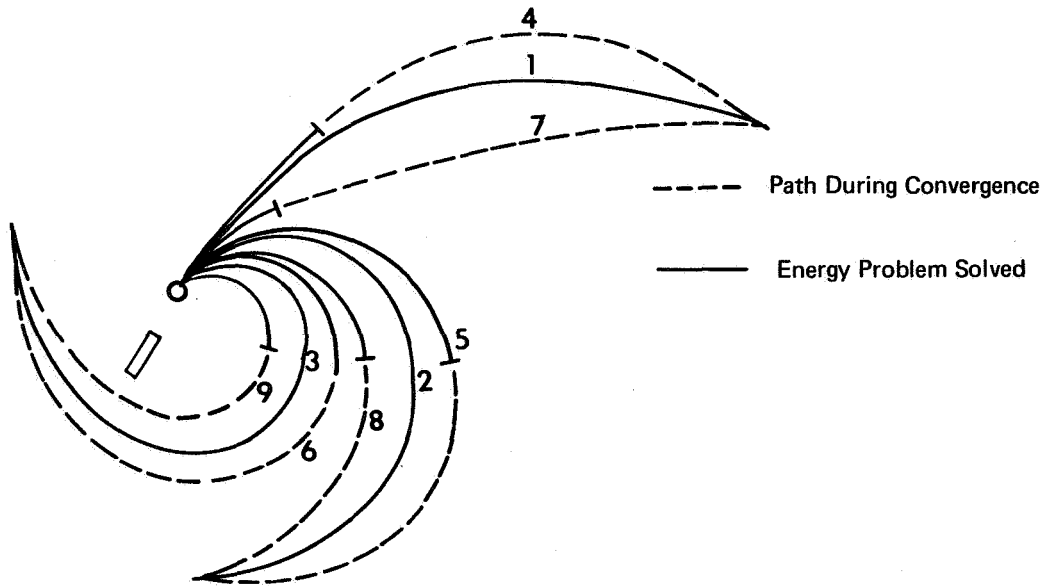
Figure 6a is a general representation of the circular approach scheme. A somewhat conic surface, based on the aerodynamic characteristics of the vehicle, is generated for various bank angles and a given approach speed and stored in a computer. The location of the aircraft in space is compared with the location of the conic surface, and the error signal is fed to a flight-director type of display system for the pilot. When the vehicle is on the conic surface, the result is a steady-state flight condition (constant bank and constant airspeed) in a curved path that will arrive at the apex in the direction of the runway.

The apex is considered to be at an outer marker or a point that coincides with the ILS localizer and glide slope beams. The conic surface resembles a tilted cone but is a distorted figure to allow for turn radius and true airspeed variations that occur during descending flight on a standard day. . .

A digital program was written to simulate the circular approach guidance system and the flight of a lifting body. The heading and glide slope commands were fed back (through a function that



a. Schematic of the IFR Circular Guidance Scheme



b. Alternate Flight Path Solutions for Various Initial Conditions

Figure 6. Derivation of Reference Profiles for the IFR Approach Sequence

simulates a pilot) to control the vehicle in pitch and roll. Figure 6b shows computed data of the performance of the system. Paths 1, 2 and 3 are nominal solutions starting at 50,000 feet altitude. Paths 4, 5 and 6 are high energy conditions, starting at 60,000 feet altitude. Because of the higher energy in paths 4, 5 and 6, the vehicle turns away from the conical apex to solve the energy problem, which results in a different solution than for paths 1, 2 and 3. The dashed portions of the paths show the convergence to a nominal solution and the path length required to solve the energy problem. The solid portions are when the energy problem is solved. Paths 7, 8 and 9 are low energy conditions which result in shorter paths.

The guidance scheme is designed to provide a minimum of pilot workload, and the commands are compatible with normal visual piloting techniques where the pilot mentally assesses his present situation and applies the best solution from that position. Because the scheme requires the pilot to maintain his position anywhere on the surface, his workload should be less than to maintain his position on a line such as with the ILS system.

To ensure compatibility between VFR and IFR techniques, the general features of the circular approach guidance scheme were adopted to define the IFR reference profile in the present study. For the IFR approach, however, the apex of the conical surface (i.e., the FAP entry point) represents the initiation of a final approach guidance scheme based on the flare and runway alignment system under development at ARC by Bell Aerospace Corporation. This system has been briefly described (Showman, 1971) as follows:

The Bell flare and runway alignment system is a predictive guidance scheme. The system predicts the point at which each event (i.e., initial flare, final flare) should occur as a function of the vehicle's current state and the environmental conditions (winds). For example, initial flare nominally occurs at an altitude of 1085 feet and a range of 21,000 feet. However, if a tailwind exists, the initial flare will occur at a higher altitude and further from the runway. Conversely, if a headwind exists, the flare will occur at a lower altitude and closer to the runway. . .

The final flare to reduce sink rate nominally occurs at 100 feet altitude and the decrab maneuver occurs at an altitude of 8 feet. Nominal touchdown sink rate and air velocity are 2.9 feet/second and 276 feet/second, respectively.

The Bell approach guidance scheme is compatible with the three-phase approach sequence depicted in Figure 5. It is assumed that an onboard inertial navigation system and guidance computer will generate the reference flight path for the approach to the pre-flare aim point and that a constant, ground-referenced flight path angle (rather than a constant airspeed) will be flown during Phase I. At the preselected flare initiation height, the vehicle will transition to a shallow decelerating glide path. Flight path guidance during this phase segment could be provided by a ground facility such as the Advanced Integrated Landing System (AILS).

In order to allow for stabilization of closed-loop tracking during both Phase I and Phase III of an IFR approach, the FAP entry and flare initiation occur at higher altitudes. This could cause the FAP entry point to be located at considerably greater distances from the runway. With the pre-flare aim point at ranges of 3 to 4 miles from the runway and retaining the nominal 10° pre-flare glide slope, the FAP entry point could be established at a distance as much as 20 miles from the runway. The high key position relative to the selected FAP entry would be similar in concept to the VFR approach sequence, although at the greater distances from the runway the concern for optimizing visual contact with the intended touchdown point would be dropped as a factor in selecting the desired high key.

CHAPTER 3

INFORMATION REQUIREMENTS FOR RECOVERY AND LANDING DISPLAYS

This chapter contains an analysis of onboard data presentation functions to support the pilot in carrying out flight control and management tasks associated with recovery and landing. The purpose of the analysis is to delineate displays essential to pilot performance under three conditions:

1. manual control (primarily in VFR conditions),
2. automatic control (primarily in IFR conditions),
3. transition from automatic to manual control (IFR or VFR).

It must be emphasized, however, that transition to manual control does not imply manual backup of the automatic system in emergency conditions. Display requirements for emergency backup cannot be formulated without a detailed study of guidance and flight control equipment characteristics to determine modes of failure and residual capability in degraded states. At this stage of SSV development such an equipment-oriented study is not practical. Therefore, transition from automatic to manual control is considered for only two circumstances—pilot option during the approach and normal transition to manual control at very low altitudes (200–300 feet) in preparation for touchdown.

Display requirement, as the term is used in this report, refers to a data transfer function and not to the medium by which the information is presented. Consequently, a statement that a display of such and such information is required implies nothing about the method of transferral, the sense modality involved, or the technique of mechanization. Likewise, no attempt is made here to specify human engineering details of displays, such as scale factors, symbology, or optimum combinations and arrangements of display elements. The purpose is to identify, at a general level, the parameters considered essential to effective pilot performance in recovery and landing operations.

The point of departure for the analysis is the generalized mission profile presented in the previous chapter. From this is developed a list of pilot functions, stated in terms of his information processing tasks during four flight segments: Maneuvering Descent, Initial Approach, Final Approach, and Landing. These functions are grouped under the rubrics of flight management, situation monitoring, and flight control. In the next step, the parameters of the flight situation which are of interest to the pilot in carrying out his functions are isolated and related to specific flight segments. This list of parameters is then expanded into families of flight situation data needed to support the pilot's management, monitoring, and control functions. The final step is a synthesis of these display referents into a tabulation of minimum requirements for information display.

The approach used in this analysis was to begin with an examination of the requirements for manual flight control in VFR conditions. Essentially, this was based on X-15 and lifting body flight test experience. The analysis was then extended by examining additional and/or modified task demands and display requirements imposed by automatic control and by reduced visibility. A step-by-step recapitulation of the analytic process is not presented in this report. Instead, the results are presented in the framework of a general operational model which incorporates both manual and automatic control and applies to VFR and IFR conditions.

Operational Model and Pilot Functions

The model used to structure this analysis contains two basic options:

1. auto-controlled maneuver and descent from 100,000 feet to a "high key" position where the pilot assumes manual control to complete the approach and landing by visual reference.
2. auto-controlled flight by instrument reference from 100,000 feet down to approximately 200 feet where the final landing maneuvers are either manually controlled or monitored by visual reference.

In either option, pilot participation or intervention in automatically controlled processes is not precluded. Thus, it is assumed that the pilot will have the capability (and will need information to permit him) to adjust the selection of and approach to control points along the flight path without disengaging the automatic flight control system or abandoning computer-derived guidance. Further, it is assumed that the pilot must have an information display which enables him to assume manual control (as an option not in an emergency) at any point in the recovery and landing sequence.

SSV design requirements specify a two-man flight crew, with the vehicle flyable by a single pilot in case the other is incapacitated. Since one-man operation is the more stringent condition, this has been assumed for the operational model employed in the display requirements analysis. However, the requirements may also be considered to apply to the nominal two-man operation, providing a suitable scheme is devised for distributing functions between crewmembers according to flight segment and/or areas of responsibility.

The pilot's role in recovery and landing operations is comprised of five generic functions: (1) flight control, (2) situation monitoring, (3) flight management, (4) subsystem control, and (5) communication. Although these are familiar terms, the following comments may be helpful in clarifying their use in this study and in interpreting the subsequent display requirements analysis.

1. Flight Control. This is the pilot function most directly related to attainment of the desired flight path and safety-of-flight objectives. As used here, the term is restricted to the control functions executed to transform navigation and guidance inputs and/or flight plan data into

appropriate control surface deflections affecting movement through the air mass. This function also includes control actions to position aircraft structures (e.g., landing gear or speed brakes) which will influence aerodynamic performance. The primary kind of pilot activity associated with this function is continuous perceptual-motor performance wherein controls are adjusted manually by reference to perceived differences between actual and desired aircraft states.

2. Situation Monitoring. This function is comprised of pilot activities entailing attention to specific objects, conditions, or events which serve as indices of system status and/or performance. Generally, monitoring involves simple discriminations and readings of natural or instrumental indications of system performance parameters. Thus, the tracking of a vertical flight path guidance signal is classified as a flight control function, while the reading of an airspeed indicator or vertical velocity indicator to assess the outcome of the control action or to diagnose the reason for the particular control action being demanded is a monitoring function. Certain judgmental performance (e.g., "out of tolerance" or "off nominal but satisfactory") is also called for in monitoring.

3. Flight Management. This function includes all activity required to assess or diagnose flight situations, environmental conditions, and aircraft states so as to formulate and resolve action-decision problems. Assessment and diagnosis do not include monitoring activities concerned with determining present status. The managerial function makes use of monitoring inputs and through the application of system criteria, distinguishes significant conditions or derives implications for future control actions. For the most part, action-decision problems will arise from the outcome of assessment and diagnosis and will cover such areas as the decision to proceed with or to deviate from the flight plan, the selection of options within the flight plan, the selection of system operating modes or configurations, and the adoption of nonroutine or emergency action.

The two remaining generic functions are subsystem control and communication. Subsystem control is concerned with turning equipment on and off, selecting and adjusting operating modes, observing its operational status, and controlling conditions which affect subsystem operation. The communication function consists of all activities associated with receipt of information from sources outside the aircraft and with the transmittal of information by the crew. While these two functions are part of the crew's overall activity during recovery and landing, they are not of central concern in this study. Therefore, the subsequent analysis of display requirements does not include a delineation of information elements specifically associated with the subsystem control and communication functions.

It is customary in the analysis of pilot functions to include a category of activities called navigation. No such function is called out here since the activities usually associated with a navigational function are subsumed under monitoring or management or are excluded from the domain of pilot functions by the highly automated nature of the SSV system. Thus, insofar as navigation consists of processing external or onboard signals relating to present position and transforming them into specific flight path guidance, this function will be performed automatically

in the SSV. Insofar as navigation entails observation of geographic or radio indices to assure that the flight plan is being followed or that guidance is correct, it is considered a part of the monitoring function. Decisions relating to the continuing appropriateness of the navigational plan and to the need for modification fall within the realm of management functions in this study.

Analysis of Pilot Functions

Specific pilot task requirements will vary as a function of vehicle characteristics, flight technique, and the mechanization adopted for navigation, guidance and flight control. At this point in the SSV development process, the system configuration and subsystem characteristics are not sufficiently defined to permit a detailed analysis of individual task elements or operational sequences. Nevertheless, it is possible to describe, at a general level, pilot functions and information processing activities during each segment of recovery and landing.

Table II is an analysis of pilot functions for the maneuvering descent, initial approach, final approach, and landing segments of orbiter recovery. For each of the pilot's three major functions (Manage, Monitor, and Control), there is a listing of the kinds of information which are of concern in the performance of those functions. These are not necessarily specific items of information, although at the flight control level they often are. At the management level, the information of interest tends to be an integration of several information elements into a comprehensive assessment of the flight situation, formulated in appropriate decision-making terms. Thus, assessment of energy state, which is a management function during maneuvering descent, represents a complex integration of altitude, airspeed, distance to the runway, flight path angle, vehicle L/D characteristics, and so on.

The analysis distinguishes between IFR and VFR conditions and incorporates options for manual or automatic flight control. The operational model employed here assumes that in VFR conditions, maneuvering descent will be automatically controlled and that the pilot will transition to manual control at the high key and fly the vehicle to touchdown, relying more and more on visual reference as altitude decreases. In IFR, it is assumed that flight will be auto-controlled to touchdown and that the pilot will not have visual reference until he reaches an altitude of 200 feet. It is further assumed in the IFR case that the pilot can exercise the option to assume manual control at any point on the flight path, flying by instrument reference. This is not to suggest operational doctrine, nor to take a position on the issue of automatic vs. manual control. It is simply an analytic technique to exercise the control/display system in a very broad context of operational conditions.

TABLE II
ANALYSIS OF PILOT FUNCTIONS

Maneuvering Descent (VFR or IFR)	
MANAGE:	Energy state (range capability), approach path to high key, adjustment of energy management plan (if required).
MONITOR:	Attitude, angle of attack, flight path angle, airspeed, track, dynamic pressure (or temperature).
CONTROL: (Optional)*	Attitude, heading, flight path angle (or angle of attack).
Initial Approach (VFR)	
MANAGE:	Energy state (range capability, compensation for wind effects, selection of pre-flare aim point).
MONITOR:	Flight path angle, angle of attack, altitude, position relative to runway.
CONTROL:	Attitude, airspeed, final approach path (FAP) entry point, FAP entry altitude.
Initial Approach (IFR)	
MANAGE:	Approach to FAP entry point, adjustment of FAP entry point (if required).
MONITOR:	Attitude, angle of attack, airspeed, altitude, position relative to FAP references (glide slope and extended runway centerline).
CONTROL: (Optional)*	Flight path angle, FAP entry point, FAP entry altitude.

*During maneuvering descent and during initial and final approach in IFR conditions, automatic control is assumed to be the nominal mode of operation with manual control available as normal (not an emergency) pilot option.

TABLE II
ANALYSIS OF PILOT FUNCTIONS (Continued)

Final Approach (VFR)	
MANAGE:	Compensation for wind effects, adjustment of aim point and/or flight path angle (γ_G) (if required), selection of flare altitude.
MONITOR:	Attitude, angle of attack, altitude, vertical velocity, flight path angle (γ_G), acceleration (during flare).
CONTROL:	Airspeed (speed brakes and/or gear extension), velocity vector (impact point) relative to aim point, cross-track error, flare (altitude and vertical velocity).
Final Approach (IFR)	
MANAGE:	Energy state in relation to range, adjustment of airspeed and/or flare altitude (if required).
MONITOR:	Attitude, angle of attack, altitude, vertical velocity, airspeed, acceleration (during flare), glide slope (γ_G) error, cross-track error.
CONTROL:	Glide slope (γ_G) error, cross-track error, flare (altitude and vertical velocity), (Optional)* airspeed (speed brakes and/or gear extension).
Landing (VFR or IFR)	
MANAGE:	Energy state in relation to range, touchdown point in relation to dispersion and velocity constraints.
MONITOR:	Angle of attack, vertical velocity.
CONTROL:	Attitude, flight path angle, airspeed, vertical velocity, cross-track error, decrab (cross-track velocity and heading relative to runway).

*During maneuvering descent and during initial and final approach in IFR conditions, automatic control is assumed to be the nominal mode of operation with manual control available as normal (not an emergency) pilot option.

Information Utilization by Flight Segment

The information processing activities tabulated above constitute a general statement of display system requirements for recovery and landing operations. To translate this into a specific statement of the required display referents, it is necessary to examine each information processing activity and identify categorically the parameters of the flight situation which must be known in order to perform the activity.

Table III is an analysis of information utilization by flight segment. The parameters of the flight situation which relate to performance of management, monitoring, and control functions are identified for each flight segment. The analysis takes into consideration the association between individual flight parameters and specific information processing activities. However, this relationship has not been preserved in Table III since the concern is to describe the totality of pilot functions not specific components of the process. Table III is therefore a consolidated listing of parameters which are of interest in performing one or more information processing activities associated with each major function in each flight segment.

TABLE III
Information Utilization by Flight Segment

PARAMETERS OF INTEREST	MANEUVERING DESCENT			INITIAL APPROACH			FINAL APPROACH			LANDING		
	MNG*	MON†	CON‡	MNG	MON	CON	MNG	MON	CON	MNG	MON	CON
Attitude (θ, ϕ, β)	✓	✓	✓		✓			✓				✓
Airspeed (V)	✓	✓		✓	Ⓛ	Ⓧ	✓	Ⓛ	✓	✓		✓
Altitude (h)	✓			✓	✓	✓	✓	✓	✓			
Vertical Velocity (\dot{h})								✓		✓	✓	
Angle of Attack (α)	✓	✓			✓			✓			✓	
Flight Path Angle (γ)	✓	✓	✓		✓	Ⓛ						
Glide Slope (γ_G)							✓	✓	Ⓛ	✓		✓
Acceleration (g)		✓			✓			✓				
Dynamic Pressure (q)		✓										
Heading (ψ)	✓		✓		✓			✓				
Track	✓	✓		✓	Ⓛ	✓	✓	Ⓛ	✓	✓		✓
Position (with respect to runway, key control points, aim points)	✓	✓		✓	✓	Ⓧ	✓	✓	Ⓧ	✓		✓

*MNG = Management; †MON = Monitor; ‡CON = Control; ✓ = VFR and IFR; Ⓛ = IFR Only; Ⓧ = VFR Only.

Identification of Display Referents

Table III identifies the parameters of interest in categorical terms, e.g., attitude (pitch, roll, and yaw). This identification is too general to serve as the basis for prescription of display requirements. For example, it is not sufficient to state that attitude information is a display requirement. The analysis must be carried one step further to identify what form of attitude information is needed for a given purpose—actual pitch attitude to determine the present vehicle state, command pitch to indicate vertical flight path corrections, and pitch limits to assess the difference between actual and commanded pitch in terms of the aerodynamic capability of the vehicle.

Table IV is an analysis of the previously identified parameters of interest, indicating the several forms of information required for management, monitoring, and control purposes. These are designated “display referents” and are divided into related groups or families (e.g., heading, track, and drift angle). Since the analysis deals with the form of information more than its application, the functional classifications of Management, Monitoring, and Control have been dropped. In their place, the following classifications are used:

1. Status – information relating to the present state of the vehicle.
2. Guidance and Navigation – information relating to the desired or predicted state of the vehicle or to directed changes of state.
3. Flight Objectives and Constraints – information relating to the flight plan, safety of flight factors, and limitations or constraints bearing on the accomplishment of flight objectives.

There is not a clear-cut one-to-one relationship between these three classes of information and pilot functions. In accomplishing the flight control function, the pilot makes primary use of guidance and navigation information, with some status information as a supplement. Monitoring is concerned primarily with status information, but flight objectives and constraints are also of interest. The management function draws most heavily on flight objectives and constraints, with status information contributing to evaluation and assessment activities. As a simplification, it may be said that status information is used for monitoring, guidance and navigation for control, and flight objectives and constraints for management. The important consideration at this point, however, is not how the information is used; this has been established in earlier steps of the analysis. The objective is to identify the various forms of information needed to support one or more of the pilot's functions.

TABLE IV
Display Referents

STATUS	GUIDANCE AND NAVIGATION	FLT OBJECTS AND CONSTRAINTS
Pitch Attitude (θ) Roll Attitude (ϕ) Yaw Attitude (β)	Pitch Command (θ_c) Roll Command (ϕ_c)	Pitch Limits Roll Limits
Airspeed (V)	Predicted Velocity (V_p) Airspeed Error (ΔV)	Nominal Velocity and Limits
Altitude (h) Vertical Velocity (\dot{h})	Predicted Altitude (h_p) Altitude Error (Δh)	Nominal Energy State at Key Control Points (h & V)
Angle of Attack (α) Flight Path Angle (γ) Glide Slope (γ_G)	Projected Impact Point Glide Slope Error ($\Delta \gamma_G$)	Angle of Altitude Limits Nominal Flight Path Angle and Limits Wind Effects
Acceleration (g)		Acceleration Limits
Dynamic Pressure (q)		Nominal q and Limits
Heading (ψ) Track Drift Angle (β_G)	Runway Heading (ψ_R) Projected Track	Heading Relative to Runway at Key Control Points Selected Track Wind Effects
Position Relative to: Key Control Points Selected Flight Path Pre Flare Aim Point Runway Aim Point	Projected Range Capability Flight Path Deviation: Lateral (X-Y) Vertical (relative to Key Control Points or Approach Path)	Selected Reentry Target Position Selected Runway Offset Position Selected FAP Entry Point Selected Pre-Flare Aim Point Selected Flare Altitude Touchdown Constraints (X, Y, V, θ , ψ_R , \dot{h} , \dot{Y})

Minimum Display Requirements

Combining the results of the previous three steps of the analysis, it is possible to state the display referents required as a minimum to support the pilot's management, monitoring, and control functions in each flight segment of recovery and landing. (See Tables V and VI.) The requirements are set down in two groups—vertical situation display and horizontal situation display, which are further differentiated according to VFR and IFR conditions. Each table lists, in addition to basic requirements, possible alternative forms for some display referents.

TABLE V
Minimum Information Requirements for Vertical Situation Display

DISPLAY REFERENTS	M A N E U V E R I N G	INITIAL APPROACH		FINAL APPROACH		L A N D I N G	COMMENTS
		VFR	IFR	VFR	IFR		
Attitude (θ, ϕ, β)	✓	✓	✓	✓	✓	✓	
Pitch/Roll Command (θ_C, ϕ_C)	✓	✓	✓	✓	✓		Manual control only
Airspeed (V)	✓		✓		✓		To monitor automatic control
Airspeed Error (ΔV)		✓	✓	✓	✓		Manual control only
Predicted Velocity	A		A		A		Alternative to ΔV in IFR/Automatic
Nominal Velocity and Limits		A	A	A	A		Alternative to ΔV
Altitude (h)	✓	✓	✓	✓	✓	✓	
Altitude Error (Δh)		✓	✓	✓	✓		Manual control only
Vertical Velocity (\dot{h})					✓	✓	To monitor automatic control
Predicted Altitude	A		A		A		Alternative to Δh in IFR/Automatic
Nominal Energy State at Key Control Points	A	A	A	A	A		Integration of ΔV and Δh
Angle of Attack (α)	✓	✓	✓	✓	✓	✓	To monitor automatic control
Flight Path Angle (γ)	✓	✓	✓				} To monitor automatic control and to interpret θ_C guidance in manual control
Glide Slope (γ_G)				✓	✓	✓	
Glide Slope Error					✓		
Projected Impact Point				✓	✓	✓	
Nominal Flight Path Angle and Limits	✓	✓	✓	✓	✓	✓	To monitor automatic control and to interpret θ_C guidance in manual control
Angle of Attack Limits	A	A	A	A	A	A	Alternative to γ limits
Acceleration (g)	✓			✓	✓		
Total Dynamic Pressure (q)	✓						To monitor descent
Heading (ψ)	✓	✓	✓	✓	✓		} To monitor automatic control and to interpret ϕ_C guidance in manual control
Runway Heading (ψ_R)	✓	✓	✓	✓	✓		

✓ = Requirement A = Alternative

TABLE VI

Minimum Information Requirements for Horizontal Situation Display

DISPLAY REFERENTS	M A N E U V E R I N G D E S C E N T	INITIAL APPROACH		FINAL APPROACH		L A N D I N G	COMMENTS
		VFR	IFR	VFR	IFR		
Position (X-Y) Relative to:							
● Reentry Target Position	✓						
● Runway Offset Position	✓	✓	✓				
● Final Approach Path Entry Point		✓	✓				
● Pre-Flare Aim Point			✓		✓		
● Runway Aim Point					✓		
Present Flight Path (Track)	✓	✓	✓		✓		} To monitor automatic control and to interpret ϕ_C guidance in manual control
Selected Flight Path (Track)	A	A	A				
Flight Path (Track) History	A	A	A				} Alternative or addition to Present Flight Path
Predicted Flight Path (Track)	A	A	A				
Flight Path Deviation	✓	✓	✓		✓		} To monitor automatic control and to interpret ϕ_C guidance in manual control
Heading (ψ)	✓	✓	✓		✓		
Runway Heading (ψ_R)	✓	✓	✓		✓		

✓ = Requirement A = Alternative

It must be emphasized that Tables V and VI are statements of requirements and not rudimentary display concepts. The grouping into vertical and horizontal situation displays does not imply, necessarily, that two display systems are involved. The grouping only serves to distinguish between these display referents associated with short-term monitoring and control (vertical situation) and those associated with long-term assessment and management (horizontal situation). Likewise, there is no suggestion that all vertical or horizontal situation referents must be combined in a single display device. As pointed out at the beginning of this chapter, the term “display” is used to denote an information transfer function, not the medium of presentation.

As a final point, it must be stressed that no attempt is made to specify indirectly the source of the required information. In the VFR condition, the information may be derived from natural visual cues or from instrument references. (IFR, by definition, requires some artificial source.) Furthermore, the listing of an item such as airspeed as a required display referent does not imply that an airspeed indicator or an electronic equivalent is the medium of display. Airspeed information could be provided by some other kind of visual analog, by an auditory signal, or by a pitch command index programmed to incorporate airspeed inputs. Similarly, glide slope (γ_G) does not suggest that the ILS or a similar radio beacon system is required. The term simply denotes that some sort of angular reference to a predetermined point on the ground is needed for flight path control or monitoring during the final approach and landing.

The requirements set forth here are intended solely as a statement of the display support which must be provided to the pilot in fulfilling his task demands during recovery and landing. The translation of these requirements into display concepts and the outlining of alternative display solutions will be taken up in Chapter 5 of this report.

CHAPTER 4

ADVANCED DISPLAY CONCEPTS AND TECHNOLOGY

The design of displays for aircraft has undergone a revolution in the past ten years. The basis for this revolution has been the computer-driven CRT, which can be used to create time-shared, multiple-item displays with a compact format. Nearly all military aircraft developed since 1960 have made extensive use of electronic displays for flight control, navigation, and system management. Experience has demonstrated the effectiveness of these advanced display concepts both in augmenting manual modes of control and in monitoring automatic guidance and navigation systems. Their principal values lie in the areas of reducing crew workload and in displaying multi-dimensional representations of the flight situation to help the crew anticipate vehicle performance during changing flight regimes.

The application of electronic displays in civil aviation has lagged somewhat behind military development, but it is interesting to note that the design of the supersonic transport and the DC-10 jumbo jet have placed heavy emphasis on advanced display techniques. The SST example is particularly relevant because of all recent system development efforts it is closest akin to the space shuttle in terms of autonomy of operation, level of automation, and complexity of mission planning and execution. One writer (Warner, 1970) has stated the belief that the computer-driven CRT forms the basis of cockpit equipment which will permit implementation of the long desired crew management concept.

This chapter is a survey of recent developments in display design. The purpose is to take stock of advanced display concepts and techniques and to assess their potential value in recovery and landing operations. The chapter begins with a discussion of some current trends in aircraft displays, including a statement of the basic design issues relating to the SSV. Following this is an examination of presently available displays with particular emphasis on advanced electronic devices and techniques. In general, this survey is intended to form the background for the subsequent chapter which outlines selected display concepts for recovery and landing operations.

Current Trends in Aircraft Displays

The advent of the digital computer and the CRT has led not just to examination of new possibilities for information display but also to a fundamental rethinking of the nature and purpose of information transfer in the cockpit. In fact, the term used to describe this function ("information transfer," rather than "instrumentation") suggests that the emphasis is not on how to measure and display individual elements of system status and the flight situation but on how the aggregate of these data is to be used by the pilot for command and control.

In part, this re-examination has stemmed from a growing awareness that the traditional approach to cockpit displays is not adequate for complex, sophisticated, and highly automated modern aircraft. Historically, instruments have been developed and introduced in aircraft piecemeal, each intended to serve a specific need without much regard for its relationship to other instruments or the pilot's overall task. The result in recent aircraft is a myriad of instruments, indicators, dials, and similar single-purpose display devices—often totalling two or three hundred. Periodic attempts, possibly motivated by a nostalgic wish for a return to simpler days, have been made to strip these imposing arrays down to bare essentials. Minimum displays, however, do not lead to optimum performance as system operation grows more complex and the demands on the pilot are increased. The real concern is not simply with the number of system parameters which the pilot must consider nor with the proliferation of instruments. Fundamentally, the problem is one of relieving the pilot of the burden of selecting and integrating these separate indications into a comprehensive picture of the flight situation. It has been established that the more data sources with which an individual must deal, the less information, in terms of deviations from normal, can he be expected to handle (Olson, 1963). The inadequacy of standard instruments becomes particularly acute in situations where it is attempted to monitor and evaluate the operation of an automatic system with displays originally designed as aids to manual control.

An alternative to the traditional, additive approach to information display begins not with an analysis of individual data elements in the system but with an examination of the nature of the pilot's participation in the system, the pilot's role. The aim is to construct a scheme into which all the various pieces of information will fit in a logical way. Carel (1965) and Roscoe (1968) have suggested that within the general task of navigation and flight control, there are four major clusters of tasks, each relating to a category of information:

1. Where am I with respect to my destination?
2. What is and what should be my velocity vector?
3. What is and what should be my attitude and/or angle of attack?
4. What should I do with the controls?

In theory, the pilot could be presented with information related to each of these tasks separately. However, since each task is hierarchically related to those listed above and below it, the categories of information are not independent but inherently related because of the way the aircraft operates. The operation upon information at one level and the selection of the appropriate control response depends, in part, upon a knowledge of how this response will be manifested at other levels. The trend in current display design, therefore, is to seek ways of integrating these classes of information into a unified, often pictorial, representation of total flight situation.

Present designs tend to be of two types: the vertical situation display and the horizontal situation display. The former represents a view ahead of the aircraft in azimuth-elevation coordinates, which provide a common frame of reference for all information shown on the display. Generally, the display contains information related to the higher frequency variables of flight control, tasks 2, 3, and 4 above. Because vertical situation displays are normally used for tracking, symbol dynamics and sensitivity are important design considerations, and frequent use is made of quickening and short-term prediction. The horizontal situation display characteristically represents the situation of the aircraft as though viewed from above, looking down at the Earth. The display contains all those elements which can be meaningfully represented in X-Y or rho-theta coordinates. Generally, the display is related to control of the lower frequency flight variables, tasks 1 and 2 of the hierarchy.

In recent years, notably in connection with the SST program, a third type of display has been developed. This is a multi-parameter display, containing information such as thrust, acceleration, fuel, time, and other items not directly portrayable in X-Y-Z aircraft coordinates. Such displays are often graphic plots of complex flight management problems, and they tend to be used by the crew for devising a general solution strategy or for monitoring long-term trends in the flight situation, especially where execution of the control functions is delegated to automatic systems.

Cutting across these types of displays, particularly the vertical situation display, are two somewhat opposed concepts of how the information is to be presented. One is the contact analog concept whose rationale is to recreate on the display an abstract rendition of the external visual scene. The display is intended to serve as an analog of the natural visual cues used in contact flight, providing the equivalent of "a perfect VFR day" within the cockpit. The basic premise of the contact analog is that pilots are accustomed to, and can perform satisfactorily with, real world visual flight cues. When these cues are diminished or denied by weather or darkness, the contact analog provides a natural and familiar substitute. Because of the emphasis on duplicating the external visual scene, the form of presentation in the contact analog tends to be pictorial rather than symbolic, and numerical and scalar indices are minimized.

An alternative to the contact analog is a concept which may be called the "instrument analog." The basic premise of this display is that flight by visual reference and flight by instrument reference are inherently different processes. While it is true that certain surrogates of the visual scene may be useful in the IFR situation, there are many flight control parameters for which no adequate external visual cues exist either IFR or VFR. This is particularly true for information relating to rates, accelerations, and higher derivatives where the unaided human capacity to make these discernments is demonstrably weak. Therefore, the purpose of the instrument analog is to create a compact, efficient, and highly usable array of instrumental references within a single display. The basic approach is to proceed from conventional panel displays, which are symbolic in form and familiar to pilots, and to seek a unified, unambiguous presentation of required information without forcing it into a predetermined pattern of literal correspondence to the external scene.

No argument is advanced here for either of these display concepts. Both are soundly conceived and indicative of ways in which an integrated, multi-dimensional rendition of the flight situation can be achieved. They typify the basic aims of most current display design, which may be summarized as follows:

1. To lessen pilot workload by reducing the number of mental transformation steps required to close the control loop;
2. To promote optimum pilot performance by selectively integrating and displaying those elements of information pertinent to related clusters of tasks;
3. To take full advantage of the flexibility and adaptability of pilots by presenting information relative to command judgments and management options as well as to flight control functions.

As a result of these aims, certain design features emerge which characterize advanced aircraft displays. As indicated earlier, nearly all derive from the versatility of computer-driven CRT technology. The contemporary aircraft display is not a dedicated (single-purpose) instrument; it can be time-shared to provide whatever information is needed for a given purpose. By means of the computer, it is possible to combine and integrate information from diverse sources and to alter these combinations in response to the demands of the situation or pilot preference. In addition, the computer can generate information which is not only descriptive of the present state but also predictive of future trends, helping the pilot to stay ahead of the situation. The CRT allows great freedom of choice in the static and dynamic properties of symbols and in display format. Thus, it is possible to circumvent the mechanical limitations of conventional instruments, and to achieve a relatively dense, but uncluttered information array. Finally, the combination of a high-speed computational device and a flexible information output device permits the presentation of solutions and options rather than just statements of problem values. Much of the preference for electronic displays shown in SSV design documents undoubtedly stems from recognition of the enormous and varied capacity of the computer and the CRT to respond to a wide range of SSV mission requirements.

The foregoing should not be interpreted as an assertion that advanced display concepts offer complete solutions to the problems of flight control, navigation, and system management. There are still a number of important issues to be resolved. However, most are concerned not so much with the technical aspects of electronic display media as with the more fundamental topics of allocation of man and machine functions, flow of information across the man-machine interface, and system integration. Three of these issues will be reviewed briefly here because of their importance in recovery and landing operations.

A central issue is the question of automatic vs. manual control. Preliminary SSV design documents suggest that essential control functions will be allocated to a flexible, sophisticated computer-avionics complex. This is, however, only a general statement of principle at the present time. What still must be determined is the specific application of the principle to recovery and landing operations. On one hand, the orbiter will be equipped with a highly versatile computer and avionics system required for other portions of the mission. It seems desirable to draw on this capability to support the recovery and landing operations and to insure its safety, especially since automatic systems are generally superior for processing large amounts of data and for responding in a repeatable way to identical stimuli. On the other hand, there is an impressive amount of evidence gained through lifting body research which suggests that manual control of approach and landing is a workable proposition (NASA, 1970b). However, the applicability of these techniques to the orbiter is not certain because of different vehicle characteristics and the more complex energy management and navigation problems relating to return from space flight. The allocation of man and machine functions in recovery and landing is a pivotal decision for display design since it will determine not just the content and form of the displays but also their nature and use.

Automatic vs. manual control is not an either-or proposition; the solution almost certainly lies in some blend of the two control modes. For those functions which are automated, there will still be an important area of pilot involvement in managing and overseeing Automatic Flight Control System (AFCS) operation. The managerial role may be defined as consisting of selecting modes of operation, entering data, monitoring performance, and intervening or overriding in case an out-of-tolerance situation develops. The delineation of display characteristics to support these activities is the second major issue in orbiter display design. Some of the questions which must be addressed in this area are:

1. What data processing and display features are required to support the crew in monitoring AFCS operation and in taking timely action if an out-of-tolerance condition develops?
2. What levels and modes of override should be available and how should the information needed to support this intervention be displayed?
3. What kinds and levels of degradation in the information processing and display equipment are tolerable if the crew is to continue to fulfill management functions?
4. What display features are needed to promote crew acceptance of, as distinct from management of, automatic modes of operation?

The third major issue concerns the implementation of display concepts for those portions of recovery and landing which will be manually controlled— either as the primary mode of operation or as an option. In terms of display design, the question here is not which information to present but in what form. To assure rapid and smooth pilot response in manual operating modes, it is desirable to eliminate as many mental integrations as possible from his overall control loop. Recent

display research has shown this is best accomplished by means of a flight director display incorporating derivative information. On the other hand, pilots have a natural and understandable reluctance to follow a highly processed steering command without some knowledge of the basic flight situation (error) which must be corrected. That is, the pilot's experience dictates that he must know not just what to do but why. Moreover, every control task involves prediction—extrapolation from the present situation and rate of change to some desired future state. All in all, this calls for a display which shows the action to be taken, the result of actions already taken, and the consequence of continuing the present actions (Walters, 1966). Computer-driven CRT displays, in general, offer a superior means for presenting these three forms of information and for integrating them in a coherent, pictorial format. The problem is to develop specific display solutions applicable to orbiter recovery and landing.

Survey of Advanced Display Technology

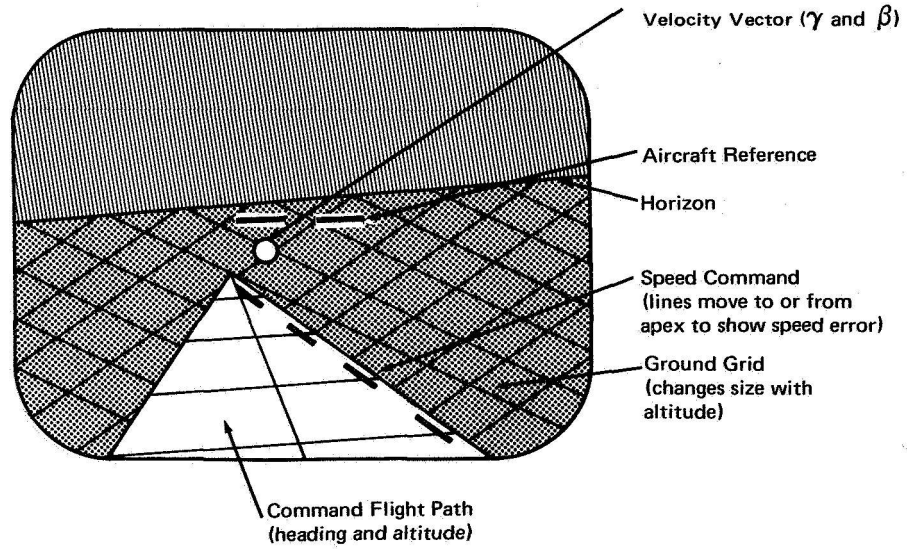
The following is a survey of the principal types of displays currently available or in advanced stages of development. The emphasis is on CRT displays since they are by far the most widespread in their use and offer the greatest variety of applications. However, a summary is also provided of non-CRT techniques such as electroluminescent displays, opto-mechanical projected displays, and some advanced types of standard instruments.

Flight Displays

The most common type of electronic display is the CRT vertical situation display. It is often called an electronic attitude director indicator (EADI), and the name suggests its major functions. It is a display of attitude information; it serves as a flight director; it provides supplemental indications such as airspeed, angle of attack, altitude, vertical velocity, and heading. In general, the EADI is intended to provide all the information needed for vertical and lateral flight path control, integrated in a pitch-roll (elevation-azimuth) coordinate system. The EADI thus combines the functions of six or seven conventional flight instruments and is, in effect, an instrument panel within the instrument panel.

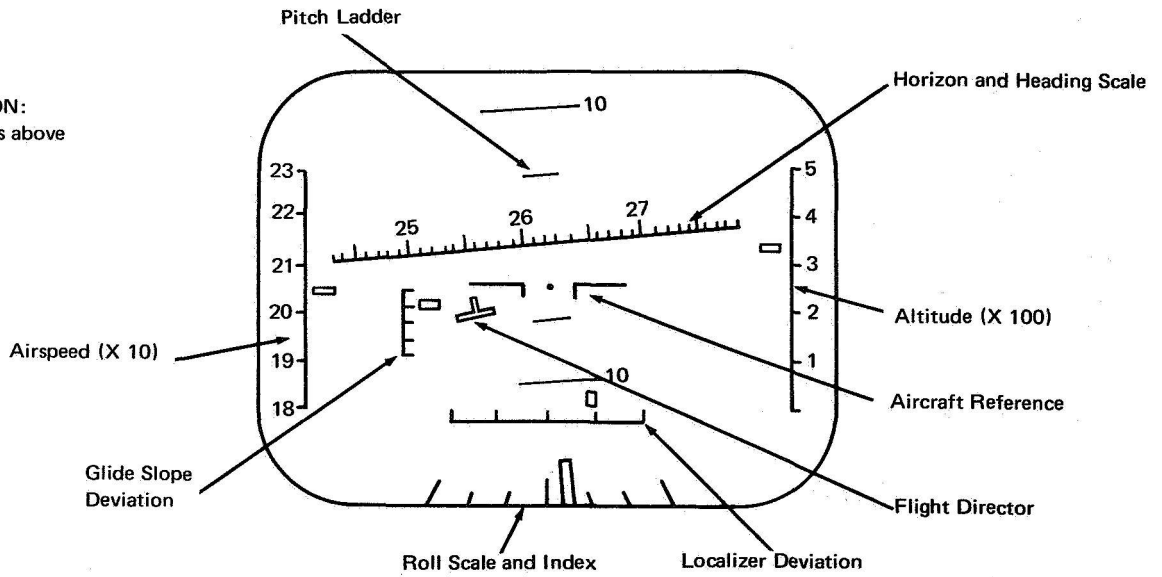
Figure 7 is an illustration of two typical EADIs. Figure 7a is a contact analog display and Figure 7b is an instrument analog display. The correspondence between the contact analog display and the external visual scene is evident in the illustration. Equally obvious is the derivation of the instrument analog from standard instrument models. In both displays all elements and symbols are entirely synthetic, i.e., they are generated by computer graphic techniques. Either raster or line-writing methods of symbol generation may be employed.

SITUATION:
 Aircraft in descending turn; Pilot in process of satisfying command to reduce altitude and turn left by flying velocity vector symbol to flight path apex



a. Contact Analog Display

SITUATION:
 Same as above



b. Integrated Instrument Analog

Figure 7. Typical Electronic Attitude Director Indicators

Figure 8 shows another type of flight display in which computer-generated symbols are combined with, and overlaid on, a video image of the external visual scene. Such displays are sometimes called "see-through" since the viewer is able to see a ground image, much as he would if the symbols were projected on a transparent surface. Several direct-imaging systems may be employed; simple television, low-light-level television, infra-red optical scanning, forward-looking radar, and microwave radiometric scanning are among the most common. Since the "see-through" display consists of two independently derived representations of the vertical flight situation, it has found primary application as an aid to low-visibility approach and landing. The direct-image portion of the display serves as a confirmation of the data presented by the symbolic, computer-generated portion, hence the name "Independent Landing Monitor" (ILM). In turn, the symbolic data (which is presented in registry with the pictorial scene) serves to enhance certain key features of the terrain and runway such as the horizon, runway outline, approach lights and references, or surface obstacles.

A third major type of flight display is the head-up display (HUD). In function, the head-up display is much like the EADI. The essential difference is that the EADI provides a flight display (with or without ILM) on the instrument panel while the HUD projects a symbolic array on a transparent surface in the pilot's forward external field of view so that the display appears superimposed on the real world scene. Because the image is collimated, the symbols appear at the same distance as, and in registry with, what the pilot sees through the windshield. Thus, he can observe natural visual cues and instrumental indices in the same field of view and at the same time. Figure 9 shows two typical head-up displays.

The HUD is intended to overcome the basic incompatibility which arises when the pilot must fly by visual reference but monitor panel instruments at the same time. The incompatibility is particularly severe when the pilot must divide his attention between instrument and visual reference during a critical flight phase, such as breaking out of the overcast on a low-visibility approach. The HUD eases the transition problem by giving the pilot instrumental information in the same visual area where he must look for external cues and in a skeletal form which will blend with the real world when it appears. Thus, the HUD bridges the gap between IFR and VFR by eliminating the need for the pilot to shift his view, change frames of reference, and accommodate to a different viewing distance (Jenney et al., 1970).

The most common technique for generating the head-up display is the CRT. However, there are alternative methods. The most important and effective is an opto-mechanical device which makes use of illuminated, servo-driven reticles to generate symbols. Through a series of mirrors the individual symbols are combined, and the total array is collimated and projected in the same way as CRT-derived displays. Since filters of almost any color may be used, the illuminated reticle method offers the additional advantage of a color-coded display. The chief disadvantage lies in the limitations on symbol dynamics imposed by the servo mechanisms used to move reticles.

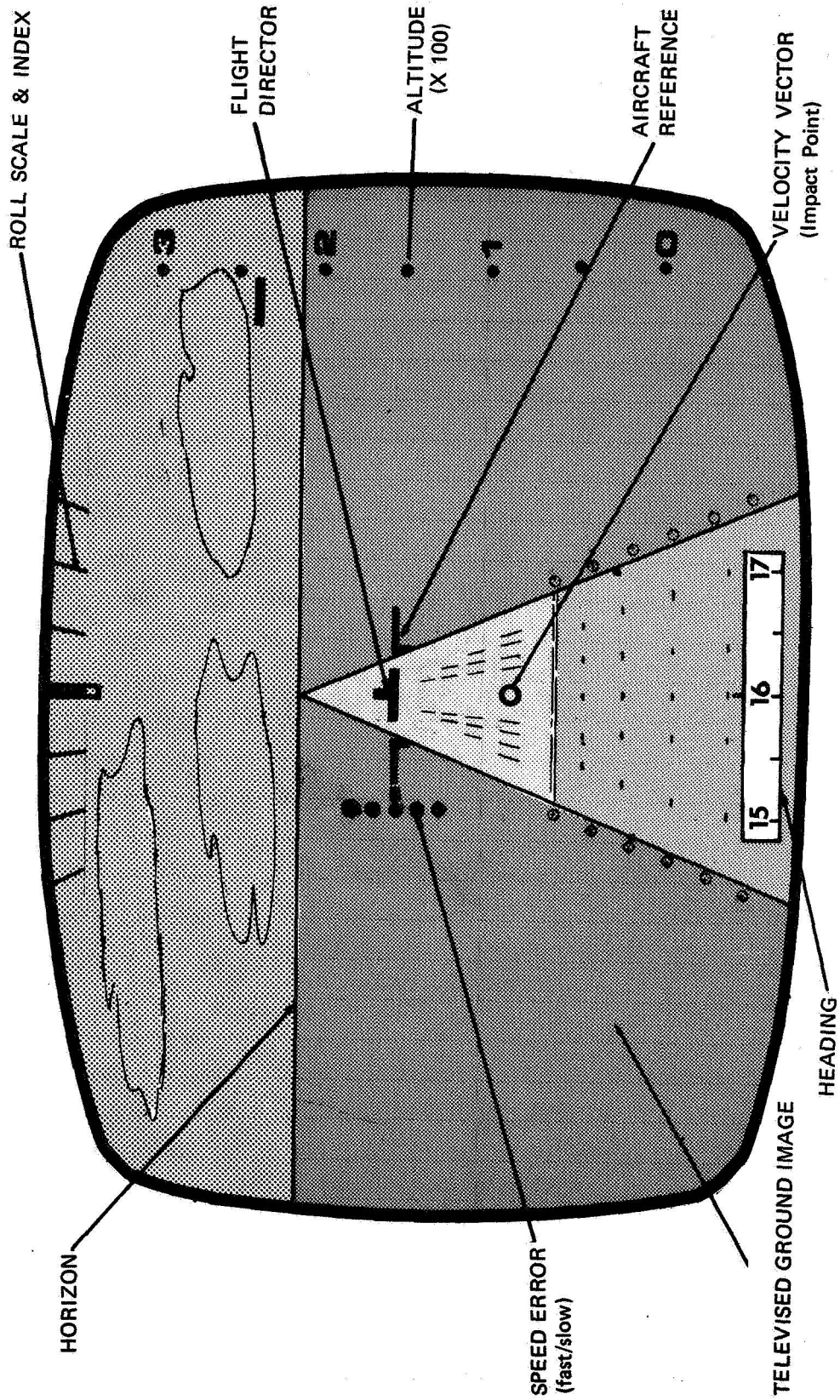
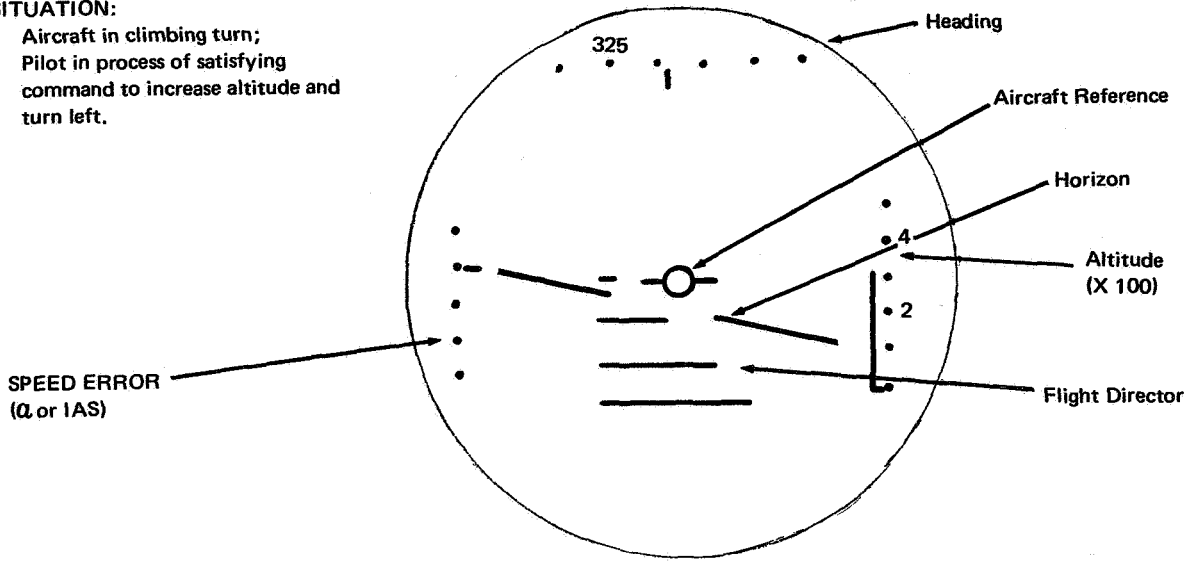


Figure 8. EADI with Independent Landing Monitor

SITUATION:

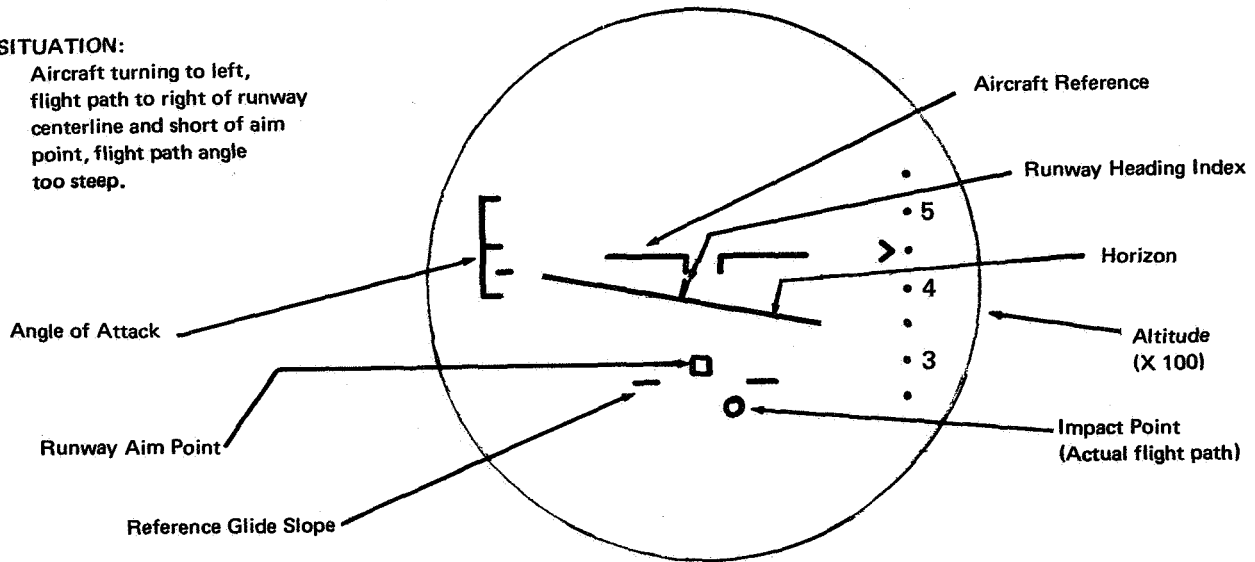
Aircraft in climbing turn;
Pilot in process of satisfying
command to increase altitude and
turn left.



a. HUD with Flight Director

SITUATION:

Aircraft turning to left,
flight path to right of runway
centerline and short of aim
point, flight path angle
too steep.



b. Flight Path Angle Display

Figure 9. Typical Head-Up Displays

Navigation Displays

For the purpose of navigation and long-term management of the flight path, there is a need to represent the situation of the aircraft in a plan position format using X-Y or rho-theta coordinates. Displays of this type are called horizontal situation displays or map displays. In general, three classes of information are presented:

1. Cartographic includes geographic and natural terrain features, compass (heading) references, and man-made elements such as radio beacons, prescribed zones of flight, and airports. Generally, such information does not vary over time and is independent of the particular flight situation.

2. Symbolic is comprised of pictorial or graphic indices of heading, course, present or predicted ground track, destination or target areas, way points, cruise range, and the like. This information varies as a function of both time and the individual flight plan.

3. Alpha-numeric is generally supplementary to the other two classes. It consists of items such as geographic coordinates, names or identifiers of display elements, and distance or time readouts.

As a whole, the horizontal situation display serves to assist the pilot in planning the flight, in maintaining orientation, and in monitoring the progress of the flight. Such displays are seldom used for the purpose of short-term flight control. However, they may be of assistance in predicting the results of specific flight control action or in selecting a control strategy.

Several display mechanization techniques are available, all more or less equally effective. The choice of which to employ depends not so much on the technical aspects of display generation as on the type of information to be presented. The following is an enumeration of the more common display techniques and their applications.

A simple and widely used technique is the moving map display, in which a topographic chart is translated and rotated with respect to an aircraft reference symbol to portray the navigational situation. (See Figure 10.) The chart may be either a printed map or the projection of a photographic film on a flat surface. Multiple maps, with different scale factors, may be used to aid the pilot in general flight planning, en route navigation, and approach to the terminal area. Map displays offer the advantages of complex chart capability and color. However, since such displays are based on stored data pertaining to the static features of the horizontal situation, they have only limited capacity for presenting time-variant and flight-peculiar information. Usually only a display of heading, present position, and relative bearing to navigation fixes is possible.

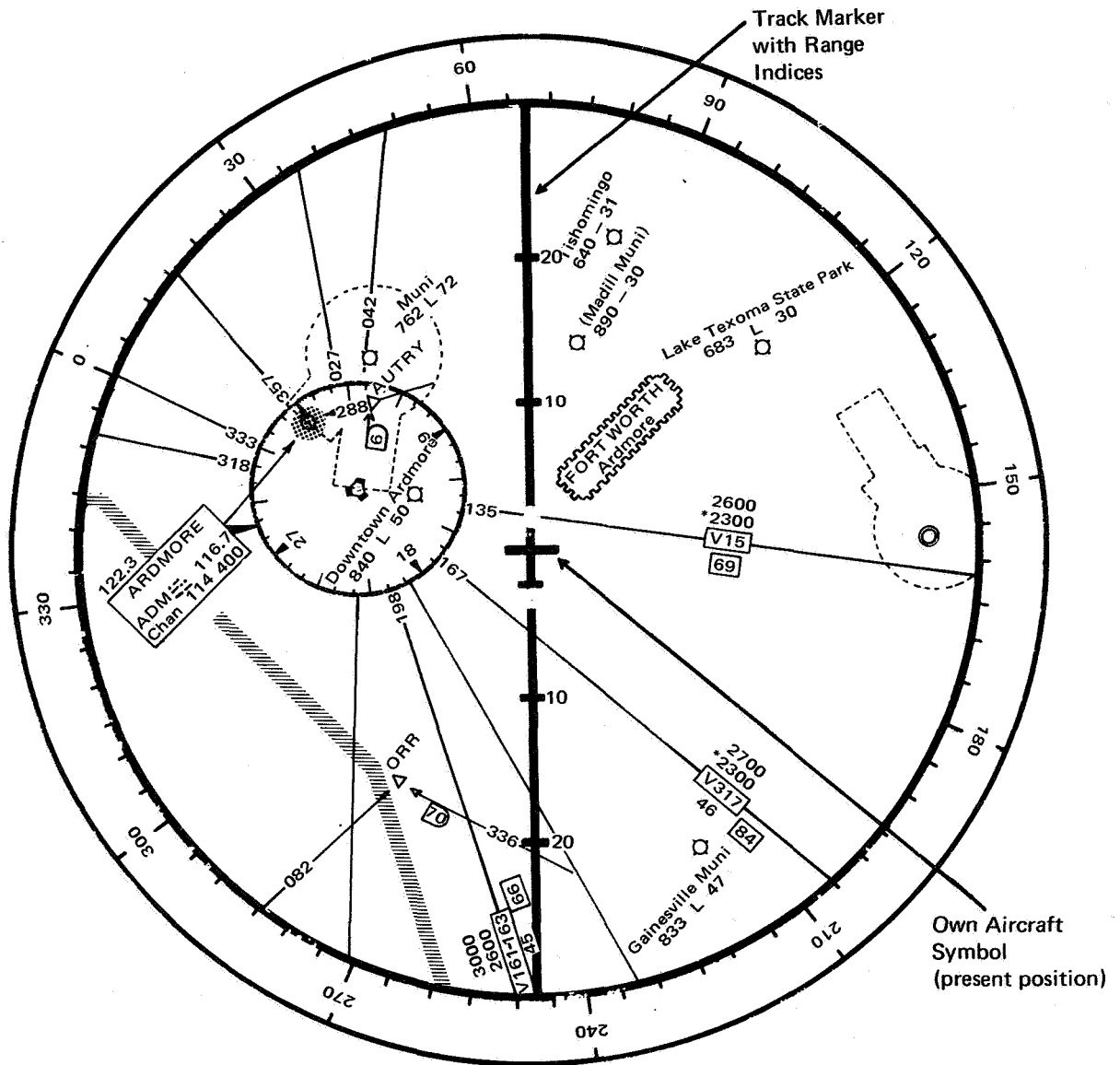


Figure 10. Moving Map Horizontal Situation Display

An alternative to the moving map display is a CRT-based horizontal situation display. (See Figure 11.) The CRT permits great flexibility in format and content, and it offers a wide variety of symbol dynamics. The cartographic capability of the CRT is somewhat weak due to limitations in symbol generation and to problems of clutter. On the other hand, the CRT is a superior medium for display of dynamic horizontal situation variables and predictor indications. Ultimately, the choice between CRT and moving map techniques rests on whether the information needed by the pilot is primarily symbolic or cartographic, i.e., more or less variable as a function of time and specific flight parameters.

A compromise solution is offered by a third group of display generation techniques which combine map and dynamic symbol features. One such technique is the rear projection CRT, in which a filmed map is projected onto the CRT face and overlaid with computer-generated symbols. Another technique employs a video scan of a printed map which is mixed with computer-generated symbols and presented on a CRT. A variation of this technique is to present a radar-derived ground map overlaid with symbolic indices.

Multi-Function Displays

As flight planning and management become more complex and as more control functions are delegated to automatic systems, the need arises for a display which permits the pilot to visualize flight problems (and their solutions) in a graphic or symbolic format which may not be directly related to the three aerodynamic axes. This is the so-called multi-function or flight management display, which is a general-purpose, time-shared CRT device presenting various kinds of system and flight operations data. The multi-function display (MFD) demands a large and versatile digital computer with the capability to generate graphic, symbolic, and alpha-numeric information. The display is often interactive, in that the pilot is able to insert specific problem values, to alter situation parameters, and to revise computer-generated solutions by means of controls which allow him to address the data processing complex directly. Another feature of the MFD is the capacity to present checkout and system programming data, usually in list form, to aid the crew in setting up subsystems for transition between major modes of operation. The MFD can also be used to present diagnostic data for assessing system operational capability or degradation.

Figure 12 is an illustration of several modes of information display which are possible with the MFD. The examples are drawn from display concepts which were developed for the SST, which was one of the first aircraft systems to envision extensive use of the MFD (Gannett, 1970). While the sample MFD modes shown in Figure 12 are not appropriate to space shuttle approach and landing operations, they are nevertheless representative of the range and potential utility of the MFD concept.

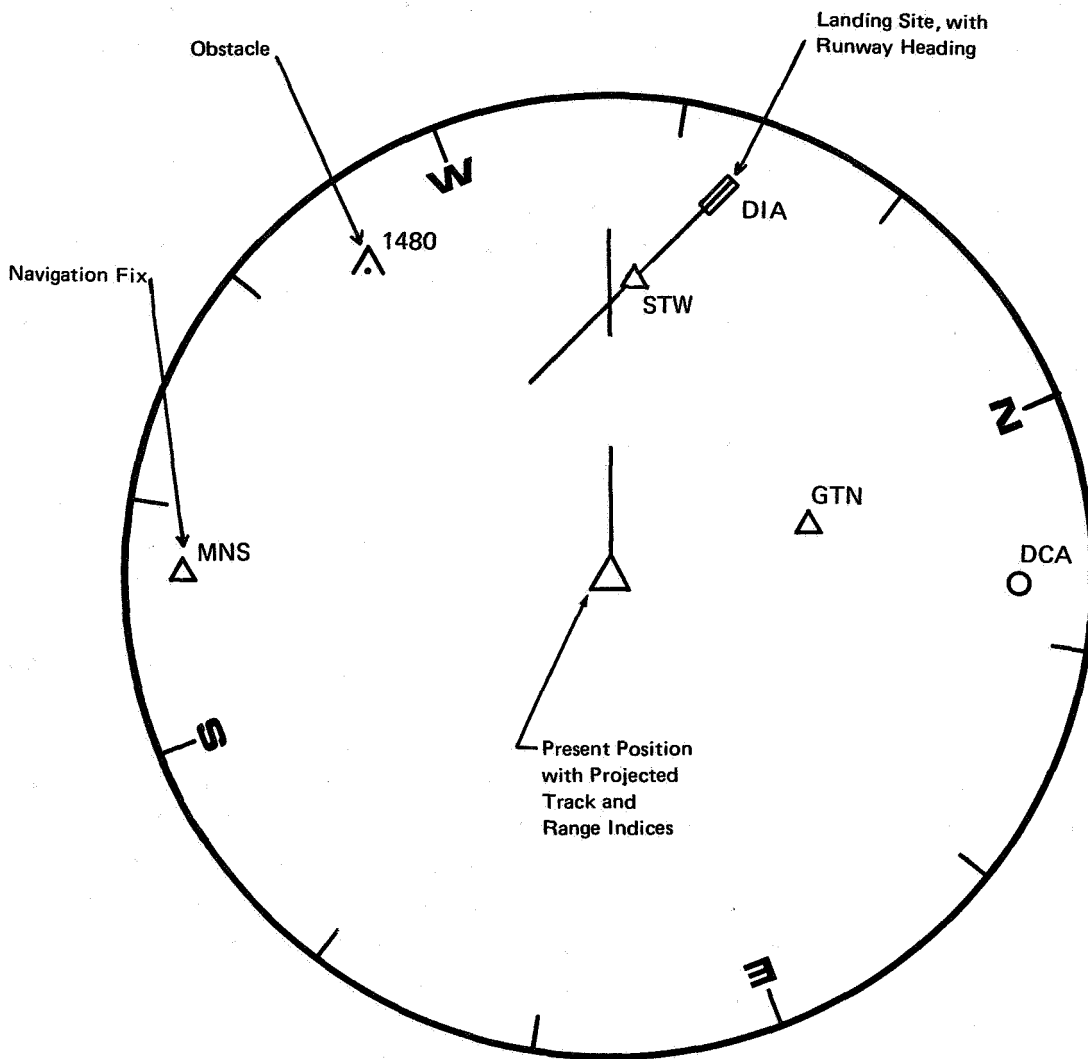
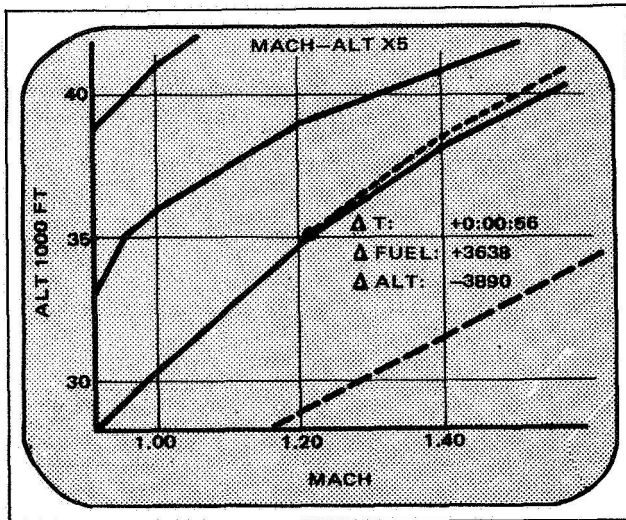
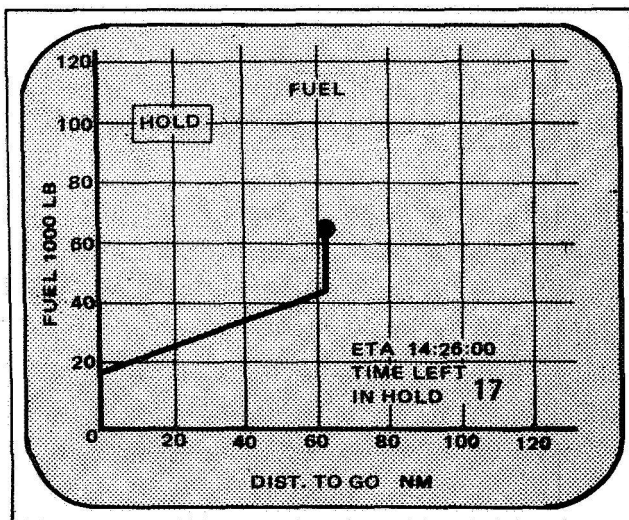
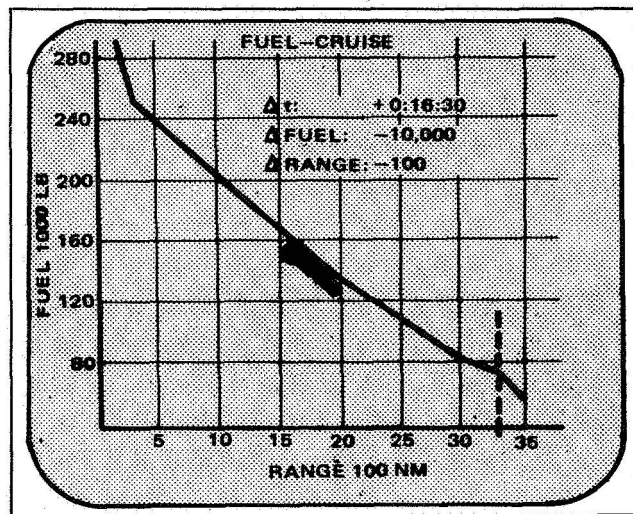


Figure 11. CRT Horizontal Situation Display



MACH. ALTITUDE MODE

FUEL MANAGEMENT MODE



HOLDING MODE

(Adapted from Gannett, 1970)

Figure 12. Multi-Function Display

Other Devices and Techniques

The foregoing survey has stressed CRT-based display techniques for two reasons. First, CRT technology is the most fully developed of all advanced electronic display systems. Second, the CRT appears to be best suited to the range of problems presented by space shuttle operations. To round out the picture, however, it is necessary to review briefly other advanced display techniques which are of potential application to the SSV. Two classes of display techniques will be considered: improved conventional instruments and non-CRT electronic devices.

Intensive effort has been devoted to development of an improved electro-mechanical ADI as a flight control display. Figure 13 is an illustration of one such display. In addition to the conventional three-axis attitude reference and flight director elements, the display includes localizer/glide slope deviation limits (bullseye), a fast-slow index (based on speed or angle of attack), and a partial altitude scale. An alternative feature of this instrument (not shown in Figure 13) is the "rising runway" element which is driven primarily by radar altitude to indicate flare initiation and to guide the flare maneuver. The instrument also incorporates advisory flags of system status and mode of operation. A display of this sort represents an electro-mechanical solution to some of the problems which have prompted electronic display research, viz., display integration and complete flight data display.

Walters (1966) reports work done at the Royal Aircraft Establishment, Farnborough, to develop an improved mechanical instrument which is called "reversionary." This device combines the features of a servo-driven instrument based on air data computer inputs with a standard, direct-drive mechanical instrument. Thus, instead of providing two airspeed indicators in the cockpit (a primary indicator derived from corrected air data from the computer and a stand-by derived from unprocessed pitot-static data), the two instruments are combined in one unit. In such a system the basic moving element (e.g., a pointer) is driven to show a simple, uncompensated value. Overriding this is a servo signal of the full corrected and highly accurate value from the computer. If the servo signal fails, the instrument reverts to direct mechanical drive. This principle can also be applied to gyro-stabilized instruments. Precision reference signals from an inertial platform, as long as they are available, can be used to control the position of a simpler, liquid-leveled gyro.

Substantial effort has been directed in recent years to development of electronic techniques to replace the CRT. None has reached the stage of development where it is an "off-the-shelf" system, but several do offer considerable promise, primarily because they can be produced in slim, lightweight packages—thus avoiding the long neck and weight of the CRT display, which may be handicaps in space vehicle installation. The chief drawbacks of these other electronic techniques in comparison with the CRT are limited range of application, low brightness, insufficient resolution, and restricted display size. The following is a brief description of the more significant potential alternatives to the CRT.

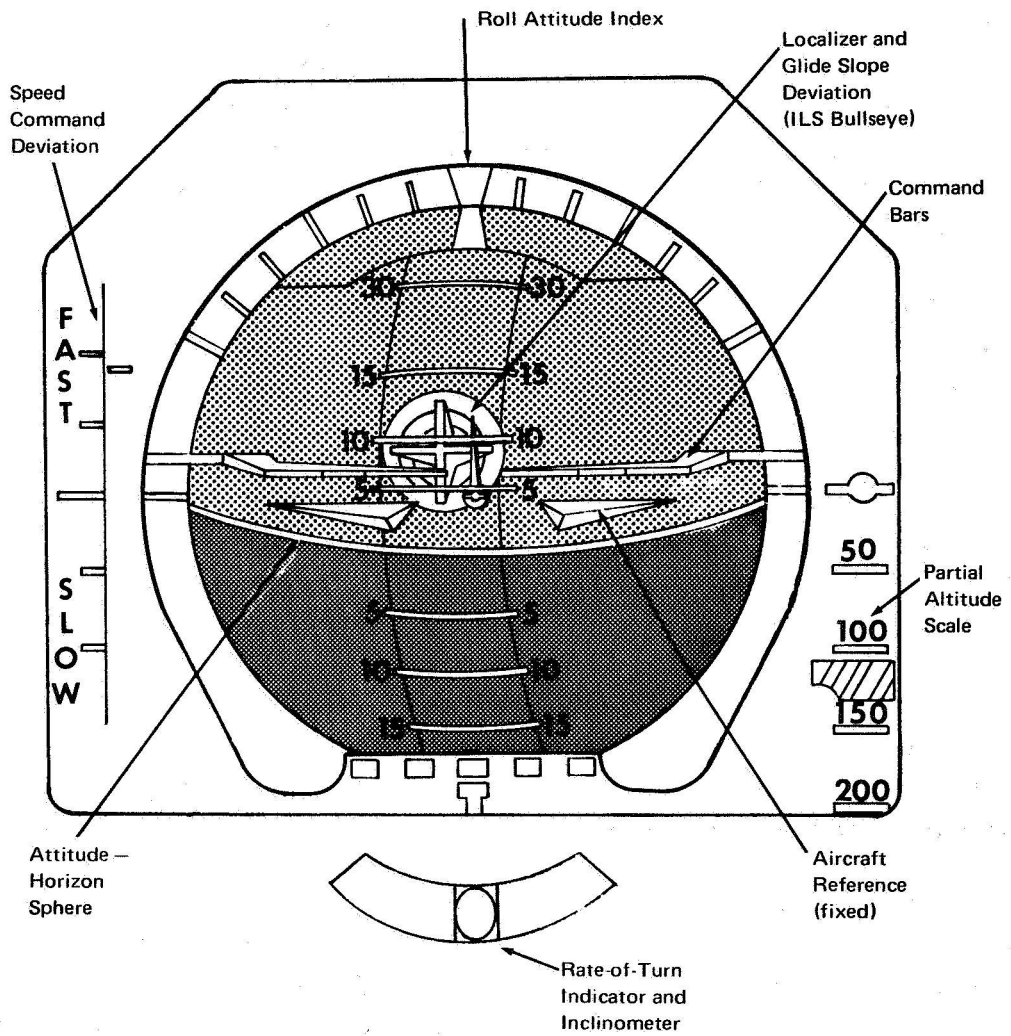


Figure 13. Electro-Mechanical ADI

1. Electroluminescence—Much work has been done on electroluminescent panels for display purposes. These panels consist of a phosphor placed between closely spaced electrodes. When a current is applied to transparent conductors on the panel, the phosphor glows. In general, light output is low, and attempts to increase brightness by increasing the amplitude or frequency of the exciting current reduce the life of the elements. Another version of electroluminescence, which gives improved brightness, and the added advantage of multi-color, is gallium arsenide or gallium phosphide excited by direct current. However, this type of EL display is still in a developmental state.

2. Plasma—A recent development is the plasma display panel, which is a matrix of individually addressable cells, each filled with an inert gas. Voltage applied across the cells causes the gas to ionize and glow. Such displays are presently limited in size; 4 x 4 inches is the largest fabricated to date. The lifetime of such displays has not yet been established, although theoretically their life should be long. Plasma displays have a relatively low brightness (about 30 foot-lamberts), which may limit their utility in airborne applications.

3. Liquid Crystal—Another recently developed display technique is based on an electro-optic effect in liquid crystals. As with the plasma display, a matrix of individually addressable cells is used. However, light is not generated by the crystals. Instead the crystals, which are opaque when deenergized and translucent when excited, selectively transmit light from an external source. Resolution is rather high with such devices, 30 to 50 lines per inch. Response time is a limiting factor because of the rise time to activate an individual cell, which would preclude its use for a highly dynamic display.

4. Light Emitting Diodes—The light emitting diode offers some attractive characteristics as a display device. Light is produced in this device by a carrier injection electroluminescent technique. Light diodes offer the advantages of high resolution (40 to 50 elements per inch), relatively high brightness (100 foot-lamberts), and low operating voltages (less than 4 volts). In addition, a multi-color display is possible. At present, however, the cost is prohibitively high, and the device has not been proven in airborne applications.

5. Laser—Considerable interest has been shown in the laser as an energy source, especially for projected, head-up displays. The brightness and precision of the laser beam are attractive characteristics, but a satisfactory method of deflecting the beam has not been perfected. Electro-optic and birefringent crystals have been experimented with, but they require very high voltages. Deflection by a rotating mirror has also been suggested, but this method poses problems of accuracy and image stability. The chief, and probably disqualifying, disadvantage of the laser in SSV applications is the extremely high power requirement.

CHAPTER 5

DISPLAY CONCEPTS

Earlier chapters in this report outlined current trends in the development of flight control techniques for SSV recovery operations and identified minimum display requirements for supporting the pilot's participation in control, monitoring, and flight management functions. Preliminary design concepts now under study suggest a strong trend toward the use of multi-mode, computer-controlled cathode ray tube (CRT) devices for meeting crew display requirements throughout the mission (Gartner, 1971). It seems clear that this display technique will be employed during recovery operations, with one or more CRT displays sequenced through appropriate modes for approach and landing. These displays may incorporate such features as time sharing, integrated symbology and direct-imaging sensor displays, pictorial and graphic formats, and the presentation of predictive information. The advantages of these display capabilities have been discussed in Chapter 4.

The scope of the present study does not extend to the specification of design requirements or selection criteria for orbiter flight instrumentation. However, the review of flight control techniques and pilot information requirements suggested that certain display concepts might contribute significantly to easing the pilot's information processing burden during the highly time-compressed recovery sequence by providing for more direct representation of key flight situation parameters than conventional flight instrumentation typically allows. The purpose of this chapter is to identify and illustrate these concepts.

The display concepts presented here do not constitute recommendations of display technique. While computer-generated CRT displays are implied in the illustration of the concepts, the focus is on display function not mechanization. In principle, alternative display techniques could be adopted. Also, display requirements are considered selectively. Most of the display requirements outlined in Chapter 3 are familiar flight situation display parameters, e.g., attitude, airspeed, altitude, etc., and no special treatment of such elements is warranted. The intent is simply to illustrate certain display features which would augment conventional flight instrumentation and to suggest that they be considered in the development of orbiter crew station equipment. It is in this sense that the concepts which follow are offered as display development objectives.

Selected Display Support Functions

Three aspects of the pilot's role in the recovery sequences outlined in Chapter 2 are of particular importance in terms of display support:

1. maintaining a clear orientation in the terminal area navigation and energy management situation during the Maneuvering Descent and Initial Approach flight segments,

2. monitoring and assessing the immediate effects of ongoing flight control activity on the flight path and on controlled L/D characteristics of the vehicle,
3. controlling the final approach and flare maneuver to cope with unusual environmental conditions (e.g., wind shear) or off-nominal guidance and control system performance.

Maneuvering and energy management in the terminal area is a critical function in establishing the desired final approach conditions. To carry out this function effectively calls for flexibility in accommodating to a wide range of possible initial conditions and for the ability to maintain orientation throughout the descent and approach. In the limited time available during the Maneuvering Descent and Initial Approach segments (4-5 minutes), the pilot needs a display which provides direct support for his continuing assessment of changes in position and direction of flight relative to key energy control points and the planned FAP entry point. To facilitate the pilot's task, the display should entail a minimum of information processing and interpretation. This general requirement can be satisfied by an integrated orientation display incorporating:

1. a dynamic, pictorial representation of present position and direction of flight relative to the final approach path (FAP),
2. a quick-reference display of range and bearing to the selected FAP entry point,
3. fixed range markers centered on the FAP entry point, indicating the maximum and optimum range surface at 100,000, 75,000, and 50,000 feet,
4. below 50,000 feet, a pictorial representation of the selected high key position and approach track relative to the runway,
5. position and direction of flight relative to selected ground navigation facilities in the vicinity of the landing site.

Additional display support which might be incorporated for further enhancement of flight management would include:

1. track projections derived from present vehicle velocity vector and turning rates,
2. programmed flight path to the FAP entry point based on the flight plan or the computer-generated energy management strategy,
3. energy state projections (altitude and airspeed) for arrival at the high key position, based on present status and estimated vertical velocity and deceleration profiles.

The primary flight control mode during Maneuvering Descent is expected to be automatic for both the VFR and IFR approach sequences. If the manual control option is exercised during this flight segment, it is assumed that computer-derived instrument guidance will be required and the pilot would fly the vehicle by reference to a flight director display. Regardless of whether control is

automatic or manual, the monitoring and assessment of the immediate effects of flight control actions during this segment is best accomplished on an integrated flight director and situation assessment display which, as a minimum requirement, incorporates a direct representation of the primary vertical flight path control parameter—vertical flight path angle (γ , air mass referenced). An additional element which may be included is a display of actual airspeed relative to a programmed reference velocity derived from the deceleration profile for the nominal flight path angle.

Augmentation of conventional attitude-director instruments for the approach sequence beyond the high key position in VFR conditions is not considered necessary. To support the IFR approach (and to enhance the flexibility and precision of the VFR approach) the following display functions should be incorporated:

1. a dynamic representation of altitude above the runway relative to the selected flare initiation height,
2. a display of velocity error (i.e., actual vs programmed)—considered essential for the final approach and post-flare decelerating glide under both VFR and IFR conditions,
3. on arrival at the FAP entry point, replacement of vertical flight path angle with a representation of ground-referenced flight path angle (γ_G),
4. a pictorial representation of the projected ground impact point (γ_G) relative to the selected pre-flare aim point,
5. flare guidance,
6. a pictorial representation of γ_G relative to the runway aim point.

Display of the γ_G element in relation to the pre-flare aim point will permit flexibility in controlling the final approach and flare maneuver. These display elements will facilitate repositioning of the pre-flare aim point and/or adjusting the flight path angle to compensate for unforeseen wind effects or off-nominal energy management earlier in the approach. A display of altitude will aid in making an adjustment of the flare initiation height, which is the other major control technique during Final Approach.

The display support functions discussed above can be consolidated in two display concepts. For terminal area navigation and energy management an Integrated Orientation Display (IOD) is required. A second type of display, an Integrated Director-Monitor (IDM) is needed for flight control and situation assessment throughout the recovery and landing sequence. The following sections contain illustrations of the IOD and IDM concepts and an account of pilot utilization of these displays.

Integrated Orientation Display Concept

Essentially, the IOD is a moving-map horizontal situation display with two modes, Descent and Approach. The basic content of the IOD in the Descent mode and an illustration of the initial flight conditions are shown in Figure 14. The IOD provides a readily interpreted, pictorial representation of the vehicle's position, range capability, and flight path relative to the planned approach to the high key position. In Figure 14, the display is centered on the *Vehicle Symbol* and shows the orbiter on a 270° track at approximately 65 miles from the landing site.

The *Range Line* is drawn through the landing site in the planned direction of landing (runway heading) and provides a continuous indication of present track relative to the FAP. *Range Markers* at 25-mile intervals originate at the planned FAP entry point. They are coded to indicate the direction of landing when the landing site is behind the orbiter or outside the display field. Energy management range circles are centered on the FAP entry point and define continuous reference surfaces for monitoring vehicle position relative to both the undershoot boundary (*Maximum Range Circle*) and the desired range (*Optimum Range Circle*) for the designated altitude. In the situation illustrated in Figure 14, the vehicle is above 100,000 feet, and the reentry trajectory is being modulated to position the vehicle just downrange of the *Optimum Range Circle* as the 100,000-foot altitude is reached.

All the above display elements are superimposed on a skeletal map of the terminal area which serves to locate key navigation facilities (e.g., those used to update the onboard inertial navigation system) and other ground features which may be useful to the pilot for geographical orientation. This plan-view situation display moves under the *Vehicle Symbol*, maintaining a "track-up" frame of reference. A selectable offset feature may be incorporated to reposition the *Vehicle Symbol* at the bottom of the display so as to keep both the vehicle and the landing site within the field of view. A compass ring on the boundary of the display field can be used to read present track against a lubber line at the top of the display.

Pilot orientation does not suddenly become a requirement at the arbitrary 100,000-foot initiation altitude for the recovery sequence; the IOD in the Descent mode represents an extension of a situation display used to monitor the entire reentry trajectory. At higher altitudes the *Maximum Range Circle* might appear as a small target circle for assessing reentry guidance. During the Maneuvering Descent segment of the recovery sequence, whether under automatic or manual control, the pilot will attend primarily to the control strategy adopted for attaining the planned approach path to the high key and for arriving at this profile control position with the required energy. The *High Key* symbol, indicating position and planned heading relative to the runway, is available in the IOD display field throughout the descent to facilitate flight path and energy management.

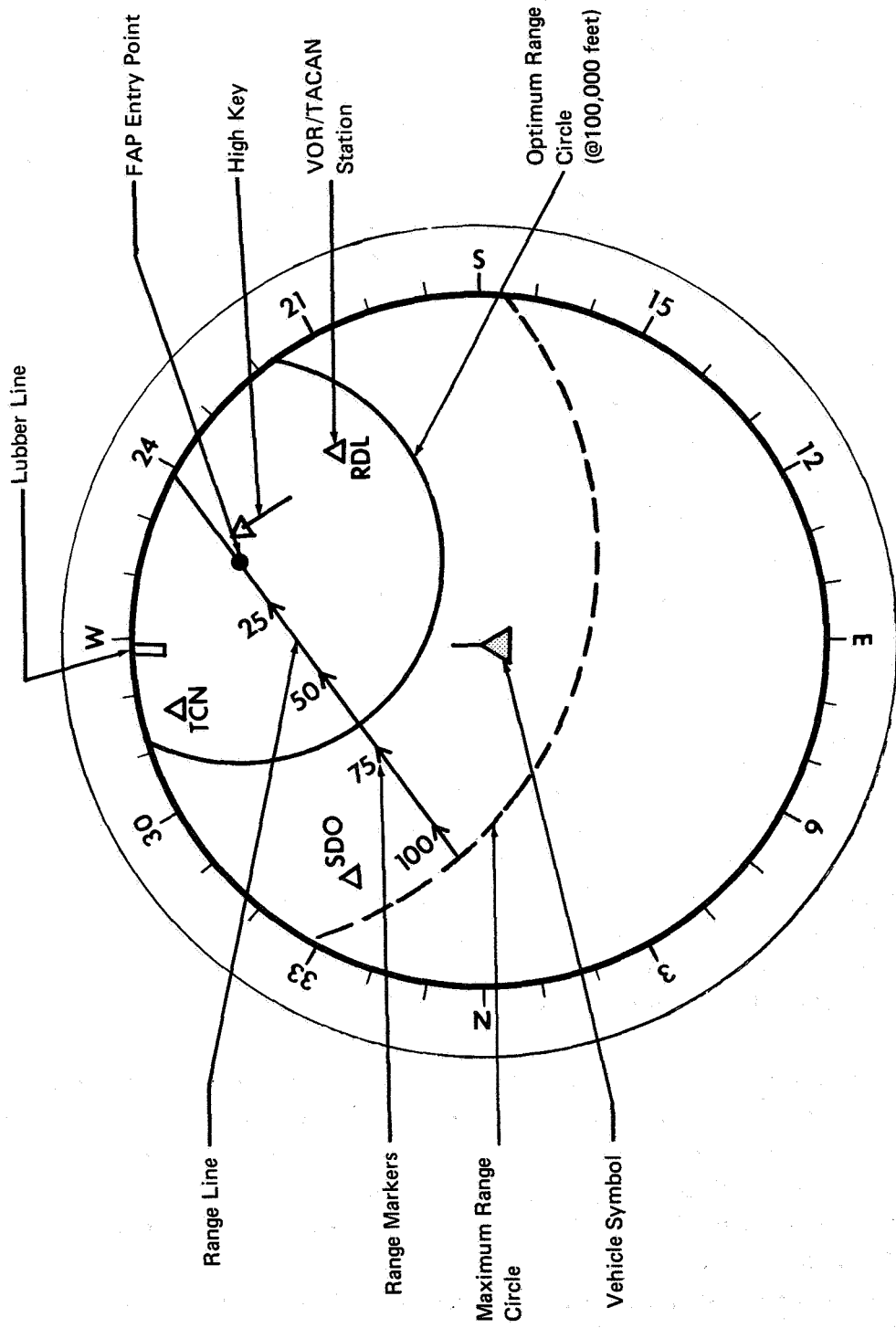


Figure 14. Integrated Orientation Display — Descent Mode

At about 50,000 feet, the display is sequenced to an Approach mode to provide a more appropriate scale factor for monitoring the initial approach. The IOD Approach mode is illustrated in Figure 15. A track-up frame of reference is retained, and the flight path relative to the intended approach to the *High Key* is clearly depicted. The *Range Line* continues to show the relative orientation of the extended runway centerline and the scale of the *Range Markers* has been expanded to two-mile increments. It is anticipated that this display format will enable the pilot to adjust the preselected high key position or FAP entry point, or both, if necessary to achieve the desired energy state. It will also enable him to monitor computer-generated flight path projections for achieving the desired FAP entry situation and to observe computer updates of the FAP entry point as the energy management solutions are narrowed and wind effect data are incorporated into the programmed control strategy.

Three of the display elements shown in Figure 15 may be considered as optional features, whose purpose is to aid the pilot in assessing the critical, close-in, energy management maneuvering. The first is a dotted line representing projected track (*Track Projection*) toward the high key for the next thirty seconds of flight. A dashed line curving into the FAP entry point is the second optional feature. It represents the *Programmed Flight Path* based on estimated airspeed and altitude at the high key and on the bank attitude schedule for a 270° turn onto the final approach. The third optional reference feature is the pair of semi-circles originating at the FAP entry point. These symbols depict the minimum turn radii and represent the *Undershoot Boundaries* for the selected FAP initiation conditions.

Integrated Director-Monitor Display Concept

The IOD is intended to keep the pilot oriented and enable him to make timely adjustments to the planned recovery flight path throughout the descent to the FAP entry point. Flight control and/or the more immediate assessment of ongoing flight control activity (whether automatic or manual) is accomplished by reference to the Integrated Director-Monitor Display (IDM). The basic features of the IDM are illustrated in Figures 16 through 18. In concept, the IDM is an electronic attitude director indicator (EADI) modified to incorporate the additional information identified in the earlier discussion of display support functions.

No position is taken here in regard to the optimum location of the IDM. It may be mechanized as either a head-up display or a head-down, panel mounted display. An important feature of the IDM concept, however, is the integration of ground-referenced display elements such as the pre-flare aim point and projected flight path impact point with conventional vertical situation display elements. These ground referenced elements provide the principal means of implementing flight path control and monitoring functions during approach and landing. In the orbiter, they may be generated by the computer or derived from direct imaging systems as described in Chapter 4 for "see through" displays. Under VFR conditions, these flight path cues may be readily available by external visual reference. However, under marginal visibility conditions or when selected pre-flare

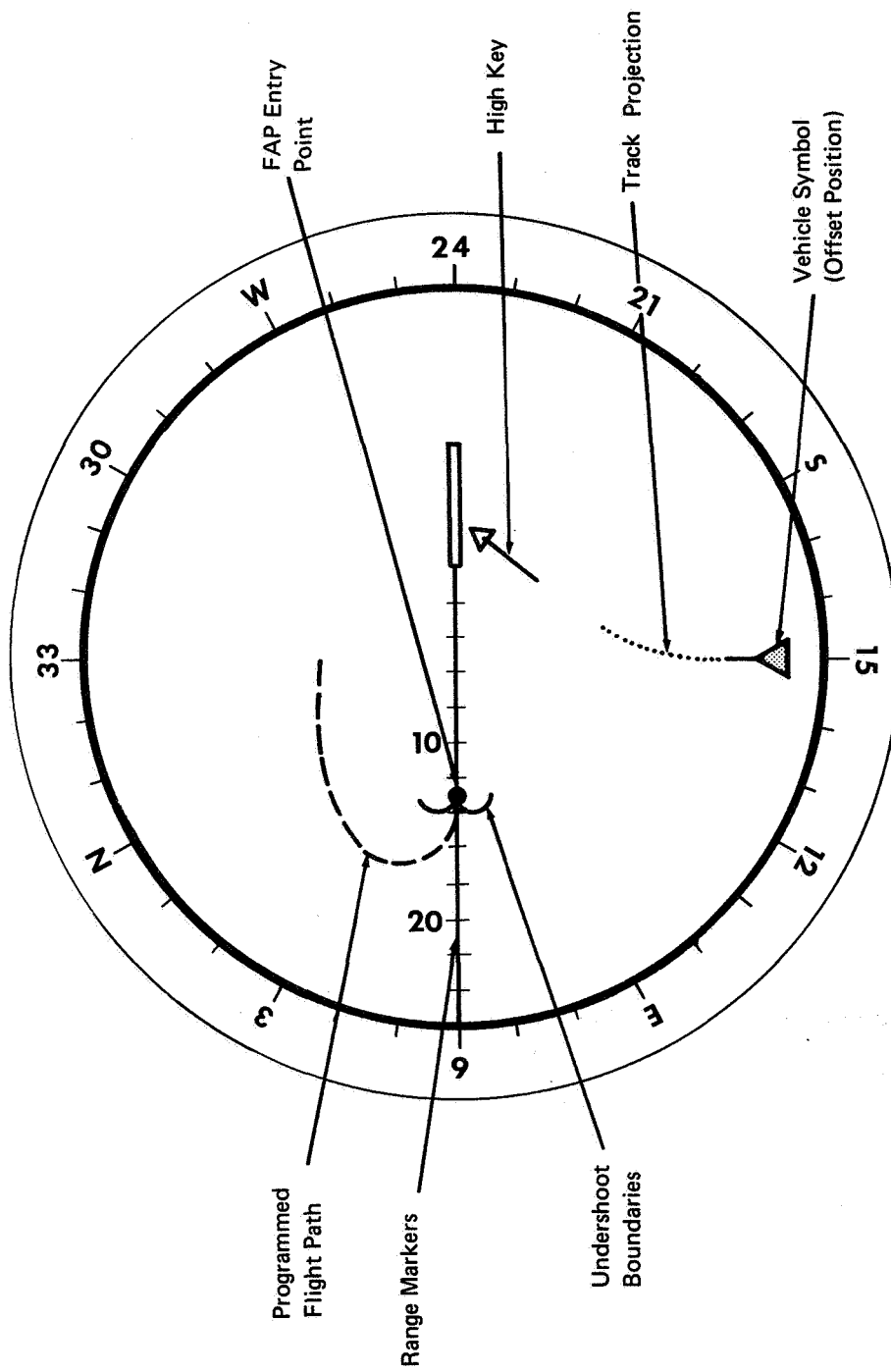


Figure 15. Integrated Orientation Display – Approach Mode

aim points are located at considerable distance from the runway, display of these elements on the IDM may be necessary for more precise control of the final approach flight path.

Although conventional EADI elements are shown in the IDM illustrations to indicate the full display content, only the augmenting display features are described. The basic IDM concept is represented in Figure 16. Manual control of the descent trajectory or the direct monitoring of automatic flight control system (AFSC) performance would be accomplished by following pitch and roll steering commands of the *Director Symbol*. The principal augmenting feature during the descent to the high key is the *Flight Path Angle (γ)* symbol.

In most of the SSV guidance and control schemes under consideration, a nominal γ derived from the optimal L/D characteristics of the vehicle is established as the primary parameter for vertical flight path control throughout the recovery sequence. By noting the position of the γ symbol relative to the pitch scale, the pilot can monitor this parameter directly. As an optional feature, the IOD might incorporate a γ *Limits* element to facilitate monitoring of constraints on vertical flight path control. For example, as the vehicle is transitioning from the reentry trajectory to an equilibrium glide path for the descent, total dynamic pressure (q) or temperature may be the governing factor, and the top and bottom of the γ *Limits* symbol would represent corresponding angle of attack (α) limits. As the equilibrium glide is established, the symbol would define maximum and minimum L/D boundaries around the nominal 10^0 flight path shown in Figure 16.

The *Reference Velocity* symbol shown as a movable index on the Mach scale is also an optional feature. At nominal γ , airspeed will continuously bleed off during the descent and the *Reference Velocity* symbol may be used either to designate a target velocity (e.g., desired velocity at the high key) or to indicate the programmed speed changes based on nominal deceleration schedules of airspeed vs. altitude. This feature could be used to indicate the need for speed brake deflection or, in conjunction with the γ *Limits* display element, to adjust the trajectory (e.g., for a maximum L/D descent).

As the vehicle approaches the FAP entry point, the IDM would be sequenced to an *Approach* mode as illustrated in Figure 17. The fixed index on the *Altitude* scale indicates that the vehicle is at 8000 feet. The *Airspeed* scale, which now reads indicated airspeed in knots rather than Mach number, shows the final approach speed to be 280 knots. In this schematic, the central display elements are deliberately displaced from the more typical "lined-up" conditions in order to distinguish more clearly their function and interrelationship.

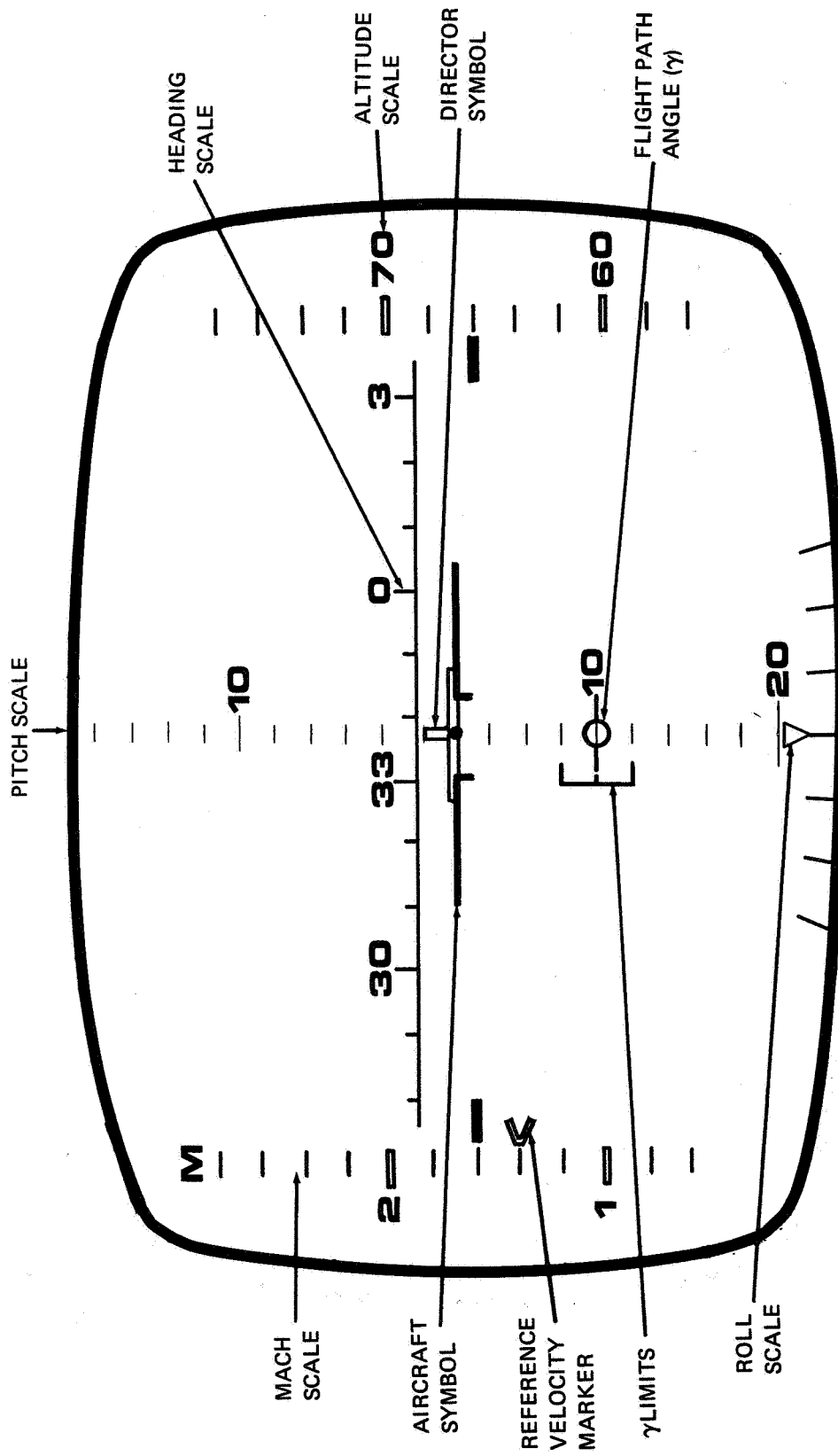


Figure 16. Integrated Director-Monitor Display – Descent Mode

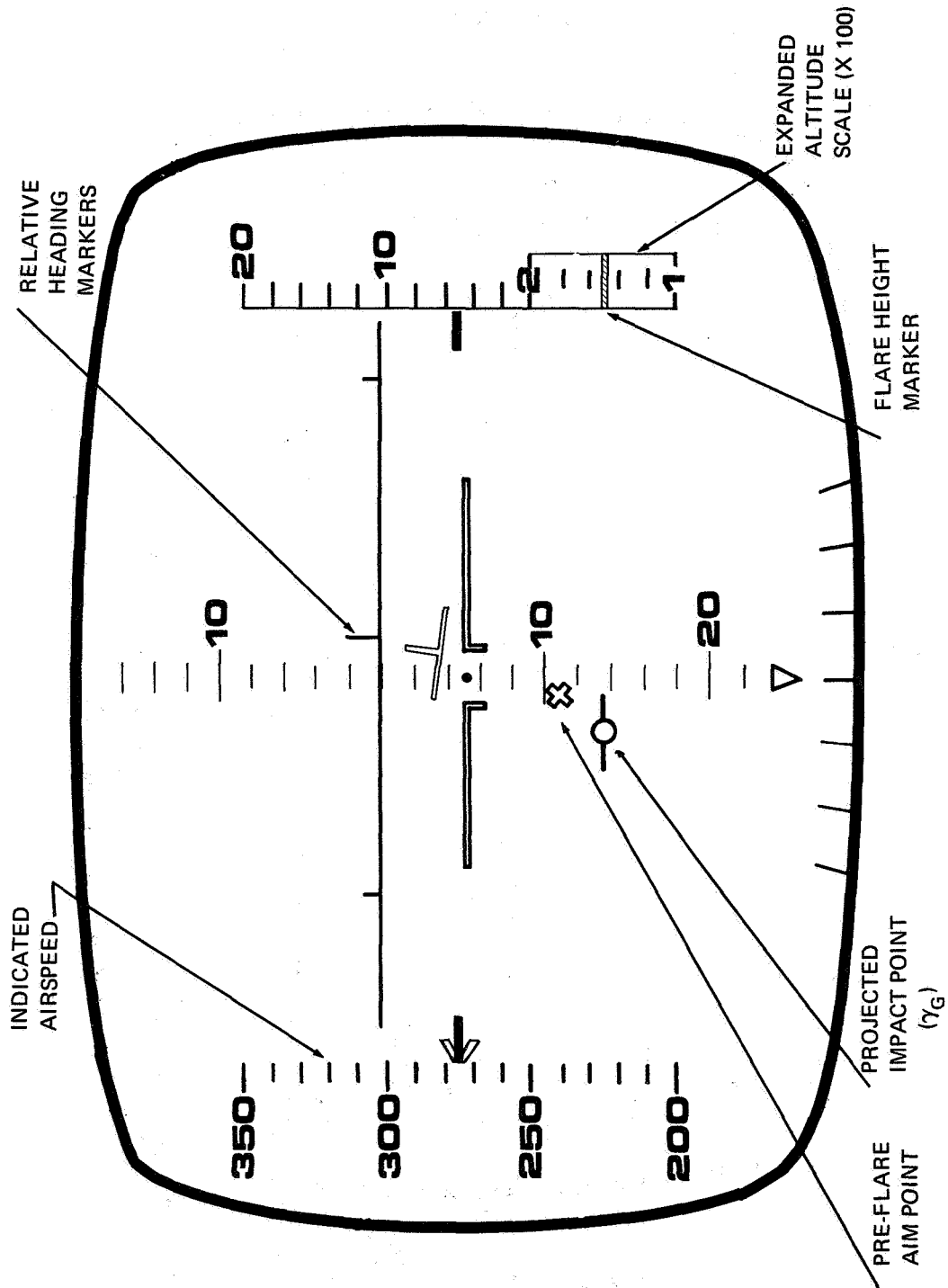


Figure 17. Integrated Director-Monitor Display – Approach Mode

Note that in the *Approach* mode, the γ *Limits* element has been deleted and that the γ symbol is now ground-referenced and represents the vehicle's *Projected Impact Point* (γ_G). The γ_G symbol is a velocity vector corrected for wind effects and is readily derived from inertially measured forward, lateral and vertical components of ground speed. Prior to flare, this display element would be used with the *Pre-flare Aim Point* symbol for direct monitoring of final approach flight path.

As in the *Descent* mode, flight control would continue to be exercised by reference to the director element, shown here commanding a slight pitch up and roll to the right. The γ_G symbol indicates that the orbiter is flying on an 11° glide path toward a point on the ground which is short and to the left of the selected pre-flare aim point. As the director command is satisfied, the γ_G symbol would "capture" and remain aligned with the pre-flare aim point at the desired 10° glide path angle. Manual flight control techniques could also be developed to establish alternate glide paths toward the same aim point on the ground.

It is important to note that the *Pre-flare Aim Point* symbol represents a selected point on the ground. (See Figure 5, Chapter 2.) This symbol must move in correct azimuth and elevation relationship to the *Aircraft* symbol, i.e., as it would if the pilot were able to see through the IDM "window" to that point on the ground. In a head-up display, this symbol might be superimposed on a terrain feature known to be located at the selected distance from the intended touchdown point on the runway. Repositioning of the aim point symbol, by the pilot or the computer, will provide for adjustments to the planned approach.

The *Altitude* scale shown in Figure 17 is a moving scale read against the fixed index aligned with the "wings" of the aircraft symbol. At 2000 feet, an expanded scale emerges from the bottom of the display and serves as a flare alert indication. The selected flare initiation height is flagged by the *Flare Height Marker*. As the vehicle descends, the movement of this marker relative to the fixed, actual altitude index allows the pilot to monitor the approach to the initial flare point. Since the rate of descent on final is expected to be approximately 100 feet per second prior to flare, the altitude scale would move toward the 2000-foot flare alert position at a rate of about one scale element (2000 feet) in 20 seconds.

Providing flare guidance or monitoring under IFR conditions is one of the most vexing problems associated with automated or semi-automated landing systems. A conventional flight director can provide guidance for manual control, but it is unsatisfactory as a monitor for automatically controlled flare. Also, a pure director symbol becomes difficult to fly if the pilot tries to introduce any variation of the programmed flare profile. Figure 18 illustrates a possible alternative solution to the problem of flare guidance and/or monitoring. As the vehicle flies through a preselected flare alert altitude (e.g., 2000 feet), two vertical bars appear on the IDM. The space between these *Flare Guidance* elements is an analog of altitude. The vertical position of the *Projected Impact Point* with respect to the *Flare Guidance* elements is an analog of rate of descent. As altitude decreases, the bars come closer together, "squeezing" the *Projected Impact Point* symbol. The pilot's task is to

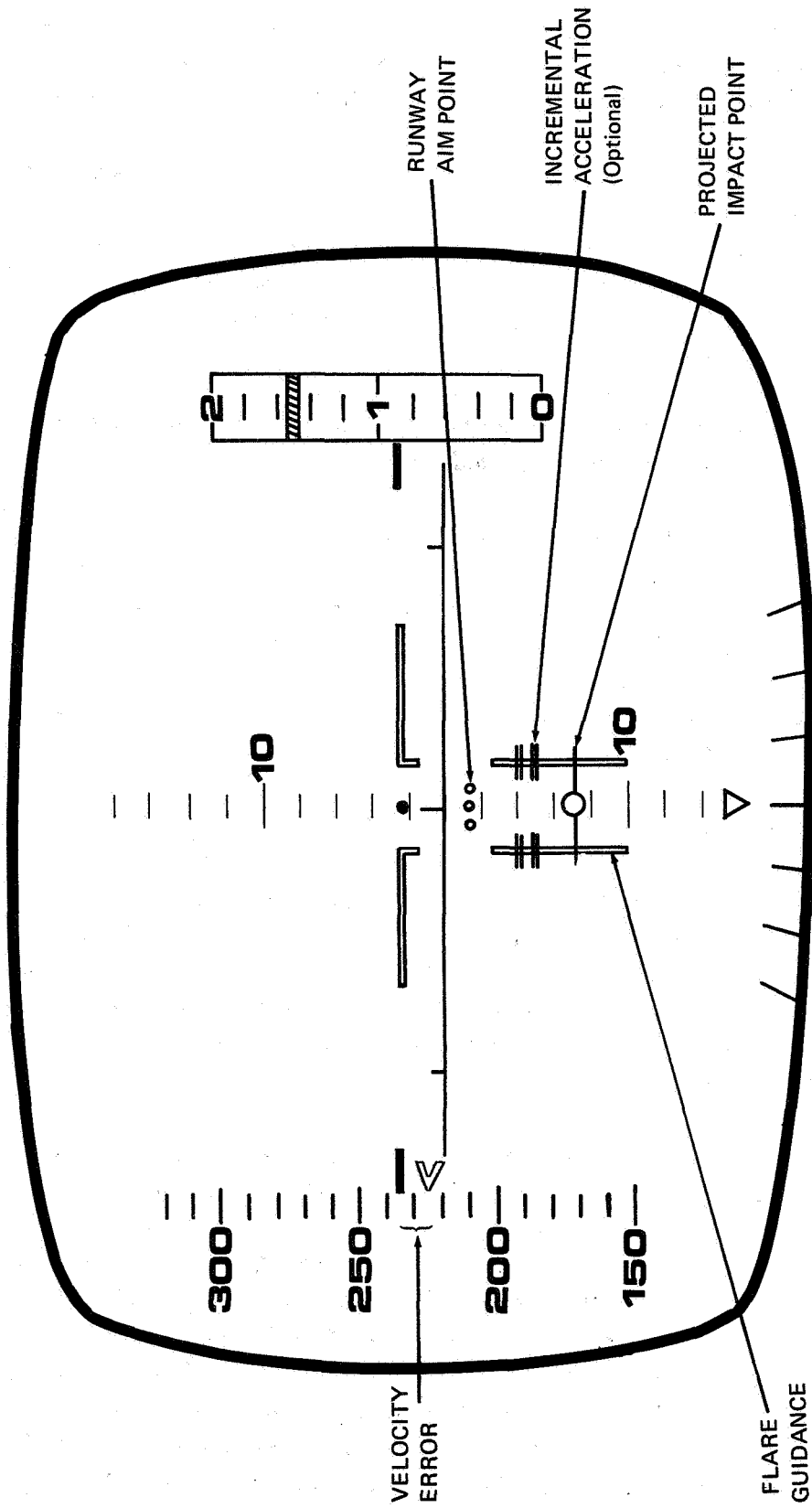


Figure 18. Integrated Director-Monitor Display – Flare Guidance Elements

control the aircraft in pitch so that the *Projected Impact Point* moves upward, denoting a decrease in sink rate. When the bars come together, the *Projected Impact Point* should be positioned on top of the bars (Jenney et al., 1971).

In the IDM concept, the *Flare Guidance* element can be used either for monitoring an auto-controlled flare or for flexible manual control of a flare by instrument reference. Note that the top of the bars corresponds to a flight path angle of 2.5° and that the bars originate at the 10° pre-flare glide path. For manual control, no exact starting point is prescribed for the flare maneuver. The pilot's task is simply to control the pull-up so that the γ_G symbol arrives at the top of the bars before they close. Familiarity with the vehicle's response characteristics and his ability to judge display element rates should enable the pilot to execute consistently smooth flight path transitions within prescribed g limits for rate of sink and deceleration control.

The transition to a shallow glide slope must be carefully controlled in the unpowered approach in order to assure attainment of planned altitude and airspeed conditions for the final decelerating approach to the runway. It may be that the scheme just described does not offer sufficiently precise guidance for the orbiter flare maneuver since there is no direct display of the g factor which governs the flare profile. If so, a third element (shown as an optional feature in Figure 18) could be added. At the flare initiation altitude, when the *Flare Guidance* bars appear, the third element (a pair of =) would also appear and begin to move upward along the bars as a function of a programmed incremental acceleration (Δg). The pilot's task would be to "capture" the Δg symbol with the γ_G symbol and to keep them superimposed as the vertical *Flare Guidance* bars close to form a single line at the desired flare completion altitude, with the γ_G and Δg symbols reaching the top as the bars meet. By thus tracking the Δg symbol with the γ_G symbol, the pilot could produce a smoothly coordinated flare under programmed g constraints.

As the vehicle flares, the pre-flare aim point would move below the field of view represented by the IDM and no longer be available or needed. A new *Runway Aim Point* symbol appears at flare initiation for flight path monitoring during IFR operations. Like the pre-flare aim point, this symbol represents a point on the ground near the intended touchdown point and must move in correct azimuth and elevation relationship to the aircraft symbol.

During the approach to the runway, the velocity error display, provided by the gap between the actual airspeed index and the *Reference Velocity* marker may be especially useful for final airspeed adjustments just prior to touchdown. The *Reference Velocity* marker could be used to represent a continuously varying airspeed based on nominal deceleration schedules, or it could be set at a single reference value for a selected pre-landing control altitude. In either event, its utility derives from the fact that the airspeed will be continuously bleeding off during this final flight segment, under both VFR and IFR conditions, and some basis for pre-touchdown velocity control will be required to minimize touchdown position dispersion due to off-nominal speeds.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The SSV is still in the early stages of development, with several important design decisions yet to be made. For example, it has not yet been determined whether to incorporate engines for power assist during approach and for a missed-approach capability. Likewise, the aerodynamic configuration of the orbiter vehicle has not been established; and, consequently, the handling qualities of the vehicle cannot be predicted with certainty. Several alternative flight control and guidance schemes are still being considered. Until one has been selected, the flight techniques to be employed by the pilot and the controlling parameters of the flight situation cannot be defined. The precise blend of automatic and manual control features is still an open question. Finally, the nature of the ground-based navigation and guidance aids, especially for severely limited visibility, has not yet been formulated; and the specific operating characteristics of the ground equipment and its airborne interface are not yet stated.

Each of these decisions will have an impact on orbiter displays and how they are used. Each display function and design feature will be a specific outgrowth of the system and its performance characteristics. Until the SSV design as a whole takes on a more definite shape, the display system will, of necessity, remain at the level of general concepts. However, as decisions are made during the continuing design and development process, display requirements and concepts can be expected to emerge with increasing clarity and to become more and more specifically suited to crew roles and needs.

The analysis of display requirements in this report reflects the preliminary state of system design and, therefore, contains certain artificialities. The mission profile was a highly generalized composite of anticipated flight situations and performance requirements. The concern was not so much with realism as with consideration of a broad range of possible conditions. The control techniques postulated in the operational model were a synthesis of the several competing schemes now under consideration. Focussing on these aspects of control technique which are common to all helped assure the validity of the analysis regardless of which scheme is eventually chosen, but at the expense of neglecting particular problems or requirements which will accompany the choice. Last, only a portion of the SSV mission has been examined. Treating recovery and landing in isolation was a convenient analytic technique, but eventually the display concepts so derived must be set back into the context of overall mission requirements and full display system characteristics.

These artificialities do not, however, invalidate the undertaking. It is useful, even necessary, at the earliest stages of system development to visualize as concretely as possible what activities the crew will perform and what display support is to be provided. This report, therefore, should be taken as an attempt to state display requirements as far as they can now be known and to suggest

avenues along which the design of displays should proceed. The conclusions reached here are preliminary but reflective of present trends in SSV development.

Summary of Conclusions

The major premises and conclusions of the report are enumerated below. For ease of reference, page numbers are given for the place in the text where each point is discussed.

1. The recovery and landing operation can be divided into four flight segments: Maneuvering Descent, Initial Approach, Final Approach, and Landing – each of which is governed by a particular control strategy. [9]
2. During Maneuvering Descent, the governing strategy will be to manage speed and altitude so as to position the vehicle at a selected runway offset position (high key) with sufficient energy for maneuver to attain final runway alignment. [11]
3. The Initial Approach will be conducted with the objectives of dissipating excess energy and establishing an approach path from which a smooth and consistent flare and landing maneuver can be flown. [12]
4. The control strategy for the Final Approach will be to maintain runway alignment and to make a transition from a steep (10°) descent to a shallow decelerating glide path toward the runway touchdown point. [12]
5. The strategy in Landing is to arrive at the touchdown point within established velocity and position constraints. The desired vehicle state at touchdown, which serves to define the goals of the entire recovery and landing sequence, is summarized in Table I. [14]
6. The distinguishing feature of the VFR profile is the selection of a high key position which optimizes visual contact with the runway, allowing the pilot to execute the approach by external visual reference. [14]
7. IFR approach procedures and techniques should be compatible with those employed under VFR, differing only as a function of the characteristics of the instrument guidance system. [18]
8. The pilot requires information to support three major functions during approach and landing: Flight Control, Situation Monitoring, and Flight Management. [24]
9. The relative priorities of these three functions will be determined by the degree of flight control system automation. [24]

10. Minimum information requirements for vertical situation display are summarized in Table V. [32]
11. Minimum information requirements for horizontal situation display are summarized in Table VI. [33]
12. The current trends in display design are:
 - a) to lessen pilot workload by using graphic and pictorial formats,
 - b) to promote optimum pilot performance by integrated displays of information related to clusters of tasks,
 - c) to present information relating to managerial as well as flight control functions. [38]
13. The major issues in the design of SSV displays are the blending of information related to automatic and manual control and the optimization of display support for each mode of control without compromising the pilot's command and management functions. [39]
14. The principal types of advanced displays applicable to SSV requirements are electronic attitude director indicators, head-up displays, integrated navigation displays, and multi-function displays. [40, 42, 45, 47]
15. Of the several possible techniques of display generation the CRT-based display is best suited to SSV requirements because of its flexibility and versatility and its advanced state of development. [50]
16. Other display techniques are less suitable because of their limited range of application, low brightness, insufficient resolution, restricted display size, or lack of proven capability in airborne applications. [52]
17. Three display support functions are of particular importance in SSV recovery and landing:
 - a) maintaining orientation during Maneuvering Descent and Initial Approach,
 - b) monitoring automatic flight control functions,
 - c) manually controlling the final approach and flare maneuvers. [53]
18. An Integrated Orientation Display to fulfill the first of the functions listed above is described and illustrated in two typical situations. [56 and Figures 14–15]

19. An Integrated Director-Monitor Display to assist manual control and to monitor automatic control is described and illustrated in descent, approach, and landing situations. [58 and Figures 16–18]

Recommended Studies

The display concepts presented in this report, while responsive to SSV requirements and reflective of current display trends, are nevertheless preliminary. The next steps are to validate the basic concepts and to refine those features which are peculiar to the SSV. The following are suggestions for studies to be undertaken as the SSV development program proceeds.

Simulator Studies

The display concepts proposed here should be implemented for simulator trials. This does not require special-purpose simulation; display trials could be conducted in a simulator intended primarily for SSV handling qualities evaluation or for development of flight control techniques. For initial trials, the test bed need not be an SSV simulator at all. Any device capable of representing the dynamics of unpowered flight (e.g., a lifting body simulator) would serve for an investigation of the general concept and of basic display dynamics and symbology. The display hardware, itself, would have to be of moderate sophistication. It should be programmable for a variety of display formats, and it should be possible to modify symbol shapes, positions, and dynamic laws as trials progress. The aims of the simulator trials would be to validate the basic concept of an integrated, pictorial display in SSV applications and to refine those features which are critical to successful crew performance. To this end, it would be desirable to conduct the trials on a comparative basis by having the capability of replacing the IOD or IDM displays with standard instruments. Performance with the standard instrument configuration would provide a valuable baseline and add another dimension to the overall evaluation of the integrated display concept.

Analytic Studies

Three types of analytic studies are called for. First, as development of the SSV advances, the display requirements analysis should be updated and made more specific to emerging vehicle characteristics and system configuration. Each of the system design decisions cited at the beginning of this chapter will have a major influence on displays and must be taken into account in shaping the displays to the crew's needs. Second, simulator trials can be expected to expose areas where a rethinking of the problems is called for or where a more fine-grained analysis must be made. Feedback from simulation will constitute an extremely valuable source of information about specific display problems and will provide leads for analytic solutions. Finally, a more extensive analysis of display requirements and technology must be made to support the writing of prototype hardware specifications. This analysis should cover such topics as display size, field of view, symbol size, brightness, resolution, data update rates, and mode switching.

Flight Testing

Ultimately, the SSV display designs must be subjected to a program of in-flight tests. The first round of tests might well occur before prototype SSV display hardware is available. In this case, an existing electronic display adapted to the SSV configuration would be adequate since the approach to flight testing at the outset should be not a comprehensive evaluation but a series of investigations, attacking the problem in tiers. Similarly, the test vehicle in the beginning need not be the SSV itself. A high performance jet (such as the F-111) or an aircraft modified to simulate SSV flight characteristics will probably be available at a relatively early date in the program. Later, as the "mini-shuttle" becomes available, it could serve as the test bed. The important point is that flight testing of displays need not, and should not, be postponed until the SSV is ready for flight.

REFERENCES

- Bray, R. S. et al. A flight study of power-off landing techniques applicable to re-entry vehicles. NASA TND-323, March 1960.
- Carel, W. L. Pictorial displays for flight. JANAIR Technical Report 2732.01/40, December 1965. (AD 627 669)
- Clark, C. Touchdown performance requirements related to rollout constraints. *Space Shuttle Guidance Navigation and Control Review*. NASA Manned Spacecraft Center. Unpublished document. April 1971.
- Dana, W. H., & Gentry, J. R. Pilot impressions of lifting body vehicles. *Flight Test Results Pertaining to the Space Shuttle Craft*. NASA Technical Memorandum TM X-2101. Symposium Proceedings, NASA Flight Research Center, Edwards, California, 30 June 1970.
- Gannett, J. R. Flight management concept II. Paper presented at the Human Factors Society 14th Annual Meeting, San Francisco, California, October 1970.
- Gartner, W. B., Price, H. E., West, V., & Parker, J. F. Human factors technology requirements in space shuttle development. Unpublished NASA Contractor Report—Contract No. NASW-1987. NASA Headquarters. March 1971.
- Hoag, P. C., & Schofield, L. IFR experience with unpowered, low-lift-drag-ratio landing approaches. *Flight Test Results Pertaining to the Space Shuttle Craft*. NASA Technical Memorandum TM X-2101. Symposium Proceedings, NASA Flight Research Center, Edwards, California, 30 June 1970.
- Jenney, L. L., Malone, T. B., & Schweikert, G. A. Head-up displays: A study of their applicability in civil aviation. NASA Contractor Report (in press) Contract NASW-1940, January 1970.
- Koch, B. M., & Fitzhugh, L. F. Approach and landing studies. *Flight Test Results Pertaining to the Space Shuttle Craft*. NASA Technical Memorandum TM X-2101. Symposium Proceedings, NASA Flight Research Center, Edwards, California, 30 June 1970.
- Mathews, C. W. The future progress of space transportation. Keynote address presented at AIAA Advanced Space Transportation Meeting, Cocoa Beach, Florida, 4-6 February 1970.
- Moore, T. Terminal area subsonic guidance. *Space Shuttle Guidance Navigation and Control Review*. NASA Manned Spacecraft Center. Unpublished document. April 1971.

- National Aeronautics and Space Administration, Office of Manned Space Flight. Statement of work, space shuttle program definition (Phase B). RFP No. 10-8423, February 1970.
- National Aeronautics and Space Administration. Flight test results pertaining to the space shuttlecraft. Flight Research Center, Edwards, California, NASA TM X-2101, June 1970.
- Olson, P. L. Variables influencing operator information processing. *Human Factors*, 1963, 5(2).
- Roscoe, S. N. Airborne displays for flight and navigation. *Human Factors*, 1968, 10(4).
- Schofield, B. L., Gaidick, H. G., & Gee, S. W. Experience with unpowered terminal-area instrument approaches. *Space Transportation System Technology Symposium*, NASA Technical Memorandum TM X-52867, Vol. VI. NASA Lewis Research Center, Cleveland, Ohio. 15-17 June 1970.
- Showman, R. D. A preliminary evaluation of navigation and guidance concepts for the space shuttle orbiter from the end of reentry to touchdown. Unpublished paper. NASA Ames Research Center, 1971.
- Thompson, M. O. Final remarks and future plans. *Flight Test Results Pertaining to the Space Shuttle craft*. Nasa Technical Memorandum TM X-2101. Symposium proceedings, NASA Flight Research Center, Edwards, California, 30 June 1970.
- Walters, D. J. Cockpit displays. AGARD Symposium on Stability and Control, Part II, September 1966.
- Warner, J. D. Advanced display systems for new commercial aircraft. Paper presented at the Human Factors Society 14th Annual Meeting, San Francisco, California, October 1970.