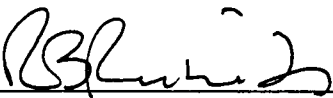


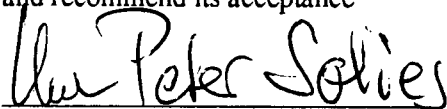
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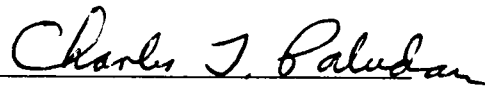


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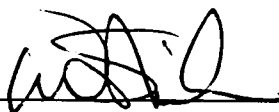
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AIRCRAFT CARRIER VISUAL LANDING AIDS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Wesley Scott Nielsen

August 1994

DEDICATION

This Thesis is dedicated to my wife, whose untiring devotion, limitless patience and gentle persuasion, always pushed me back on the path I originally intended. I owe every personal achievement and professional success to Kelley.

ABSTRACT

In the late 1960's when carrier visual landing aids (VLA) were coming of age, a great deal of research, time and energy was invested in understanding the requirements of the task and the physiological limitations of the aviators expected to use them. Many research oriented companies and government organizations embarked on nearly a decade of conceptual investigation, publication of results and recommendations, and system evaluation that focused many different educational disciplines on this complex problem. Not only did the effort culminate in the current VLA configuration in operation Navy wide, it left a documentation legacy that covered literally hundreds of design concepts (many that never left the drawing stage) and a general understanding of the complex nature of effective VLA design. Through the years, much of this foundation has eroded because the current VLA systems have been in operation for so long and conceptualizing new systems has been replaced with understanding the current system. While a great deal of engineering expertise and system knowledge is available, the "why" these systems were designed in such a way, is murky at best. There is more to successful, effective VLA design than meets the eye, literally.

The intent of this Thesis is to refresh the important complexities and considerations, across a variety of disciplines that affect successful VLA design in a single volume. It was written for an audience with a wide range of backgrounds, professions and experience levels and covers material from various disciplines. LSOs, Aviators, Engineers and Aviation Physiologists will each find certain sections surprisingly superficial while other chapters convey completely new concepts.

PREFACE

"Most of us, most of the time, live in blissful ignorance of what a small, elite, heroic group of Americans are doing for us night and day. As we speak, all over the globe, American sailors and submariners and aviators are doing something very dangerous. People say, 'Well, it can't be too dangerous because there are no wrecks.' But the reason we don't have more accidents is that these are superb professionals; the fact that they master the dangers does not mean that the dangers aren't real."

"Right now, somewhere around the world, young men are landing high-performance jet aircraft on the pitching decks of aircraft carriers - at night! You can't pay people to do that; they do it out of love of country, of adventure, of the challenge. We all benefit from it, and the very fact that we don't have to think about it tells you how superbly they're doing their job - living on the edge of danger so that the rest of us need not think about, let alone experience, danger."

Source: George Will, commenting during the ABC news special coverage, on Jan 28, 1986 on the space shuttle *Challenger* disaster.

TABLE OF CONTENTS

INTRODUCTION

PART I - DESIGN CONSIDERATIONS

CHAPTER 1 - THE TASK.....	5
APPROACH GEOMETRY	4
AIRCRAFT INTERVAL	4
CASE 1	5
CASE 3	6
TOUCH DOWN GEOMETRY	9
GLIDE SLOPE BASIC ANGLE	9
HOOK TO RAMP (H/R) VALUE.....	12
HOOK TOUCH DOWN POINT (HTDP)	12
HOOK TO EYE (H/E) VARIATION	14
LINE UP	17
VLA FIELD OF VIEW	19
SHIPBOARD PLACEMENT CONSIDERATIONS	19
LINE OF SIGHT OBSTRUCTION AVOIDANCE	20
GLIDE SLOPE COVERAGE	21
CHAPTER 2 - ENVIRONMENTAL CONSIDERATIONS	27
ENVIRONMENTAL CONDITIONS	28
COLOR ABSORPTION	28
REFLECTIONS OFF THE WATER	29
CORROSION.....	30
TEMPERATURE VARIATIONS	30
SHIP MOTION	32
CENTER OF GRAVITY (CG)	32
CENTER OF ROTATION (CR).....	33
SHIP'S TRIM	34
PITCH	35
ROLL	37
HEAVE	41
YAW	43
SWAY	44
SHIP'S SPEED	44

WIND EFFECTS	46
WIND EFFECT ON TOUCH DOWN GEOMETRY	46
CARRIER WIND PATTERNS	50
WIND EFFECT ON PILOT PERFORMANCE	54
OPTIMUM RECOVERY WIND	55
 CHAPTER 3 - PHYSIOLOGY	57
THE NERVOUS SYSTEM	58
NERVE IMPULSES	58
GRADED EVENTS	59
SIGHT	60
STRUCTURE OF THE EYE	61
EYE MOVEMENT	67
DEPTH PERCEPTION	68
MOVEMENT DETECTION	69
ILLUSIONS OF MOVEMENT	73
PERCEPTION OF BRIGHTNESS	77
COLOR VISION	79
EQUILIBRIUM	85
ACCELERATION	85
ORIENTATION	85
TOUCH	87
 CHAPTER 4 - PSYCHOLOGY	88
PILOT TRAINING	88
THE "PIPE LINE"	88
FCLP	89
ILLUSIONS FROM SHIP MOTION	91
PITCH MOTION PERCEIVED AS A CHANGE IN GLIDE SLOPE	92
YAW PERCEIVED AS A LINE UP DRIFT	93
TENDENCY TO APPEAR HIGH	95

PART II - CURRENT VLA SYSTEMS

CHAPTER 1 - GLIDE SLOPE.....	98
PADDLES	99
MIRROR OPTICAL LANDING SYSTEM (MOLS)	101
FRESNEL LENS OPTICAL LANDING SYSTEM (FOLS)	103
FOLS GENERAL ARRANGEMENT	103
OPTICAL CHARACTERISTICS OF THE SOURCE	105
FIELD OF VIEW (FOV)	109
SENSITIVITY	111
EFFECTS OF TEMPERATURE	113
FOLS SOURCE MOTION CAPABILITY	113
STABILIZATION	115
CHAPTER 2 - LINE UP.....	118
FLIGHT DECK MARKING	119
NON-SKID	119
RUNWAY CENTERLINE STRIPE	121
RUNWAY EDGE LADDER	121
AFT ATHWARTSHIP STRIPE	122
DECK LIGHTING	123
RUNWAY EDGE LIGHTS	124
RUNWAY ATHWARTSHIP LIGHTS	124
RUNWAY CENTERLINE LIGHTS	125
TUNNEL DECK LIGHTING	126
VERTICAL DROPLINE LIGHTS	127
OVERHEAD FLOODLIGHT ILLUMINATION	129
RED FLOODLIGHTS	130
YELLOW FLOODLIGHTS	130
WHITE FLOODLIGHTS	130
LOW PRESSURE SODIUM FLOODLIGHTS	131

PART III - FUTURE VLA SYSTEMS

CHAPTER 1 - IMPROVED CARRIER OPTICAL LANDING SYSTEM (ICOLS)	133
LINE-UP SYSTEMS	134
CROSSBAR LONG RANGE LINE-UP SYSTEM (LRLUS)	134
LASER CENTERLINE LOCALIZER (LCL)	135
COMBINED CROSSBAR LRLUS AND LCL	136
GLIDE SLOPE DISPLAY SYSTEMS	137
FORE AND AFT LONG RANGE GLIDE SLOPE INDICATOR (LRGSI)	137
LASER GLIDE SLOPE INDICATOR (LGI)	137
 CHAPTER 2 - LONG RANGE LASER LINE-UP (LRLS) FLIGHT TEST	 140
LRLS TEST PROGRAM OVERVIEW	141
LRLS SYSTEM DESCRIPTION	142
GENERAL	142
LRLS OPTICAL DESIGN	142
LRLS STABILIZATION	146
LRLS TEST INSTALLATION	149
DESCRIPTION OF TESTS	152
GROUND TESTS	152
SIMULATION TESTS	153
FLIGHT TESTS	155
INSTRUMENTATION AND DATA EXTRACTION	158
PALS INSTRUMENTATION	158
SIMULATOR DATA EXTRACTION	160
AIRCRAFT INSTRUMENTATION	160
TEST RESULTS AND CONCLUSIONS	161
COMPATIBILITY WITH VISUAL LANDING AIDS (VLA)	161
VISUAL UTILITY	164
OPTICAL SYSTEM PERFORMANCE	164
STABILIZATION SYSTEM PERFORMANCE	174
COMPATIBILITY WITH ELECTRONIC LANDING AIDS (ELA)	183
CREW COORDINATION	185
BIBLIOGRAPHY	187
VITA	190

LIST OF FIGURES

I-1-1	CASE 1 LANDING PATTERN	8
I-1-2	CASE 3 LANDING PATTERN	9
I-1-3	BOLTER PATTERN	10
I-1-4	BASIC ANGLE GEOMETRY CONSIDERATIONS	12
I-1-5	GLIDE PATH GEOMETRY	17
I-1-6	GLIDE SLOPE VERTICAL COVERAGE LIMIT	24
I-1-7	HORIZONTAL COVERAGE LIMIT	26
I-2-1	SUPERSTRUCTURE AND FANTAIL VLA REFLECTIONS	29
I-2-2	CARRIER CENTER OF ROTATION	33
I-2-3	HTDP AND H/R COMPENSATION FOR BOW-UP SHIP'S TRIM	34
I-2-4	HTDP AND H/R COMPENSATION FOR RAMP-DOWN PITCH CYCLES	36
I-2-5	HTDP AND H/R COMPENSATION FOR RAMP-UP PITCH CYCLES	37
I-2-6	FLIGHT DECK LATERAL DISPLACEMENT DUE TO SHIP'S ROLL	39
I-2-7	SHIP'S ROLL AFFECT ON GLIDE PATH GEOMETRY	40
I-2-8	SHIP'S ROLL AFFECT ON GLIDE PATH GEOMETRY (TWO- DIMENSIONAL APPROXIMATION)	41
I-2-9	ACTUAL FLIGHT PATH DUE TO SHIP'S SPEED	45
I-2-10	WIND EFFECT ON ACTUAL FLIGHT PATH	47
I-2-11	GLIDE PATH GEOMETRY (INCLUDING WIND EFFECTS).....	48
I-2-12	DOWNWASH AND ROOSTER TAIL WIND PATTERNS	51
I-2-13	ISLAND TURBULENCE WITH AXIAL WINDS.....	52
I-2-14	ANGLE DECK UP-WASH	54
I-3-1	LINES OR OBJECT?	61

I-3-2	THE HUMAN EYE	62
I-3-3	NEURAL STRUCTURE OF THE RETINA.....	66
I-3-4	DEPTH PERCEPTION FROM CONVERGENCE	68
I-3-5	THE IMAGE/RETINAL SYSTEM OF MOTION DETECTION	70
I-3-6	THE EYE/HEAD SYSTEM OF MOTION DETECTION.....	71
I-3-7	A WATERFALL EFFECT INDUCING SPIRAL.....	75
I-3-8	THE HUE DISCRIMINATION CURVE	83
I-4-1	CHANGES IN LANDING AREA PERSPECTIVE	91
I-4-2	PITCHING DECK OR GLIDE SLOPE CHANGE?	94
I-4-3	TENDENCY TO APPEAR HIGH	95
II-1-1	THE LSO'S NIGHT RECOVERY UNIFORM.....	100
II-1-2	MIRROR OPTICAL LANDING SYSTEM	101
II-1-3	MOLS GLIDE SLOPE PRESENTATION.....	102
II-1-4	FRESNEL LENS OPTICAL LANDING SYSTEM (FLOLS) LOCATION	104
II-1-5	FRESNEL LENS OPTICAL LANDING SYSTEM	104
II-1-6	REAL IMAGE VERSUS VIRTUAL IMAGE	106
II-1-7	EFFECT OF RADIUS OF CURVATURE ON FOCAL PROPERTIES	106
II-1-8	EFFECT OF ABERRATION ON A PLANO-CONVEX LENS	107
II-1-9	GEOMETRY OF THE FRESNEL LENS	108
II-1-10	GEOMETRY OF THE LENTICULAR LENS	109
II-1-11	FLOLS SOURCE VERTICAL FIELD OF VIEW	110
II-1-12	SOURCE PITCH ANGLE FOR BASIC ANGLE ADJUSTMENT	114
II-1-13	SOURCE ROLL ANGLE FOR H/E ADJUSTMENT	115
II-1-14	LINE STABILIZATION OF BASIC ANGLE.....	117
II-1-15	POINT STABILIZATION OF BASIC ANGLE	117
II-2-1	USS SARATOGA (CV-60) FLIGHT DECK LANDING AREA MARKINGS	119

II-2-2	FLIGHT DECK LIGHTING	123
II-2-3	DROPLINE LIGHT PERSPECTIVE CUEING	128
III-1-1	LASER GLIDE SLOPE INDICATOR (LGI)	138
III-2-1	LRLS HORIZONTAL COVERAGE	143
III-2-2	LRLS VERTICAL COVERAGE	144
III-2-3	LRLS OPTICAL HEAD	145
III-2-4	LRLS HELIUM NEON LASERS AND PRISM ARRANGEMENT	146
III-2-5	LRLS YAW ALPHA FILTER STABILIZATION	148
III-2-6	LRLS YAW WITH POINT STABILIZATION	149
III-2-7	SHORE BASED LRLS TEST INSTALLATION	150
III-2-8	SHIPBOARD LRLS TEST INSTALLATION	151
III-2-9	ICLS AND LRLS RESPONSE TO SHIP TURNS	178
III-2-10	CONFLICTING LRLS AND ICLS GUIDANCE INFORMATION	178
III-2-11	YAW STABILIZATION FAILURE PERFORMANCE	180
III-2-12	PITCH STABILIZATION PLATFORM PERFORMANCE	181
III-2-13	ROLL STABILIZATION PLATFORM PERFORMANCE	181
III-2-14	PERCENTAGE OF TIME F-14 OUTSIDE AMBER CORRIDOR DURING INSTRUMENT APPROACHES	183
III-2-15	PERCENTAGE OF TIME F/A-18 OUTSIDE AMBER CORRIDOR DURING INSTRUMENT APPROACHES	185

LIST OF TABLES

I-1-1	HOOK TO RAMP CLEARANCE VS AIRCRAFT CARRIER	15
I-1-2	HOOK TO EYE VALUES FOR AIRCRAFT IN THE NORMAL LANDING CONFIGURATION	18
II-1-1	FLOLS SOURCE VERTICAL FIELD OF VIEW	110
II-1-2	FLOLS STABILIZATION LIMITS	116
III-1-1	INDIVIDUAL VERTICAL COVERAGE'S OF LGI CORRIDORS	138
III-2-1	DESIGN LRLS HORIZONTAL COVERAGE'S AND FLASH RATES	142
III-2-2	LRLS LASER CONFIGURATION IN EACH CORRIDOR	145
III-2-3	LRLS DESIGN SHIP MOTIONS AND VELOCITIES FOR STABILIZATION	147
III-2-4	SIMULATION SCOPE OF TEST	154
III-2-5	SEA STATE CONDITIONS	154
III-2-6	LRLS SHORE BASED SCOPE OF TESTS	156
III-2-7	LRLS SHIPBOARD SCOPE OF TESTS	157
III-2-8	PALS AND STABILIZATION INSTRUMENTATION PARAMETERS	159
III-2-9	RECORDED SIMULATION PARAMETERS	160
III-2-10	DROPLINE LIGHT CONFIGURATIONS TESTED ABOARD CVN-73	161
III-2-11	CENTERLINE LIGHT CONFIGURATION AND TEST LOCATION	163
III-2-12	LRLS ADM LABORATORY DETERMINED FLASH RATES	165
III-2-13	METEOROLOGICAL CONDITIONS AND LRLS ACQUISITION RANGES	167
III-2-14	DESIGN AND ACTUAL HORIZONTAL COVERAGE	168
III-2-15	DESIGN AND ACTUAL VERTICAL COVERAGE	170
III-2-16	COMPUTER ANALYSIS OF STABILIZATION PERFORMANCE	174

LIST OF ABBREVIATIONS AND NOMENCLATURE

ADM	Advance Development Model
AOA	Angle of Attack
arcmin	arc minute
ARL	NAMRL report designation
BKN	Broken
Bolter	a failed arrested landing attempt
Burble	combined effect of the downwash and rooster tail
CCA	Carrier Controlled Approach
CDP	Cross-deck Pendant
CG	center of gravity
CLR	Clear
CQ	Carrier Qualification
CR	Center of Rotation
CV	Class designation for conventionally powered aircraft carriers (CV-60)
CVN	Class designation for nuclear powered aircraft carriers (CVN-73)
cyc	cycle
deg	degree
ELA	Electronic Landing Aids (instrument approach devises)
EMCOM	Emission and Communication restricted
FCLP	Fleet Carrier Landing Practice
FLOLS	Fresnel Lens Optical Landing System
Foul deck	landing area not configured or ready for aircraft arrestment
FOV	Field of View

FTM	Flight Test Manual
FWTCI	Frequency Weighted Task Complexity Index
Groove	the last 16 to 18 seconds of a carrier approach
Island	aircraft carrier superstructure
HMRL	Humbug Mountain Research Laboratory
HTDP	Hook Touch Down Point
ICLS	Instrument Carrier Landing System (U. S. Navy ILS)
ICOLS	Improved Carrier Optical Landing System
ILS	Instrument Landing System (civilian)
JBD	Jet Blast Deflectors
kt	knot (1 nautical mile per hour)
kts	knots
lb	pound (force)
LCL	Laser Centerline Localizer (later renamed LRLS)
LGI	Laser Glide Slope Indicator
LRGSI	Long Range Glide Slope Indicator
LRLUS	Long Range Line Up System (different system than LRLS)
LSO	Landing Signal Officer
Max trap	Maximum aircraft gross weight allowable for arrested landing
Meatball	Fresnel Optical Landing System
MFS	Manned-Flight Simulator
MK	Mark (U. S. Navy designation for some equipment)
MOLS	Mirror Optical Landing System
NAMRL	Naval Aerospace Medical Research Laboratory
NATOPS	Naval Aviation Training and Operation Procedures Standards
NAVAIR	Naval Aircraft System Command (procurement organization)
NAWC	Naval Aviation Warfare Center

NAWCAD	Naval Aviation Warfare Center, Aircraft Division (subdivision of NAWC)
nm	nautical mile (minute of latitude)
nms	nautical miles
NRL	Naval Research Laboratory
Ramp	furthest aft edge of the angle deck landing area
Round down	see ramp
On-speed	optimum angle of attack for approach
OVC	Overcast
SA	Strike Aircraft Test Directorate
SCT	Scattered
Source	the image of the FLOLS
SPN	U. S. Navy designation for sea-based radar systems
TPS	Test Pilot School
TRN	Navy designation for land-based navigation systems
USS	United States Naval Vessel designation (USS GEORGE WASHINGTON)
VLA	Visual Landing Aids
VMC	Visual Meteorological Conditions

INTRODUCTION

In the late 1960's when carrier visual landing aids (VLA) were coming of age, a great deal of research, time and energy was invested in understanding the requirements of the task and the physiological limitations of the aviators expected to use them. Many research oriented companies and government organizations embarked on nearly a decade of conceptual investigation, publication of results and recommendations, and system evaluation that focused many different educational disciplines on this complex problem. Not only did the effort culminate in the current VLA configuration in operation Navy wide, it left a documentation legacy that covered literally hundreds of design concepts (many that never left the drawing stage) and a general understanding of the complex nature of effective VLA design. Through the years, much of this foundation has eroded because the current VLA systems have been in operation for so long and conceptualizing new systems has been replaced with understanding the current system. While a great deal of engineering expertise and system knowledge is available, the "why" these systems were designed in such a way, is murky at best. There is more to successful, effective VLA design than meets the eye, literally.

The intent of this Thesis is to refresh the important complexities and considerations, across a variety of disciplines that affect successful VLA design in a single volume. It was written for an audience from a wide range of backgrounds, professions and experience levels and covers material from various disciplines. LSOs, Aviators, Engineers and Aviation Physiologists will each find certain sections surprisingly superficial while other chapters may convey completely new concepts.

Existing publications, technical reports, academic textbook and the author's experience categorize the four general information sources used to write this Thesis. Existing publications and operating manuals were the primary information source about VLA systems currently in use. While these sources provide excellent information about current system design, maintenance and operation, they fail to provide detailed information about the system development.

A wide variety of technical reports and industry proposals were available to the author from within the Naval Air Warfare Center, the aviation system acquisition organization of the U. S. Navy. Many of the more experienced engineers had acquired an extensive personal library of reports, publications and proposals. What information was not locally available was provided by the Defense Technical Information Center (DTIC) that catalogues and collects technical reports specifically for later use and reference. Many of these technical reports provided very necessary information about a system's development from proposal to implementation.

Information on the physiological aspects of vision, equilibrium and touch were available from a variety of academic textbooks. Finally, the author's experience with naval aviation and flight "test and evaluation" provides the fourth general source of information upon which this Thesis is based.

This Thesis is organized in three Parts. Part I, "Design Considerations" establishes a foundation of information, concepts and procedures, and introduces terms that continually arise throughout the remaining Parts. It describes the established limitations and constraints of the carrier landing task, reiterates the environmental considerations of VLA system design, discusses psychological and physiological characteristics of sight, touch and equilibrium that is pertinent to aviation.

Part II, "Current VLA Systems" discusses the VLA systems that are currently in use by the U. S. Navy and is separated into chapters on glide slope and line-up systems. This Part includes system descriptions, design criteria, and implementation and addresses some of the desirable and deficient characteristics of each.

Part III introduces "Future VLA Systems." The first chapter, "Improved Carrier Optical Landing System" contains a brief discussion on some of the system proposals for the next generation of carrier VLA systems. Of the ICOLS systems evaluated and flight tested, the Long Range Laser Line-up System (LRLS), having shown the best potential to fill the need for long range visual line-up cueing, was selected for accelerated development and the flight test program that followed is the subject of the second chapter.

PART I
DESIGN CONSIDERATIONS

Chapter 1

The Task

Simply landing high performance military jet aircraft is in itself a demanding task. Complicate this further by requiring the pilot to place the aircraft on a 120 foot by 70 foot moving runway, day or night, in conditions of rough seas and bad weather, and it becomes rapidly apparent that the task of carrier landings is significantly different from field landings.

If sufficient funds existed to build an 8000 foot long, 200 foot wide floating runway, the differences between field and carrier landings would diminish significantly. But, this is unrealistic. The U. S. Navy has had a fleet of aircraft carriers in operation for many years and changing the dimensions of the flight deck or re-configuring the arresting gear system is cost prohibitive, even if time were available in their busy schedule. Naval aviators will continue to operate from the flight decks of these carriers as they are currently configured for decades and nothing will change this.

Effective Visual Landing Aid (VLA) system engineering depends on the designer's understanding of the carrier landings task requirements.

APPROACH GEOMETRY

The end result of every approach procedure is to place the aircraft in a three-dimensional window from which the pilot can continue visually to a safe arrested landing. The exact procedures utilized to arrive at this position is of interest only because it sets the stage leading up to the use of VLA and illustrates where VLA systems are expected to be effective.

Case 1 recoveries are used during daylight recoveries in good weather and rely on the pilot's ability to sequence himself into the landing pattern. Case 3 recoveries are used at night (or poor weather daytime recoveries) when visibility precludes pilot control and rely on the ability of the shipboard radar operators to control traffic sequencing and spacing. Case 2 is a combination of each of these. This approach procedure puts the aircraft in the case 1 visual landing pattern. Understanding the VLA requirements of case 2 recoveries only calls for understanding the final portion of case 1 recoveries.

Regardless of the case recovery in use, the pilot must re-configure the aircraft in preparation for arrested landing. This includes lowering the landing gear and arresting hook, extending the flaps and speed brakes, and ensuring his aircraft gross weight is below the maximum allowable arrested landing weight (called "max-trap" gross weight). The pilot must also establish the aircraft at the optimum airspeed (called "on-speed") that corresponds to the angle of attack or attitude the aircraft was designed to arrest at.

AIRCRAFT INTERVAL

There are two goals of each of these approach procedures. Put the first aircraft in the arresting gear as soon as the flight deck is ready to recover, and minimize the interval between recovering aircraft as much as possible. Every second the aircraft carrier is steaming into the wind for recovery is another second it's not steaming toward its intended destination. Minimizing wasted time is very important.

At the instant of touch down, the pilot applies full power as the arresting gear pays out. This ensures that if the arresting gear is missed (called a "bolter") or the hook fails, the aircraft

will have enough thrust to continue flight after rolling off the angle deck. Once the aircraft comes to a complete stop, the pilot retards the throttle to idle and as soon as he raises the hook, the arresting wire begins retraction in preparation for the next aircraft. As the pilot makes a right turn to exit the landing area, all four arresting gear engines are set for the maximum gross weight of the next aircraft to arrest. When the arresting gear are "in battery" and the preceding aircraft is clear of the landing area, the deck is "clear" and ready for the next arrestment. This entire evolution takes about 35 seconds, just enough time for the next aircraft to reach the "wave-off window" or the closest point during an approach that an aircraft can be allowed to approach the flight deck without a clear deck. A 45 second interval is considered optimum. Just enough time exists to re-set the arresting gear engines and ensure the previous aircraft has exited the flight deck as the approaching aircraft is nearing the wave-off window.

If the interval is too short, the aircraft will have to be waved-off and perform another approach. If the interval between consecutive aircraft is too long, valuable clear deck time is not being used to full capacity. In both cases, the interval is the cause of an extended recovery and wasted time.

CASE 1

Case 1 recovery procedures allow the most expeditious recovery of aircraft. Pattern entry and control, recovery sequence, and traffic separation are controlled by the pilots airborne. As the next "cycle" of 12 to 14 aircraft finish being launched, the recovering aircraft watch the flight deck so as to arrive in the landing pattern as soon as the deck is ready to begin recoveries. If the launch is delayed, the aircraft holding overhead adjust their arrival accordingly. Since these procedures hinge on the ability of the pilots to watch the flight deck and sequence themselves among other aircraft, case 1 recovery procedures require good weather conditions and are only used during daylight hours.

VLA system design and development need only be concerned about the final portion of the case 1 pattern. Aircraft sequence themselves into the landing pattern to arrive abeam the carrier

configured for recovery, just below "max trap" gross weight, 45 seconds behind the preceding aircraft. As illustrated in figure I-1-1, the pattern calls for a descending turn to final. Rate of descent is gradually increased to achieve particular altitude gates so as to arrive on glide slope and centerline with 16-18 seconds before touch down.

Once on final, the pilot relies on VLA to maintain glide slope and centerline until arresting aboard. VLA design need only be effective from the turn to final to arrestment during case 1 recoveries.

CASE 3

Case 3 recoveries resemble most land based field instrument approaches. The approach is commenced from 26 to 36 miles from the carrier and sequences aircraft onto the final approach course (called "final bearing"). As depicted in figure I-1-2, inside ten nm the aircraft is configured for landing. At three nms, glide slope intercept occurs and the pilot establishes a rate of descent to maintain it.

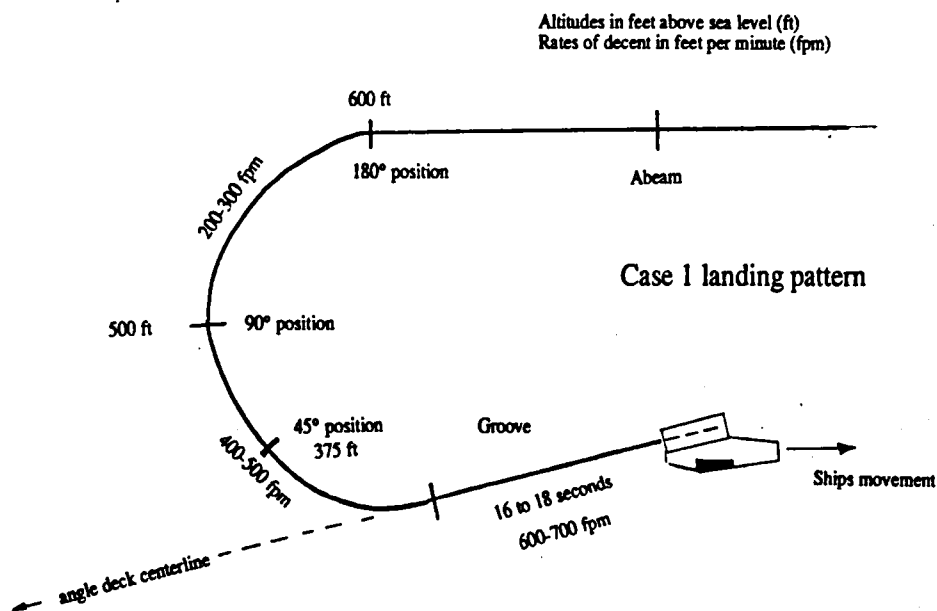
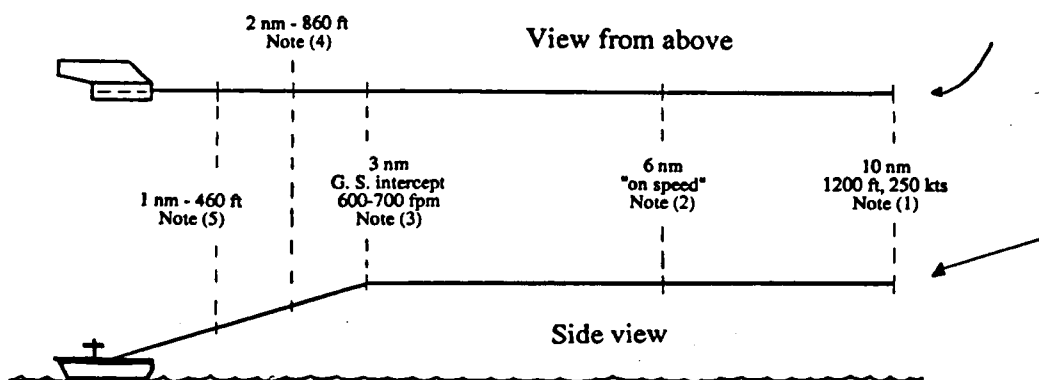


Figure I-1-1
CASE 1 LANDING PATTERN

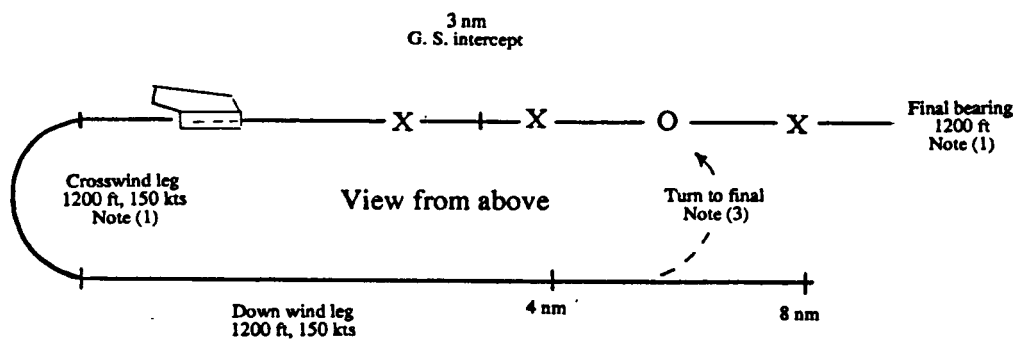


- Notes: (1) By 10 nm, each aircraft should be on final bearing at 1200 ft altitude, 250 kts airspeed. At 10 nm, re-configuration begins by extending the landing gear and speed brakes, lowering the hook and slowing to 150 kts. Actual gross weight must be below "max trap."
- (2) Aircraft maintain 1200 ft, 150 kts until reaching 6 nm where each slows to "on speed" depending on actual gross weight and aircraft type.
- (3) At 3 nm, glide slope intercept occurs and 600 to 700 fpm rate of decent is established.
- (4) Altitude should be 860 ft by 2 nm.
- (5) Altitude should be 460 ft by 1 nm.

Figure I-1-2
CASE 3 LANDING PATTERN

Bolter Pattern

The bolter pattern is part of the case 3 recovery procedures. It is an effective way to sequence aircraft back to final bearing following an unsuccessful attempt to arrest (bolter, wave-off, foul deck, etc.) If the recovery goes like clockwork, the bolter pattern is not utilized. As depicted in figure I-1-3, between every fourth or fifth aircraft, a sequencing slot is left open. This slot is programmed into the sequence in anticipation of having to absorb traffic from the bolter pattern. The approach controllers time the turn from downwind so that interval between each aircraft on final remains one minute and recovery interval is preserved.



- Notes: (1) "X" represents aircraft on final at 1 minutes intervals, approximately 2 nm spacing. "O" represent a "slot" available for sequencing bolter pattern traffic back onto final.
- (2) Following an unsuccessful attempt at arrestment, the aircraft climbs straight ahead to 1200 ft before turning left to downwind while maintaining 150 kts.
- (3) After 4 nm downwind, the aircraft is turned to final. This turn is executed when a slot comes available, usually every 4th or 5th aircraft on final. Once established on final, the aircraft maintains "on speed" airspeed, and completes the remaining portion of the case 3 recovery procedures.

Figure I-1-3
BOLTER PATTERN

TOUCH DOWN GEOMETRY

Landing aboard an aircraft carrier has been described as a "controlled crash." The pilot flies his aircraft on centerline at a constant glide slope, rate of descent and angle of attack (at least as nearly as humanly possible) until touching down on the flight deck. Four arresting wires cover about 120 foot length of the flight deck and start about 150 feet from the runway threshold (called the "round down" or "ramp"). A more conventional flared landing is not possible because of the inherent unpredictability of precisely controlling touch down point and altitude while crossing above the round down.

An understanding of "The Task" is continued by looking at the required touch down geometry and tolerable deviations from optimum that remain within design limits of the aircraft and shipboard landing systems.

GLIDE SLOPE BASIC ANGLE

The basic angle is the glide slope the aircraft flies with respect to the touch down point. During no-wind conditions and a stationary landing area the basic angle becomes the actual glide slope that the aircraft flies through the air mass. During approach to a field landing, this angle is typically about 3° while carrier operations call for basic angles in the range of $3\frac{1}{2}^\circ$ to 4° . The ability to change the basic angle during shipboard operations is necessary to compensate for certain environmental conditions that will be discussed in Chapter 2 of this Part. For the time being, the range of glide slope basic angle selection is limited by aircraft-to-ramp clearance (on the shallow side), and engine performance and aircraft structural design (on the steep side).

Shallow Limit

The more shallow that the basic angle becomes, the less clearance exists between the aircraft and the round down of the landing area as depicted in figure I-1-4. So it makes sense that the shallow limit of basic angle is set by minimum tolerable ramp clearance.

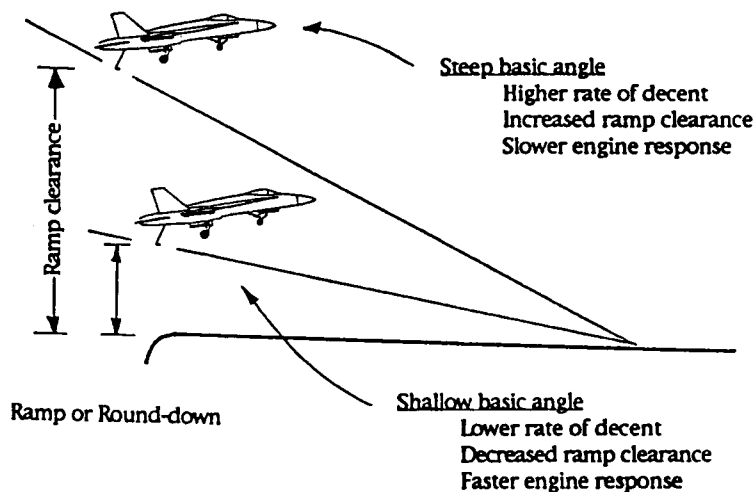


Figure I-1-4
BASIC ANGLE GEOMETRY CONSIDERATIONS

Steep Limit

Simply increasing basic angle would seem a reasonable way to increase ramp clearance to acceptable values. Increased clearance crossing the round down equates to greater safety margin for unavoidable glide slope deviation. However, the highest basic angle that can be selected is limited by several inherent aircraft related characteristics: engine response time and aircraft structural limitations.

Engine Response Time

Jet engines do not produce thrust immediately in response to changes in throttle setting (engine momentum, fluid dynamics, etc.). This effective "engine lag" complicates the pilot's

ability to maintain optimum glide slope during approach. Throttle corrections during approach must be anticipated well before the actual thrust becomes required. This lag increases significantly when initiated from lower throttle settings. A perfect example is the length of time the engines in a large airliner take to "spool up" after taxiing onto the runway for take off. The pilot is not being gentle with the throttles, he is patiently waiting for the engines to catch up with throttle position and produce the thrust he has commanded. Earlier jet engine technology produced aircraft that had significant engine lag. The pilot in an *A-7E CORSAIR* may wait up to 17 seconds for the engines to achieve full thrust after throttle selection from "idle" to "full." Newer engines are much faster to respond to throttle inputs. Even though the Navy's newest carrier based aircraft, the *F/A-18 HORNET*, takes only six seconds to achieve full thrust from idle at sea level, there will always exist (at least in the foreseeable future) some degree of undesirable thrust lag by the very nature of jet engines.

Since engine lag has been reduced as much as current technology allows, aircraft aerodynamic design can partially compensate. Aircraft configuration during approach is partially designed to force approach throttle settings higher by incorporating high lift and high drag devices, such as flaps and speed brakes. Higher maximum lift allows reduced approach speed, which is obviously desirable. A consequence of higher lift coefficients is increased induced drag which in turn requires higher throttle settings to maintain an equivalent rate of descent. So in an indirect way, aircraft aerodynamic design partially reduces engine lag by forcing the nominal throttle setting higher during approach.

For a given approach speed, increased glide slope will always require a higher rate of descent and a lower throttle setting to maintain it regardless of elaborate aircraft design and engine technology. Take any aircraft in the same configuration and the higher the glide slope, the larger the engine lag. So, from the pure engine response point of view, for a given configuration, each aircraft type will benefit from as low a glide slope as practical. At some point, the benefit of raising the basic glide slope angle to increase ramp clearance is

defeated by the decreased glide slope control introduced with reduced engine response from lower power settings.

Structural Design

In the quest for increased ramp clearance, structural design limitations must be considered. The higher basic angle is pushed, the higher the rate of descent required to maintain it. These higher descent rates equate to higher landing gear loads at touch down. Aircraft do not last forever and eventually fatigue due to the structural stress associated with carrier operations. The higher the loads, the sooner the aircraft will reach its "fatigue life," beyond which, structural integrity is questionable. Add some deck motion and unavoidable deviations from optimum rate of descent at the instant of touch down and the fatigue life will be compromised, not to mention the possibility of exceeding the ultimate strength of the aircraft landing gear. Therefore, from a purely structural standpoint, shallower basic angles reduce aircraft structural loads and extend aircraft fatigue life.

HOOK TO RAMP (H/R) VALUE

Ten feet is considered the minimum "hook to ramp" clearance for normal shipboard arrestments and eight feet for barricade arrestments. Since the distance from the round down to the touch down point varies slightly between carriers, H/R clearance at a $3\frac{1}{2}^\circ$ basic angle also varies. Table I-1-1 lists these variations between different carriers.

HOOK TOUCH DOWN POINT (HTDP)

Where the hook of the arresting aircraft strikes the flight deck is driven by hook to ramp clearance (H/R) and arresting gear run out distance.

Given that the aircraft flies a constant glide slope, the touch down point must be set sufficiently forward of the round down to provide adequate H/R clearance. Simple trigonometry

Table I-1-1
HOOK TO RAMP CLEARANCE VS AIRCRAFT CARRIER

Aircraft Carrier	Hook to ramp clearance (ft)
CV-60	10.9
CV-61	11.9
CV-62	11.3
CVN-65	14.2
CV-67	14.4
CV-63, 64, and 66	14.3
CVN-65	14.2
CVN-68 - CVN-73	14.1

Source: *Aircraft Recovery Bulletin No. 62-12C, Mark 6 Mod 3, Fresnel Lens Optical Landing System (FLOLS)*, Washington D. C.: Department of the Navy, Naval Air Systems Command, 02 Dec 1992, (NAVAIRWARCENACDIVLKE-IS14).

dictates that at a 3 1/2° basic angle, HTDP must be at least 182 ft forward of the round down to preserve ten ft of H/R clearance.

How far forward to program HTDP depends on arresting gear run out and aircraft dimension. During arrestment, the aircraft pulls out the "constant run-out" arresting gear wire approximately 320 ft before coming to a stop. This distance is very consistent because the system is designed to pay out the same length regardless of small deviations in airspeed or gross weight at the time of arrestment. Aircraft length must be accounted for because the arresting hook is mounted at the rear of the aircraft and some room must be available to taxi clear of the landing area. A good example of the criticality of these dimensions is observable aboard the *USS KITTY HAWK (CV-61)*. The pilot in an *F-14 TOMCAT* engaging the fourth arresting gear cable will be looking at only a few feet between the nose of his aircraft and the forward edge of the angle deck when his aircraft comes to stop: quite remarkable for a 54,000 lb aircraft that only 320 ft before, was traveling at 127 kts.

The ideal trade off is to program HTDP between the second and third arresting wires. This preserves H/R clearance, and allows arresting gear run out distance sufficiently aft of the angle

deck top while still providing two wires fore and aft of the hook to allow for unavoidable HTDP deviations.

HOOK TO EYE (H/E) VARIATION

It should be no surprise at this point that touch down geometry must be based on the flight path of the aircraft hook as opposed to the path of any other part of the aircraft. During approach, the flight path of every aircraft hook must be the same to maintain identical H/R clearances and HTDPs. Ideally, each aircraft hook, regardless of aircraft type, should touch down between the second and third cross deck pendent.

If all aircraft had identical dimensions, programming a visual landing aid for the pilot to control hook glide path would be an easy task. But, each type of aircraft has its own unique design, shape and size that is driven by mission requirements. 'Fighters' are different from 'light attack' aircraft that are different from 'early warning' aircraft and so on. If constant hook path is the goal, these differences must be recognized if compensation is to be made. One dimension of concern is called the aircraft's "hook to eye" (H/E) value.

As depicted in figure I-1-5, the aircraft's H/E value is the *vertical* distance between the path of the pilot's eye and the aircraft's arresting hook relative to the carrier. For any given aircraft, discarding any effect of recovery head wind, the H/E value is a function of three variables related by equation (I-1-1).

$$H / E_{(ket)} = \frac{L \sin(\theta + \alpha)}{\cos \phi} \quad (I-1-1)$$

Where: L = distance from the pilot's eye to the aircraft hook point.

θ = angle between the aircraft's longitudinal axis to the hook-to-eye line.

α = aircraft's angle of attack (or AOA).

ϕ = the approach basic angle.

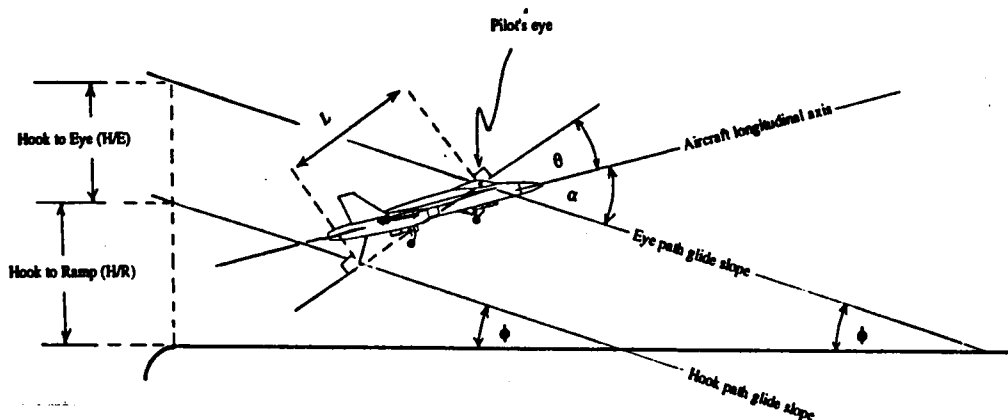


Figure I-1-5
GLIDE PATH GEOMETRY

Adapted from: *Aircraft Recovery Bulletin No. 10-10C, For All Arresting Gear and Optical Landing Systems*, Washington D. C.: Department of the Navy, Naval Air Systems Command, 28 Jan 1991, (NAVAIRENGCEN-5161).

At the small basic angles (ϕ) that carriers operate (5° glide slope or less), the differences in H/E value for changes in ϕ are insignificant. Equation (I-1-1) simplifies to an expression which is independent of glide slope.

$$H / E_{(feet)} \approx L \sin(\theta + \alpha) \quad (I-1-2)$$

Aircraft dimensions (L and θ) are determined from general arrangement drawings provided by the contractor and are considered constants. Since the sum of θ and α will always be less than 90° , equation (I-1-2) indicates an increase in H/E value with increasing values of α . The question remains, "How can α vary during approach?"

One way α can vary is to change aircraft configuration. Since configuration requirements are put forth by aircraft operating manuals, this only occurs during emergency situations, ie:

single engine approach may require half flaps. Any changes to the aircraft landing configuration (half flaps) may change approach α resulting in a corresponding change in H/E.

If an aircraft flies an approach a few knots slower than optimum airspeed, α will change. AOA (α) will have to increase to provide the equivalent lift to maintain glide slope and consequently H/E increases.

Yet another example: a pilot pulls the nose up just before touch down, the tail moves down (increased α) and H/E increases. So, analytically, H/E is "constant", but in practical operation it is a significant variable. The realistic consequence of H/E changing by one foot moves HTDP by 18 ft.

H/E values for all shipboard aircraft in their normal landing configuration are presented in table I-1-2 for comparison. The F-14 *TOMCAT* has the largest H/E value because the aircraft is not only very long (large L) but comes aboard at a very high true AOA (α). The E-2C *HAWKEYE* is about the same length but has a much smaller α or "flatter" approach AOA than the *TOMCAT*. Both these aircraft with their long fuselages have the same potential of dramatic changes in H/E (from perturbations in α) which results in significant deviations in HTDPs.

Table I-1-2
HOOK TO EYE VALUES FOR AIRCRAFT IN THE NORMAL LANDING
CONFIGURATION

Aircraft Model	Hook to eye value (FT)
TA-4J	16.25
A-6 series	16.75
EA-6B	18.75
S-3A	14.50
E-2C	15.00
F-14 series	19.70
F/A-18 series	16.70
T-2C	12.00

Source: *Aircraft Recovery Bulletin No. 62-12C, Mark 6 Mod 3, Fresnel Lens Optical Landing System (FLOLS)*, Washington D. C.: Department of the Navy, Naval Air Systems Command, 02 Dec 1992, (NAVAIRWARCENACDIVLKE-IS14).

LINE UP

Touch Down Position

The safely-usable landing area is 100 ft wide, forward of the arresting gear wires on most aircraft carriers. "Foul lines" are painted on the flight deck to mark this area. Since space on the flight deck is a commodity in high demand, aircraft, servicing gear and tractors are routinely parked only inches outside these foul lines on both sides of the landing area. The *E-2C HAWKEYE* has the largest wing span of any aircraft that currently deploys aboard a carrier. To ensure the wing tip remains inside the foul line, the pilot must put the *HAWKEYE* within nine ft of centerline (half the flight deck width minus half the wings span).

Aircraft with shorter wing spans are not allowed much more deviation. After an arrestment of greater than ten ft off centerline, the structural integrity of the cross deck pendant (or CDP: the replaceable part of the wire that is exposed on the flight deck) is questionable. A single hit outside ten ft requires the replacement of the CDP which will delay the recovery.

A single hit outside 20 feet requires an overhaul of that arresting engine below deck and will be unavailable for use for several days. During "blue water" operations where the only divert air field may be thousands of miles away, four fully operational arresting gear are the only thing that prevents 12 to 14 aircraft from being lost at sea.

Touch Down Drift Rate

It is not enough that aircraft must touch down within ten ft of centerline. Any lateral drift rate at touch down results in the aircraft completing landing roll out off centerline. Arresting gear engine design assists in reducing aircraft displacement from centerline as the engine pays out. When engaged off center, one side of the arresting gear engine experiences higher forces. The low force side of the engine compensates by increasing resistance during run-out and effectively pulls the aircraft back toward centerline. This design feature, does not eliminate all of the off-center geometry or drift rate during run-out, but does assist in doing so.

Aircraft Heading

If the aircraft is not pointed directly down the landing area at touch down, once the tires contact the flight deck, the aircraft will tend to roll in the direction it is pointing. This may sound like it would be an unusual event but it is not. The angle deck is canted 10° to 13° from carrier centerline and is not parallel to the direction of movement of the ship. The carrier is effectively moving to the right during approach as viewed from the aircraft. To maintain angle deck centerline during approach, the aircraft must crab nose right with respect to the carrier. The aircraft is maintaining balanced flight with respect to the relative wind but is pointing slightly right of angle deck centerline at touch down.

VLA FIELD OF VIEW

With a rudimentary knowledge of approach and touch down geometry, the limits of required visual coverage can be established. VLA systems should be designed to provide the pilot visual guidance to place the aircraft within the geometric constraints previously discussed. If the system is to be effective, the pilot must first be able to view it throughout the portion of the approach it is designed to cover.

SHIPBOARD PLACEMENT CONSIDERATIONS

Designers can physically place a VLA system anywhere on the ship such that it remains visible to the pilot throughout the approach. Some locations are more desirable than others while some are simply not practical.

At ranges beyond about one mile, the entire ship does not subtend very much of the pilot's field of view, so any VLA system intended to be useful at these ranges can be placed anywhere practical. Stabilization requirements become more difficult to overcome with locations far away from the landing area. These difficulties may become insurmountable depending on the stabilization requirements and can force VLA location if good stabilization is critical.

As range to touch down decreases, the carrier fills more and more of the pilot's field of view. The angular separation between any two stationary items on the flight deck increases, as the pilot's distance from them decreases. Placement of VLA systems intended for use all the way to touch down will have to remain in the pilot's general field of view.

Several factors must be considered to approximate the area on the ship that is visible throughout the approach. As discussed in Chapter 3 of Part I, the area of highest visual acuity (called the fovea) that is used to see detail, only covers about 2° of our vision, about the size of a dime held at arms length. If an object of interest lies only a few degrees outside this region, a person can rapidly adjust the position of his eyes to see. If an object lies outside of about 15° , human beings tend to adjust their eyes *and head* to re-direct line of sight. So it seems that if

several VLA system locations are involved, locating them within approximately 15° of each other will allow "eyes only" gaze re-direction and minimize the time spent moving from one to the other. Outside of 15°, head movement will either increase the time between VLA scans or the pilot will sacrifice sighting one system in favor of sighting the other continuously.

LINE OF SIGHT OBSTRUCTION AVOIDANCE

Shipboard Obstructions

As previously discussed, the flight deck is crowded with parked aircraft, support equipment and personnel. There is little (if any) room available for a VLA system to the right of the landing area. If it is an above deck design then it must be located outside the safe landing area. To keep the pilot's line of sight to the system unobstructed, aircraft, equipment or personnel can not be allowed aft of the system. The loss of such a large area of the flight deck that is typically packed with aircraft undergoing maintenance is unacceptable.

Flight deck space to the left of the safe landing area is considerably smaller allowing only a couple of aircraft to be parked here. Rapid access for the majority of personnel to this portion of the flight deck during recovery operations is difficult because they have to cross the landing area to get there. Consequently this space is typically occupied by aircraft that will not be utilized in the near future to free space along the right of the landing area for aircraft intended for more near-term use. As is the case with the area to the right of the landing area, this area to the left is an impractical location for VLA systems because of line of sight obstructions.

If the system is designed for flush deck mounting, the requirement to keep it outside of the safe landing area is removed. Location choice now includes the landing area itself which eliminates line of sight obstruction concerns. However, structural design that must allow for 54,000 lb of weight landing on top of it at velocities in excess of 700 ft per minute may likely make this location choice too costly.

Traffic Obstructions

Line of sight obstructions from one aircraft blocking another aircraft's view of the system can not be completely eliminated and will occur from time to time. With both aircraft airborne, this probably won't last long enough to significantly affect pilot performance. Furthermore, the second aircraft is still far enough away from arrestment that any small degradation in approach performance can be corrected when line of sight is resumed.

The temptation to place flush mounted VLA in the forward portion of the angle deck can lead to another traffic obstruction. Following arrestment, the aircraft takes time to retract the arresting hook and exit the landing area. During this time if this aircraft is blocking the view of the pilot next to recover, performance degradation is likely to result in a wave-off which lengthens the recovery phase unnecessarily.

Cockpit Obstructions

Cars frequently bump up against the curb while pulling into a parking space. The reason is because the view of what's in front of the car is obstructed by the hood. The same can be said of an aircraft: the pilot's line of sight is obstructed by the portion of the aircraft in front of the cockpit. Although this is more of an aircraft design than a VLA system issue, it must be considered. If the system is obstructed by the nose of the aircraft during the final portion of approach (as is the aft portion of the angle deck), then it can hardly be expected to remain visible to the pilot. Clearly stated, VLA intended for use close to touch down, must be located far enough forward (or off to one side) to avoid line of sight obstruction with the aircraft nose.

GLIDE SLOPE COVERAGE

The pilot must be able to precisely control his glide slope from about 3/4 nm to arresting wire engagement. If at anytime during the approach, his eyes fly out of coverage, he will lose critical glide slope feed back and consequently, his ability to control glide slope will likely be degraded.

Vertical Coverage

Vertical coverage is the vertical angular dimension that a directional VLA system can be seen while on approach. Actual vertical coverage necessary to provide the pilot continuous view of the glide slope VLA can only be determined by actual flight test. So many variables are involved that engineering analysis, no matter how thoroughly and comprehensively undertaken may not prove to be adequate once in use. There are some rudimentary approximations that will give the reader a basic idea.

An approximation of necessary coverage can be determined by looking at aircraft geometry at the instant of hook touch down, as depicted in figure I-1-6. The top limit of necessary coverage is set by an aircraft engaging the fourth arresting wire. If the pilot's eye ends up above this limit, HTDP will be farther up the angle deck and the aircraft will bolter.

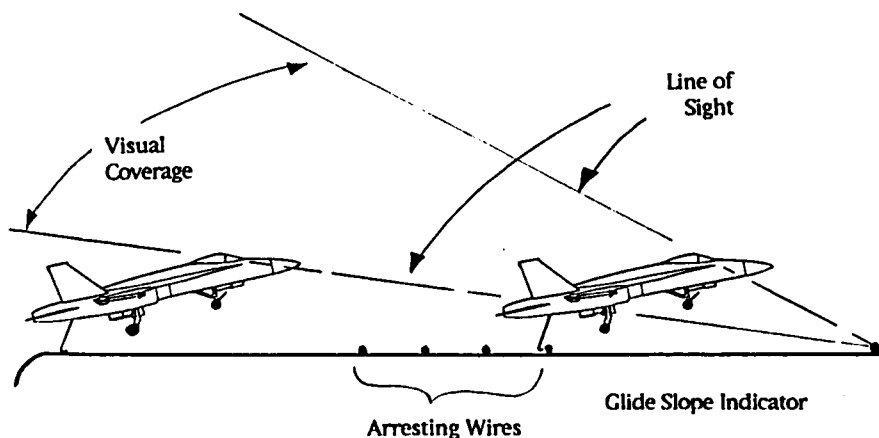


Figure I-1-6
GLIDE SLOPE VERTICAL COVERAGE LIMIT

The bottom limit of coverage is depicted by a HTDP just forward of the round down. Any flight path below this lower limit will result in the undesirable impact of some part of the aircraft with the round down (called a "hook slap" or "ramp strike").

This approximation illustrates only the concept of necessary coverage rather than the actual requirement. Many critical items have been left out for concept simplicity. For example, if the aircraft approach speed is only a few kts slower than design condition, the H/E value will increase (increased α) and push the HTDP aft. In this case, the aircraft on the right in figure I-3-5 may fly slightly above coverage and still engage. The aircraft on the left will hook slap while still in visual coverage. Consider the aircraft that is above coverage five seconds before touch down. Providing the pilot visual coverage to permit correction back to glide slope may lead to exceeding structural limitations. Actual flight test is the only way to determine required vertical coverage.

Horizontal Coverage

The concept of necessary horizontal coverage can be illustrated in very much the same manner as vertical coverage. If any glide slope VLA is mounted to the left of the landing area, figure I-1-7 illustrates the geometric considerations of coverage required to the right. This coverage should probably extend farther to the right to allow viewing when engaging slightly right of angle deck centerline. Required coverage on the left side of centerline is not nearly as critical and is dependent upon the case 1 landing pattern. The daytime landing pattern requires a left hand, circular approach until centerline capture. The sooner the pilot can precisely determine his glide slope during this turn, the more time he has available to capture and stabilize on optimum glide slope. Essentially, the more, the better. However, stabilizing the glide slope presentation at such angular extremes from centerline is complicated.

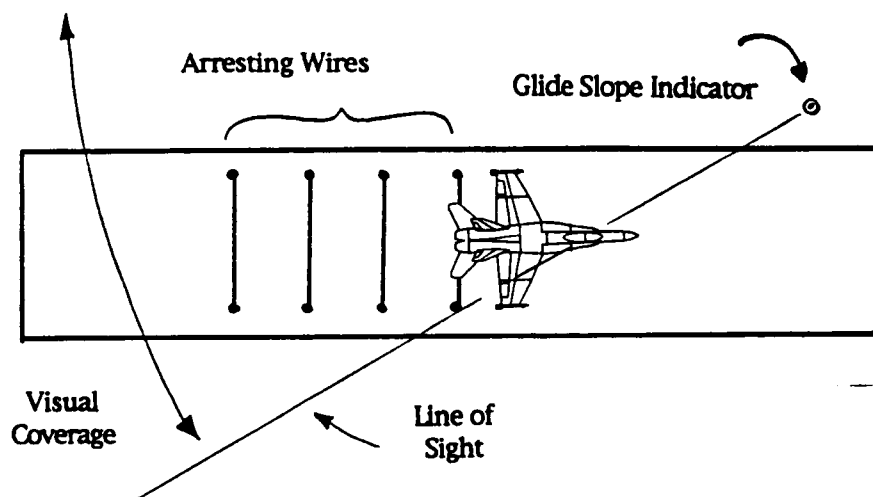


Figure I-1-7
HORIZONTAL COVERAGE LIMIT

Chapter 2

Environmental Considerations

"An analysis of past carrier landing mishaps has shown that over 25% of causal factors were environmental in nature. Pitching deck was the single most influential factor, involving 15% of all mishaps. The next most influential factor was "no horizon", or black night which was related to over 5% of mishaps. Other environmental factors contribute to a lesser degree." (LSO Reference Manual)

NASA endeavors to understand the environment of space to further human understanding of the universe as well as our planet. The driving techniques utilized in an automobile change with road condition, visibility, traffic, and type of car (Formula One or VW bug). An understanding of the design requirements is not complete without consideration of the environmental conditions these systems will operate in. Prevailing environmental conditions, ship motion and wind effects are essential to develop or improve equipment designed to enhance the pilot's ability to operate from the aircraft carrier.

ENVIRONMENTAL CONDITIONS

This section focuses on the environmental conditions that can not be controlled. If their possible adverse effects are not considered, system design will likely fall short of expectation. Since there are few bodies of water into which the carrier cannot go, adverse environmental factors of absorption, reflection, temperature variations and corrosion can be anticipated.

COLOR ABSORPTION

Use of multicolored VLA is an excellent way to grab the pilot's attention. However, it is susceptible to the problems that arise from atmospheric absorption. This is especially detrimental to the effectiveness of long range VLA systems. The pilot may perceive a change in intensity concurrent with a change in color, depending on his range from the source. This intensity change can be significant enough to detract from the intended dramatic effect of using different colors in the first place.

Light of different wavelength is absorbed in the atmosphere at different rates. The degree of absorption is a function of light wavelength, distance traveled and the moisture content of the atmosphere. This relationship does not account for the difference between actual intensity and our perception of it (brightness). In fact, our perception of brightness is fairly complex and depends on a number of factors in addition to intensity (Chapter 3 of Part I).

VLA color selection should be driven by physiological reasons to achieve the desired effect rather than absorption avoidance. Once color scheme is decided, the best solution to overcome absorption complications is to allow separate intensity selection and variation for each color in use. In this case, a simple cure is far easier than attempting to understand the complexities of the problem.

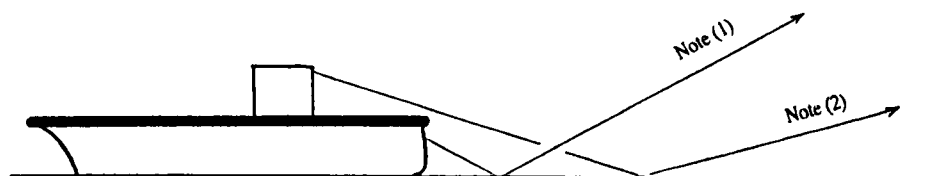
REFLECTIONS OFF THE WATER

In the middle of the ocean, perhaps more than a 1000 miles from the nearest street lamp, ambient light under a new moon is, for all practical reasons, non-existent. At the shallow grazing angle of the pilot's view of the carrier during approach, VLA reflections from the surface of the ocean can easily be mistaken for the actual system, the consequences of which can be disastrous.

VLA systems

Flight deck mounted VLA systems don't typically have a reflection problem for a number of reasons. Most VLA systems are very directional by design and can be adjusted to avoid radiance in the direction of the ocean surface. For incandescent style VLA systems where radiance is not so directionally limited, the immense flight deck physically blocks any light below the horizon. This may be fine in the static case but not once the flight deck begins to pitch and roll.

Reflection potential is far greater when VLA lighting emanates from vertical surfaces that face aft, toward final bearing. Two locations that fit this description are the fantail or a location high up on the super structure, as depicted in figure I-2-1.



- Notes (1) Reflection from a light source on the fantail.
(2) Reflection from a light source on the superstructure.

Figure I-2-1
SUPERSTRUCTURE AND FANTAIL VLA REFLECTIONS

Star Light

This is not as much of a VLA design issue as an explanation of the environment that the pilot must operate in. Any pilot who has logged any flight time at night knows that there exists no visible horizon. Man-made lights serve to "suggest" where the ground is, but pilots really can't make out the ground itself. Enough aircraft have crashed into the side of a mountain to prove this.

Flying over sparsely populated terrain with no man made lights may still have a different visual texture than the sky: the ground beneath the aircraft may be completely void of any light while the sky above may be filled with stars. This may be enough for peripheral vision to keep the pilot reasonably oriented.

While flying over water, star light reflection on the ocean surface introduces a unique problem for the pilot. The surface below resembles the sky above: stars appear everywhere, not just in the sky. It looks like one is flying in space and keeping oriented, even keeping basic "up" from "down" straight, is difficult at best.

CORROSION

Only a quick trip to the ship yard will illustrate the chronic problem of corrosion. Carriers operate at sea and ocean spray can not be avoided. Any VLA design must be able to withstand long term exposure to the corrosive effects of salt spray.

TEMPERATURE VARIATIONS

Global Temperature Variation

Water covers the great majority of the earth's surface and there are very few places an aircraft carrier can not go. Temperatures can range from well over 100°F near the equator to sub-zero above the Aleutian island chain. VLA systems must be designed to operate efficiently over a wide range of global climates.

Flight Deck Temperature Variation

Up to 30 aircraft (60 jet engines) with exhaust gas temperatures on the order of 500°C may be running on the flight deck at one time. Hot exhaust gasses exit the engine at such high velocities and travel such distances that men and equipment have been blown over the side. As aircraft taxi around prior to launch or following recovery, there is not a single location on the flight deck that is immune to exhaust gas impingement. A system that 30 minutes ago was frozen by ambient temperatures below zero may now be experiencing rapid heating from exhaust gasses. Such extreme temperatures may not last long but any design must recognize the potential for rapid short term temperature changes.

If system design performance requires very controlled temperatures, then one compensation is to incorporate internal air-conditioning. Any system that can overcome very high temperatures for short duration will be costly. Perhaps the best solution for temperature sensitive designs is to avoid location on the flight deck altogether.

SHIP MOTION

Carriers are over 1190 ft long, 280 ft wide, manned by nearly 5,000 personnel, can carry about 80 aircraft and displace millions of tons of water to stay afloat. The flight deck is 60 ft above water level. The superstructure climbs an additional ten to thirteen stories above that. It's hard to imagine such an immense vessel being affected by modest sea swell of seven to ten feet, but significant ship motion is a reality that VLA design must face to remain effective.

The discussion on touch down geometry in Chapter 1 of Part I, was under steady state conditions assuming a level deck. In reality, the ship is rarely level or completely stationary. Ship motion can be separated in the same fashion aircraft modes of motion can be separated.

Static motion is the long term change in position of the vessel and flight deck. It can float perfectly level, list to one side or even ride higher or lower in the water depending on loading conditions. This condition can persist for several hours until corrected. This long term change in position is called "ship's trim." Dynamic motion is short term, oscillatory motion that depends largely on environmental conditions such as sea-state. The vessel simply bobs and rolls about while on the high seas. Location of "center of gravity" and "center of rotation" play a part in both ship's trim (static position) and dynamic ship motion.

CENTER OF GRAVITY (CG)

A theoretical center of gravity (CG) exists for each carrier depending on the vessel class and over all weight distribution. Millions of gallons of fuel and water, once loaded, can be moved between huge holding tanks for storage or consumption. There may be as many as 80 aircraft aboard (some weighing as much as 48,000 lb empty), some in the hangar bay and others on the flight deck, or there may be only a few aircraft aboard. Clearly, this location varies slightly over time because the weight distribution changes continuously and this impacts the character of both static and dynamic ship motion.

CENTER OF ROTATION (CR)

The theoretical center of rotation (CR) is the location that any rotational motion of the vessel can be thought to revolve around. There exists separate CRs for each pitch, roll and yaw for each different carrier. Since the shape of the hull influences ship motion, CR is not necessarily collocated with the CG. Furthermore, the distance and direction from one CR to the CG will influence ship's motion.

If the goal was to design a VLA stabilization system to compensate for ship motion, CR and CG moment arms and locations for each carrier are readily available from a variety of sources including the *LSO Reference Manual*. But the goal is to get a feel for ship motion and how it affects the task of carrier landings. To this end, the approximate location of CR and CG need only be conceptualized, as illustrated in figure I-2-2.

These CRs are neither conveniently located with the intended HTDP nor coincident with angle deck centerline. This geometric arrangement not only complicates stabilization algorithms, it also produces axes coupling (motion in one axis causes motion in another).

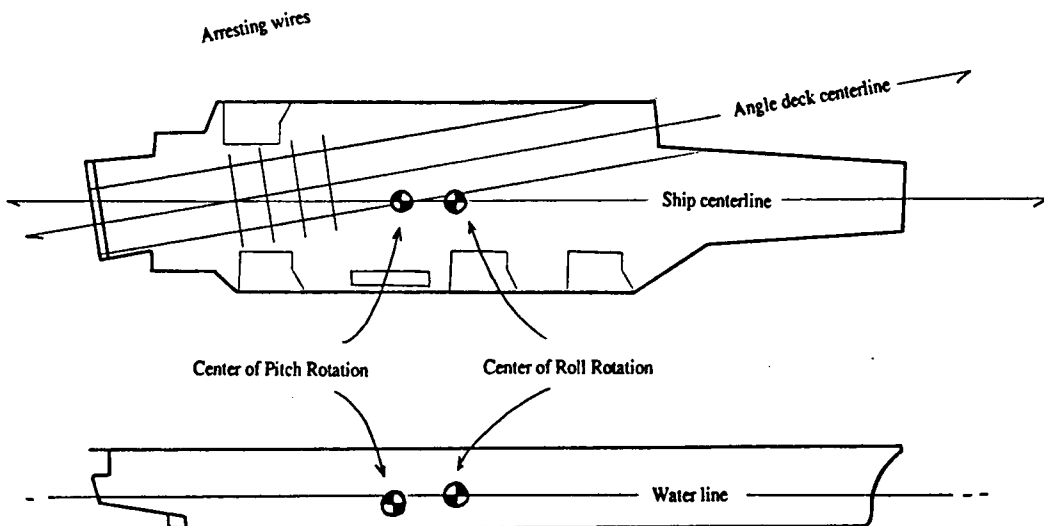
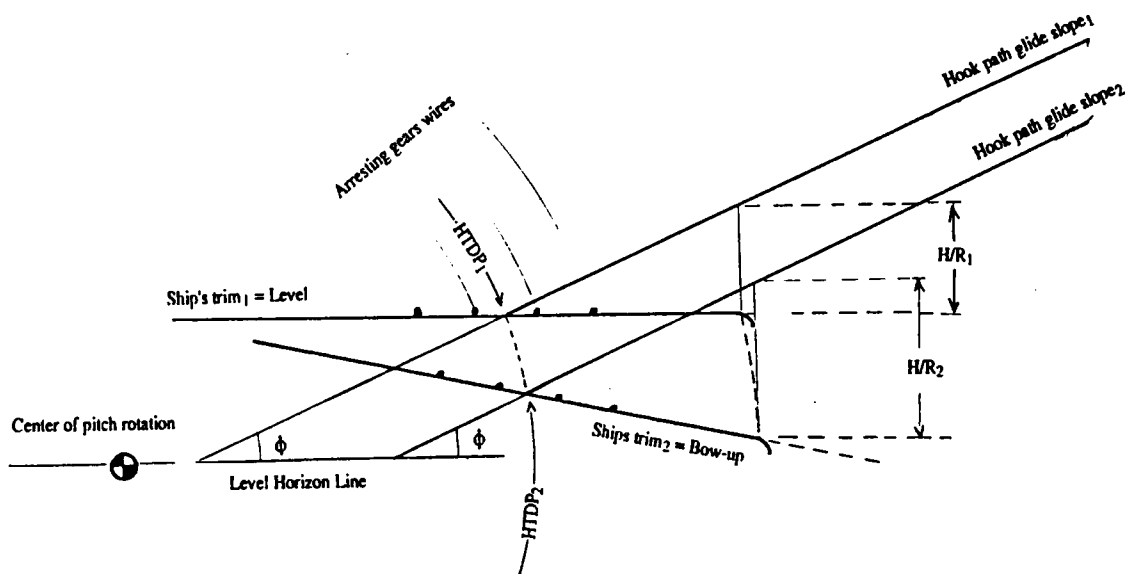


Figure I-2-2
CARRIER CENTER OF ROTATION

SHIP'S TRIM

The ability to adjust the CG allows the carrier to adjust its static position, called ship's trim. Obviously if weight distribution were not balanced (recently on-loaded supplies), the ship will list to one side or sit "bow-up" or "bow-down" until CG can be adjusted. In the mean time, if the deviation between current and ideal ship's trim is known, simply changing touch down geometry by adjusting VLA presentation will compensate for present ship's trim.

Figure I-2-3 illustrates an example of this compensation for a bow-up trim condition. If the ship is trimmed slightly bow-up, adjusting HTDP such that the hook still strikes the flight deck at the same position is one alternative. H/R has been allowed to increase while holding basic angle (or hook path angle) constant.



In ship's trim Condition 1, the flight deck is level with the horizon and touch down geometry yields a basic angle ϕ , hook to ramp clearance H/R_1 , and hook touch down point $HTDP_1$.

In ship's trim Condition 2 (bow-up), if we desire to hold the HTDP to the same spot on the deck, we must account for the positional rotation of $HTDP_1$ to $HTDP_2$. We can achieve this by keeping the basic angle the same ϕ which will increase hook to ramp clearance from H/R_1 to H/R_2 .

Figure I-2-3
HTDP AND H/R COMPENSATION FOR BOW-UP SHIP'S TRIM

In a bow-down condition, one can adjust touch down geometry by varying the same parameters as done so for the bow-up condition: maintain the same HTDP (with respect to the flight deck) by rotating it about the CR of pitch, maintain the same basic angle and allow H/R clearance to decrease.

During dynamic conditions, ship's trim is fictitious: the ship really never settles into a static condition. Ship's trim must still be determined by averaging all motion over a long period of time. This fictitious trim condition is needed because it permits programming of "static" values for HTDP and H/R. These static values become a "base line" from which compensation for dynamic ship motion can be calculated, then programmed into the VLA presentation.

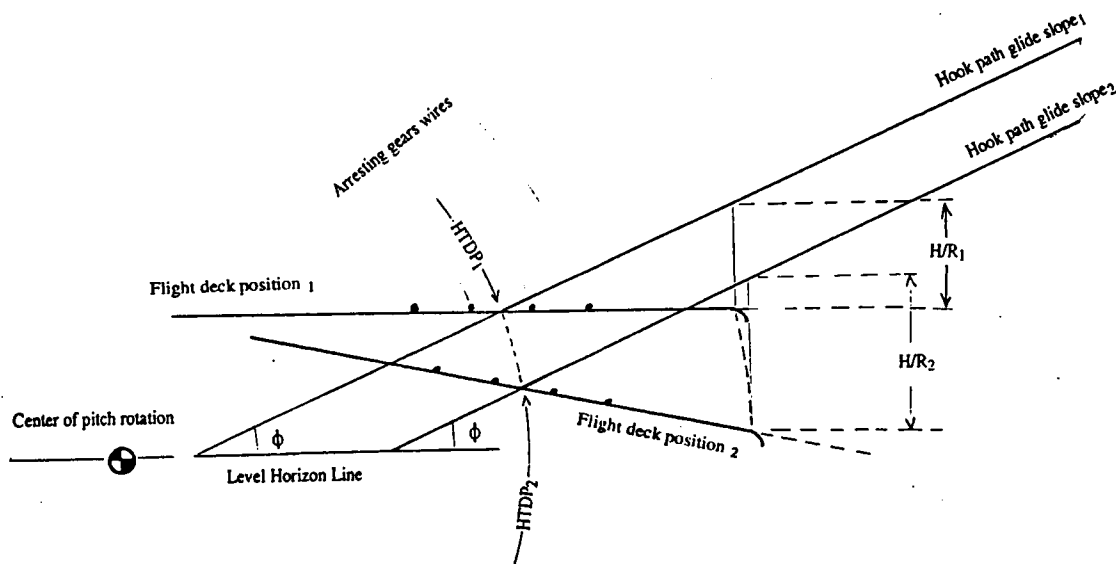
PITCH

Pitch is the most dramatic mode of ship motion and profoundly affects touch down geometry and the pilot's perception of glide slope. It is characterized by oscillatory, harmonic vertical motion of the round-down. As the ship oscillates in pitch, the entire flight deck rotates around the CR for pitch. During normal operations, pitch excursions rarely exceed $\pm 1.5^\circ$ (LSO Reference Manual). With such long distances from the CR to the ramp, these small angular deviations translate to large vertical motion at the ramp. In rough seas, the author has witnessed pitch deviations in excess of ± 18 ft of vertical ramp motion as measured from equipment on the LSO platform. Ship's pitch motion can be conceptualized as a steady harmonic oscillation, but this approach does not recognize the unpredictability of wave motion that causes continuous changes in phase and amplitude.

The pitch CR is roughly located 200 ft forward of the ideal HTDP, to the right of angle deck centerline and slightly below the waterline that lies about 60 ft below the flight deck. As the ramp descends, the touch down area also descends because it is located aft of the CR and the angle deck located forward of the CR ascends. Conversely as the ramp climbs, touch down area ascends and angle deck in front of the CR descends.

Touch down geometry can be stabilized in very much the same way variations in static position (ship's trim) were account for. Figure I-2-4 illustrates an example of this compensation during the a "ramp-down" cycle. When the ramp moves down, adjusting HTDP such that the hook still strikes the flight deck at the same position is one solution. H/R has been allowed to increase while holding basic angle (or hook path angle) constant.

When the ramp is on the upward cycle, adjusting these variables and constants depends upon the magnitude of ramp motion. When upward ramp motion is relatively small, the same stabilization compensation as used in the ramp-down cycle may be adequate: H/R is allowed to decrease so that HTDP stays at the same location on the flight deck. When H/R reaches the minimum tolerable clearance, stabilization scheme selection must be changed in order to preserve H/R. For example, in the case of large Nimitz class carriers, static H/R is about 14 ft (table I-1-1). If pitch motion is ± 8 ft, only six ft of H/R clearance exists at the top of the



Flight deck position₁ indicates the fictitious ship's trim from which static touch geometry is based: basic angle ϕ , hook to ramp clearance H/R₁, and hook touch down point HTDP₁.

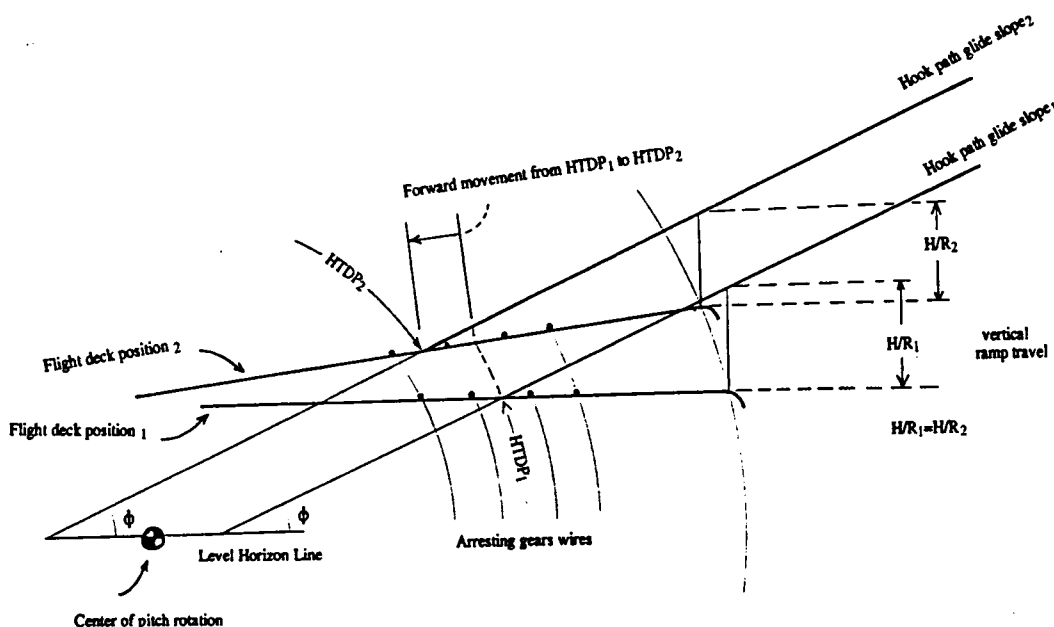
In flight deck position₂, we hold HTDP to the same point on the flight deck by allowing ramp clearance to increase from H/R₁ to H/R₂ at identical basic angle ϕ .

Figure I-2-4
HTDP AND H/R COMPENSATION FOR RAMP-DOWN PITCH CYCLES

ramp cycle. One solution is to program HTDP forward along the flight deck so that H/R is constant as illustrated in figure I-2-5.

ROLL

Ship roll is the next mode of motion that has a large impact on the ability of the pilot to land aboard the carrier. In the case of aircraft, any roll about the longitudinal axis will rotate the wing tips up or down. Left roll moves the left wing tip down and the right wing tip up. The wing roots, which are located closer to the axis of rotation (shorter moment arms) rotate the same angular amount but with less magnitude. In the same way, left rolling motion of the carrier (as viewed from the aircraft during approach) causes anything located to the left of the ship's roll axis to rotate down, and anything to the right, to rotate up. Longer distances from the axis of



Flight deck position₁, indicates the fictitious ship's trim from which static touch geometry is based: basic angle ϕ , hook to ramp clearance H/R_1 , and hook touch down point HTDP₁. Ramp-up cycle can be large enough to put minimum acceptable H/R clearance in jeopardy.

In flight deck position₂, we have elected to maintain the same ramp clearance ($H/R_1 = H/R_2$) at identical basic angles ϕ , by allowing HTDP to program forward along the flight deck from of HTDP₁ to HTDP₂.

Figure I-2-5
HTDP AND H/R COMPENSATION FOR RAMP-UP PITCH CYCLES

rotation produce larger displacements even though the angular rotation remains the same (assuming the carrier is a rigid, inflexible body). Rolling motion typically does not exceed $\pm 2.2^\circ$ of static ship's trim routinely (LSO Reference Manual). In the author's experience, rolling motion large enough to slide chairs and desks around office spaces with surprising regularity has been observed.

If the angle deck centerline was coincident with the vertical plane of the roll axis of rotation, the flight deck would roll about very much like an aircraft: left roll = left side rotating down and the right side rotating up. Herein lies the problem with ship roll motion. The flight deck is located about 60 ft above the roll CR and is canted 11° to 13° from the ship's centerline. There are several consequences of this geometric arrangement.

Lateral Displacement of the Landing Area

Since the distance from the CR to the flight deck is about 60 ft, any rolling movement will displace the flight deck laterally according to the magnitude of angular rotation. Figure I-2-6 is a simplified two dimensional illustration of this effect. Equation (I-2-1) relates these variables to approximate lateral displacement of the flight deck due to ship's roll.

$$D = 2d \sin(x/2) \quad (I-2-1)$$

Where: D = total lateral displacement of a point in the landing area.

d = distance from the CR.

x = total angular roll.

In the case of the *USS THEODORE ROOSEVELT* (CVN-71) with a 53.6 ft distance from its roll CR to the flight deck and assuming total roll is 4.4° ($\pm 2.2^\circ$), equation (I-2-1) yields a total lateral displacement of 3.7 ft from peak left roll to peak right roll. This may not sound like much at first glance but considering the pilot's task, it is significant. If the aircraft is about five seconds from touch down with the ship at peak roll, the pilot is doing his very best to put his aircraft right

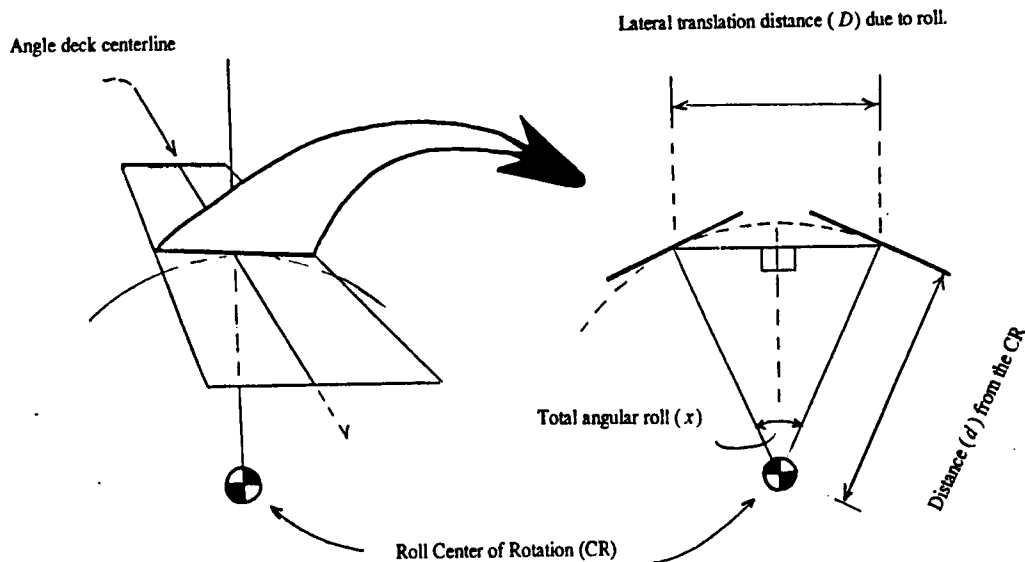


Figure I-2-6
FLIGHT DECK LATERAL DISPLACEMENT DUE TO SHIP'S ROLL

on centerline (which is displaced left or right). In the following five seconds, the ship reaches peak roll to the other side, centerline has moved 3.7 ft and the aircraft will touch down off centerline. Maximum tolerable off-center engagement is ten ft due to arresting wire integrity (some are restricted even further because of large wing spans: Chapter 1, Part I). Ship's roll has reduced allowable centerline touch down error by 37%. The problem can get even worse when the pilot is trying to "catch up" or "chase" centerline by establishing left or right drift rate to correct for perceived line-up deviation. When the aircraft is approaching centerline as ship's roll reverses, not only will lateral displacement due to roll cause an overshoot, but the established drift rate will carry the aircraft further past centerline. And the pilot can't be faulted because, from the cockpit, there is no discernible difference between a line up drift caused by aircraft motion and lateral displacement due to ship's roll: they look identical from the cockpit.

Roll Influence on H/R and IITDP

Another consequence of the landing area not being coincident with the roll axis is variations in H/R and HTDP. This is fairly difficult to conceptualize and can wrongly be discounted as trivial. Figure I-2-7 assists in visualizing ship's roll affect on glide slope geometry in three dimensions. Since lateral displacement of the landing area during roll motion has been previously introduced, the effect of vertical distance from the roll CR to the landing area can be eliminated. This places the roll axis of rotation in the plane of the landing area. It remains true that anything left of the ship's roll axis still rotates down during left roll and anything right of the roll axis ascends.

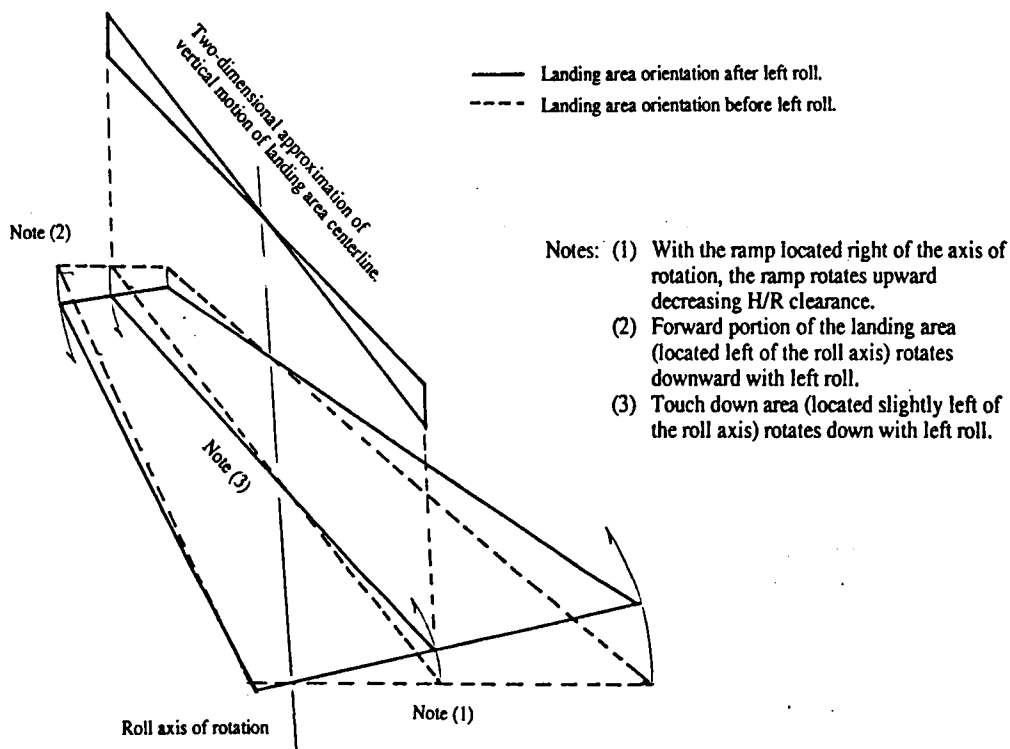


Figure I-2-7
SHIP'S ROLL AFFECT ON GLIDE PATH GEOMETRY

By looking at this along the centerline only, the effect becomes clearer. Figure I-2-8 shows the two-dimensional consequences on H/R clearance and HTDP. It resembles the effect of pitching motion on touch down geometry with one very large difference: rotation is not occurring at the pitch CR, it is occurring through the CR of roll. By collapsing the analysis to two dimensions, the flight deck is rotating about a location on the flight deck where the ship's roll axis and angle deck centerline coincide. This is roughly near the number one wire for Nimitz class carriers.

HEAVE

Heave is strictly the vertical motion of the ship: as the ship transits the water, the ship rises and falls according to wave motion and water displaced by the hull. Heave typically does not

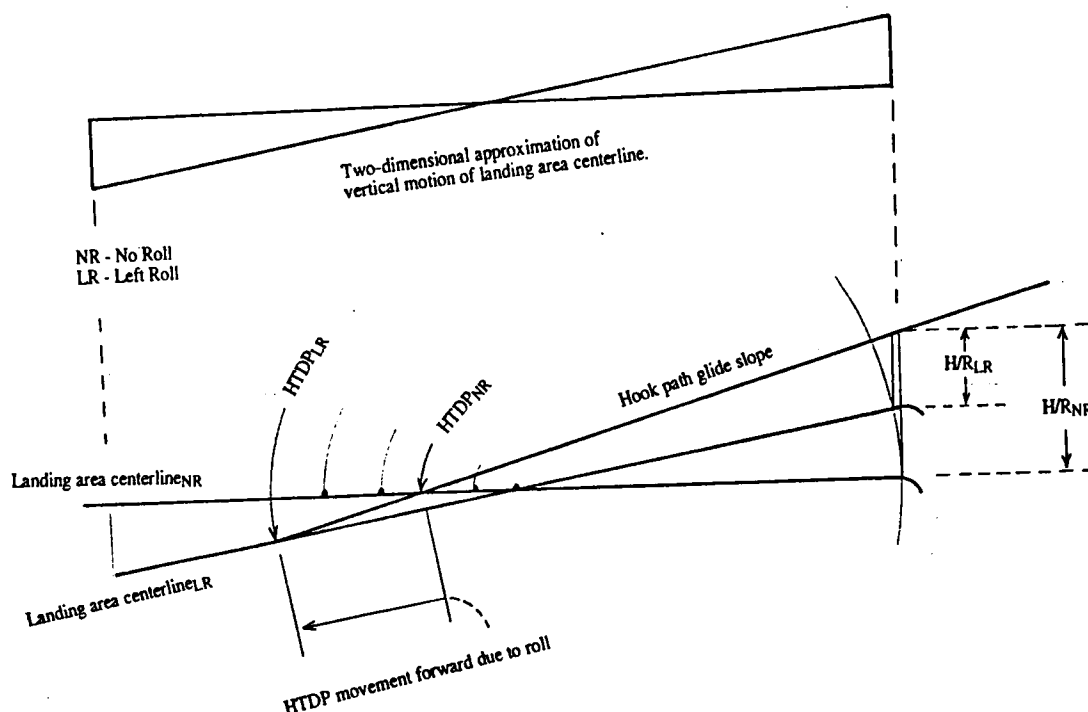


Figure I-2-8
SHIP'S ROLL AFFECT ON GLIDE PATH GEOMETRY (TWO-DIMENSIONAL APPROXIMATION)

exceed a range of 5.5 ft (LSO Reference Manual). Its influence on touch down geometry is simple to understand.

One way of dealing with heave is to allow VLA location to account for ship's heave motion. If a VLA system is mounted near the flight deck, it's moving up and down at the same rate and magnitude as the general touch down area. Consequently, any glide slope presentation from this location is also heaving up and down along the approach corridor. Sacrificing H/R for HTDP as done so during pitch motion compensation is not necessary. Touch down geometry remains relatively fixed on the flight deck which is a distinct advantage of mounting VLA on the flight deck.

There is a disadvantage that may not be evident until heave becomes large. The aircraft may not be physically capable of making such quick changes in glide slope. Consider the situation of the pilot trying to follow the ship on a downward heave by increasing rate of descent as called for by VLA presentation. If ship's heave reverses, and starts upward just prior to touch down, total relative closure rate (rate of descent of the aircraft and rate of ascent of the flight deck) is increased. For this reason, these rates may be high enough to warrant some sort of stabilization scheme to compensate for heave motion.

One way to deal with heave is to stabilize the basic angle along the approach corridor rather than the flight deck. The ship is allowed to rise and fall independently without affecting the three dimensional position of the glide slope with respect to space. Exact touch down geometry is being sacrificed in favor of an absolutely heave-stabilized glide slope presentation. Trigonometry states that for $3\frac{1}{2}^\circ$ basic angle, every foot of heave moves the HTDP 18.2 ft. Total heave motion (5.5 ft) will cause 100 ft of HTDP movement. Likewise, one foot of heave will cause one foot of H/R change. So when heave becomes large enough, this form of compensation will program unacceptably large deviations in H/R and HTDP. The advantage of providing a stabilized glide slope presentation may be overshadowed by the disadvantage of large deviations in touch down geometry.

The advantages of relatively fixed touch down geometry while providing a relatively stabilized glide slope presentation to the pilot can be achieved by reaching a compromise between these two concepts. Allowing HTDP and H/R to vary by some fraction of that called for by absolute heave-stabilized glide slope presentation can achieve this. For example, allowing HTDP to move aft only nine ft (as opposed to 18.2 ft) for every foot of upward heave while glide slope moves vertically only 1/2 ft is one possible compromise. There will exist some relationship between these two methods that provides a satisfactory compromise that retains the good characteristics from both while minimizing the disadvantages of either.

YAW

Since the ship moves about on the two-dimensional surface of the ocean, the only way to turn is via yaw which is described by clockwise or counterclockwise rotation of the ship as viewed from above. When a right turn is desired, huge rudders located below the waterline at the stern of the ship, displace a massive amount of water so that the stern moves left. The longitudinal axis of the ship ends up rotating to the desired direction of travel.

During recovery operations the ships is continually trying to keep the relative wind directly down the angle deck. Small continuous heading changes are required to achieve this and consequently cause the pilot has to contend with varying amounts of yaw motion. Corrections to ships heading of up to 20° is not unusual, although $\pm 5^\circ$ is more the norm. The ship also simply yaws as a consequence of wave motion as it transits the water.

The effects of yaw have the largest impact on those systems designed for long range line-up cueing. As the ship yaws about (either from ship heading changes or wave motion) landing area centerline does also. A few degrees of yaw may not amount to much at 1/2 nm but can be substantial at four nm: a 10° ship turn displaces the approach corridor centerline nearly 3,700 ft from its previous position. An aircraft that was on centerline ten seconds ago is now nearly 2/3 nm off centerline.

Stabilization of line up systems with yaw is fairly straight forward and its success lies primarily with time constant selection (how rapidly the VLA system catches up with actual landing area centerline). Some yaw stability for line up system is desirable. If small yaw oscillations were not accounted for, dramatic angular swings of approach corridor centerline would eliminate any system's effectiveness and defeat the intended purpose. At the other extreme, stabilization with very long time constants, centerline presentation is slow to catch up with actual centerline and fails to provide accurate usable information for the pilot to follow. Effective stabilization becomes a balancing act between sensitivity and performance: enough sensitivity to provide accurate timely information about changes in centerline position without over-reacting to insignificant perturbation in ship's yaw.

SWAY

Sway is the lateral or sideways translation of the ship. Its equivalent in aircraft modes of motion is sideward motion due to side force. Any lateral movement of the ship while an aircraft is on approach will equate to an equivalent lateral deviation from angle deck centerline. Sway by itself is relatively small. However, sway during ship turns can be substantial because the rudders literally push the stern left or right to adjust ship's heading.

SHIP'S SPEED

Optimum wind for recovery operations is 25 kts, along angle deck centerline (*Aircraft Recovery Bulletin No. 10-10C*). When ambient wind velocity is different, the ship will have to steam in a particular direction with a certain velocity to develop the desired recovery winds. If the natural wind is 25 kts, the ship merely has to point in the proper direction to receive the proper recovery wind direction. What is of interest in this discussion is the additional effect ship's translation through the water has on approach geometry.

In the case of 25 kts of natural wind, Mother Nature is providing the optimum wind velocity for recovery and the ship needs only to point in the right direction to keep the wind blowing

straight down the angle deck. The ship must still maintain enough speed to control heading (minimum steerage speed) but this is insignificant for the approaching aircraft at nearly 137 kts. The aircraft longitudinal axis (assuming no side slip) will be pointing right down the angle deck during approach. This is the same as a field-based approach in the absence of cross wind.

When the ship has to generate a portion of the recovery head wind, the approach corridor which is aligned with the angle deck (not the longitudinal axis) is moving to the right as viewed from an approaching aircraft. As illustrated in figure I-2-9, the aircraft's flight path is directed toward the location where the ship *will be* at touch down. In the case of the *USS KITTY HAWK* (CV-63) with $11^{\circ} 20'$ of angle deck cant, making 25 kts of recovery head wind, an F/A-18 *HORNET* on approach maintaining 137 kts will be pointed in excess of $5 \frac{1}{2}^{\circ}$ to the right of current ship's position to maintain landing area centerline (law of sine's). This is different from a cross wind landing because there is no cross wind at the angle deck and yet the aircraft must continue to point to the right of centerline as if there were a cross wind. This is not overwhelming for a pilot to deal with, but he will have to compensate for ship's speed or line-up performance will be degraded.

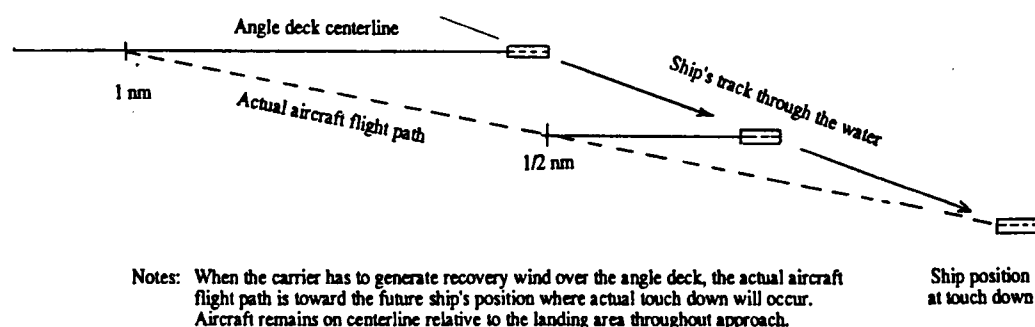


Figure I-2-9
ACTUAL FLIGHT PATH DUE TO SHIP'S SPEED

WIND EFFECTS

WIND EFFECT ON TOUCH DOWN GEOMETRY

Variation in Actual Flight Path

As an aircraft maintains glide slope during approach, the actual flight path angle through the air mass is slightly less than the basic angle (basic angle is the angle between the aircraft and the flight deck as described in Part I, Chapter 1). The best way to visualize this is to remember the ship is moving away from the aircraft during approach. At any instant in time, the aircraft's actual flight path will be directed toward the *future carrier position* when touch down will occur. From the ship's perspective, the aircraft is maintaining constant glide slope (basic angle) but the aircraft's flight path *through the air mass* is different. Wind over the deck affects relative closure between aircraft and carrier, and will have the same effect on actual flight path. In both cases, actual flight path depends on aircraft movement through the air mass and basic angle is the relative glide slope between the aircraft and the carrier. Figure I-2-10 illustrates this effect of wind on the actual aircraft flight path during approach. Equation (I-2-1) is an expression that relates β and the magnitude of head wind involved.

$$\sin \beta = \frac{W \sin \phi}{V} \quad (I-2-1)$$

Where: β = decrease in aircraft flight path due to head wind.

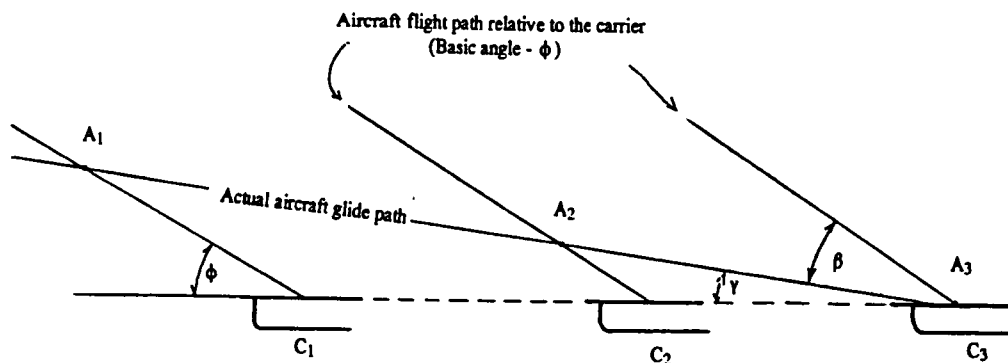
W = relative head wind along approach centerline (knots).

ϕ = the approach basic angle.

V = aircraft true airspeed in knots.

With the small angles involved, equation (I-2-1) can be approximated as follows:

$$\beta \approx \frac{W \phi}{V} \quad (I-2-2)$$



At position A₁, the aircraft is maintaining the basic angle (ϕ) with respect to the flight deck which is at carrier position C₁.

As approach continues through A₂ (carrier at C₂) to touch down (A₃, C₃), the actual flight path (γ) of the aircraft through the air mass is clearly less than ϕ due to ship's movement or recovery head wind. This difference between γ and ϕ is labeled β .

Figure I-2-10
WIND EFFECT ON ACTUAL FLIGHT PATH

Adapted from: *Aircraft Recovery Bulletin No. 10-10C, For All Arresting Gear and Optical Landing Systems*, Washington D. C.: Department of the Navy, Naval Air Systems Command, 28 Jan 1991, (NAVAIRENGCEN-5161).

Equation I-2-2 shows β increases for increasing relative head wind which reduces actual flight path angle of the aircraft through the air mass. For example, the actual flight path of an approaching aircraft at 130 kts, on a $3\frac{1}{2}^\circ$ basic angle, with 30 kts of recovery wind is 2.7° ($\beta \sim 0.8^\circ$). In other words, the aircraft is maintaining a $3\frac{1}{2}^\circ$ basic angle with respect to the ship, while flying an actual flight path angle of 2.7° . Under no-wind conditions ($\beta = 0$), the actual flight path and the basic angle would be the same: 3.5° .

As previously discussed, engine response time is affected by basic angle selection (Part I, Chapter 1). The same argument can be applied to the effect of higher winds. Increasing recovery winds will in effect shallow the approach flight path angle and decrease engine response time (which is a desirable effect).

Variation in H/E Value

As discussed in Chapter 1 of Part I, the H/E value of an aircraft depends on its size, angle of attack (α) and basic angle. This discussion did not include the influence of relative head wind on H/E in favor of saving the discussion for this section. Equation (I-1-1) related the variables illustrated in figure I-1-5 which excluded any effect of wind. Figure I-1-5 has been reproduced and slightly modified to include the effect of wind (β) and is presented as figure I-2-11. Since the actual aircraft flight path through the air mass is different from the basic angle, and α is the angle between the aircraft longitudinal axis and relative wind, equation (I-1-1) can be modified to include the reduction in actual flight path β , equation (I-2-3).

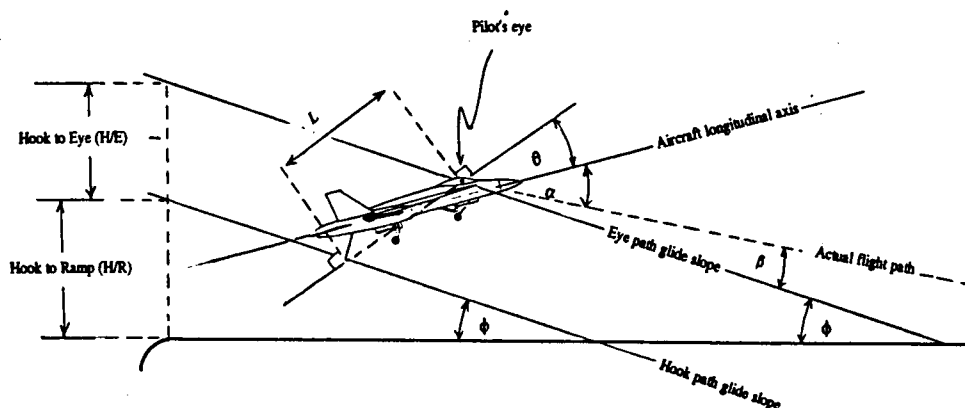


Figure I-2-11
GLIDE PATH GEOMETRY (INCLUDING WIND EFFECTS)

Adapted from: *Aircraft Recovery Bulletin No. 10-10C, For All Arresting Gear and Optical Landing Systems*, Washington D. C.: Department of the Navy, Naval Air Systems Command, 28 Jan 1991, (NAVAIRENGCEN-5161).

$$H / E_{(feet)} = \frac{L \sin(\theta + \alpha + \beta)}{\cos \phi} \quad (I-2-3)$$

Where: L = distance from the pilot's eye and the aircraft hook point.
 θ = angle from the aircraft's longitudinal axis to the hook-to-eye line.
 α = aircraft angle of attack (or AOA).
 ϕ = the approach basic angle.
 β = change in aircraft flight path due to recovery head wind.

At the small basic angles (5° or less), the differences in H/E value for changes in ϕ are insignificant. Equation (I-2-3) simplifies to an expression which is independent of glide slope.

$$H / E_{(feet)} \approx L \sin(\theta + \alpha + \beta) \quad (I-2-4)$$

Clearly, any increase in β will increase H/E which will move HTDP aft if not corrected.

Basic Angle Selection

Part I, Chapter 1 introduced the important factors that can *limit* selection of basic angle. To achieve consistent repeatable pilot performance during landing, every attempt should be made to provide consistent, repeatable approach conditions. Basic angle selection is a variable that can be controlled so that the airplane maintains a consistent flight path angle through the air, for each approach. This is an important distinction that must be understood. Engine response depends on initial throttle setting which is determined by actual flight path angle, not basic angle. The pilot's perspective during approach depends on basic angle.

Altering basic angle so that the pilot flies the same actual flight path provides consistent aircraft performance and handling qualities that will improve pilot performance, and indeed this is what each carrier does. Typically, if recovery head winds are above 35 kts, basic angle will be increased to 4.0° from 3.5° as the LSO Reference Manual recommends.

CARRIER WIND PATTERNS

When carriers were first conceived, there was a great deal of research and study on wind patterns as the air mass moves up, over and around the flight deck. Each carrier has its own unique wind patterns very much the same way each aircraft type has its own unique aerodynamic characteristics. The difference between each class of carrier is substantial while variations between each vessel of the same class are noticeable but not significant. The results of wind pattern studies are very detailed and document velocities and directions for a given location with every conceivable combination of wind direction and speed. This discussion will be limited to the more significant wind patterns that affect the pilot's task of recovering his aircraft aboard.

The strength of each wind pattern changes and is dependent on recovery head wind direction (with respect to angle deck centerline) and the velocity. Furthermore, each aircraft reacts differently to each of these because of aerodynamic and structural design differences.

The Burble

The combined effect of the downwash, the rooster tail and island turbulence (each explained in the following sections) is commonly referred to as "the burble." Academically each can be discussed individually, but in reality the aircraft will experience a combination of several patterns simultaneously.

Downwash and Rooster Tail

The downwash and rooster tail are directional disturbances that affect airflow vertically along the approach corridor as depicted in figure I-2-12. As the air mass moves aft along the angle deck, it remains relatively level with the horizon. When it reaches the ramp, it turns downward toward an area of low pressure that exits behind the carrier, hence the term downwash. As it continues aft along the ocean surface, it combines with air coming from the sides of the ship and as the pressure rises, the air is pushed upward (rooster tail).

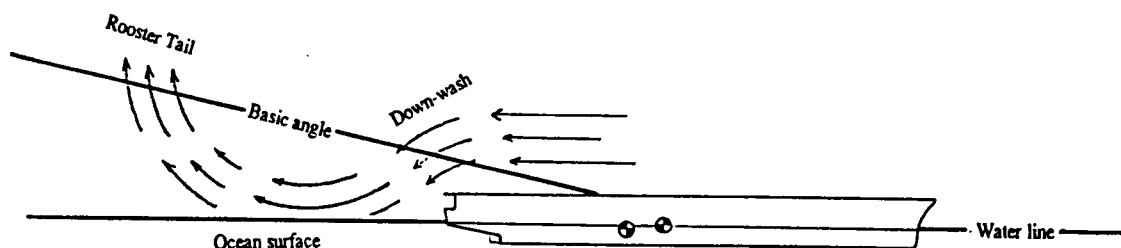


Figure I-2-12
DOWNWASH AND ROOSTER TAIL WIND PATTERNS

Approaching aircraft must contend with these changes in vertical air mass direction or glide slope performance will be degraded. Whether these manifest themselves as transient changes in AOA or glide slope is largely dependent on the aircraft aerodynamics. Those airframes that are very sensitive to small perturbations in α (steep $C_{L\alpha}$ curve) will be more affected by the rooster tail and downwash.

Aircraft during approach, first pass through the rooster tail and the pilot will have to reduce power to keep from ballooning above glide slope. Shortly thereafter, the aircraft will transit through the downwash requiring an opposite correction: the pilot will have to add power briefly to prevent settling below optimum glide slope. These can be surprisingly difficult to contend with for the less experienced carrier pilot. The rooster tail requires the pilot to reduce power, sometimes for an uncomfortably long period of time when the rooster tail is strong. As the pilot leaves the rooster tail, the aircraft is correcting back to glide slope from above (under powered). So, the aircraft arrives in the downwash with a higher rate of decent (above glide slope and correcting), under-powered, with a downward momentum. If these corrections are not anticipated, even full power may not be sufficient to change the aircraft downward momentum and arrest the settle. At the very least, the aircraft will settle onto an early wire after passing the

ramp without enough clearance. If the rooster tail and downwash are anticipated, their effects can be substantially reduced.

The strengths of these depend mostly on the velocity of recovery head wind. The higher the wind over the angle deck, the stronger both these patterns become. A stronger rooster tail requires larger more aggressive pilot corrections which will compound the re-correction in the downwash.

Island Turbulence

That part of the air mass that circulates around the huge superstructure or "island" will become turbulent as it proceeds aft. If the recovery wind is directly down the angle deck, turbulent air flow around the island does not substantially impact the approach corridor, but rather moves parallel to angle deck centerline. When the ship is generating its own recovery wind, the direction is straight down the longitudinal axis of the ship (called "axial winds") and the turbulence blows across the approach corridor as illustrated in figure I-2-13. Since the superstructure is about 60 ft high, any direct effect of island turbulence is limited to below about

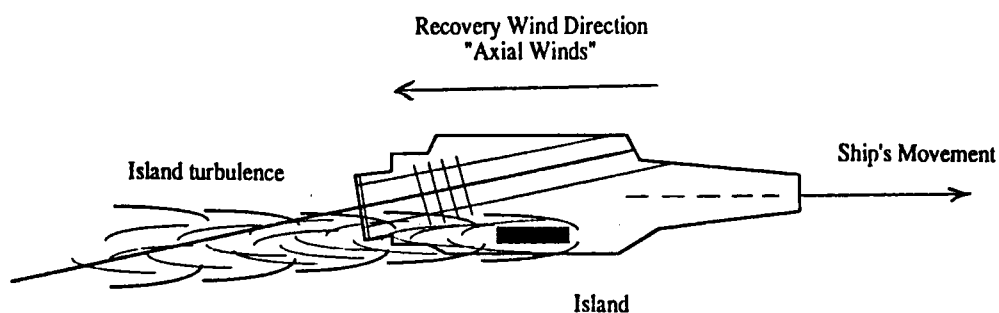


Figure I-2-13
ISLAND TURBULENCE WITH AXIAL WINDS

100 ft of altitude above touch down. Consequently, it affects the approaching aircraft about the same location as the downwash does which is very close to crossing the ramp.

Unlike the rooster tail and the downwash, which were directional disturbances, island turbulence is primarily a magnitude disturbance. Wind directly behind the island is nearly still. Moving farther aft, velocities begin to increase proportionally to the distance traveled. Eventually, turbulence subsides very far from the island, but unfortunately this distance is well beyond the point where island turbulence crosses the approach corridor.

This is the same effect experienced by the driver and passenger of a convertible automobile on the freeway. The driver of the convertible does not experience as much wind velocity as the rear seat occupant does. Both driver and passenger experience turbulence by feeling their hair blowing about in rapidly changing directions, the rear seat more violently than the front.

Island turbulence primarily affects the approaching aircraft by reducing the magnitude of the relative wind. If an aircraft is suddenly five kts slower than it was a second ago, the wings will no longer be generating the same lift (constant AOA) and aircraft rate of descent will increase. Those aircraft that are very lift sensitive to perturbations in dynamic pressure will be affected more detrimentally by island turbulence.

The other obvious effect of island turbulence is the instability of the air. Slight, random unpredictable variations in wing attitude and AOA are attributed to island turbulence.

Flight Deck Turbulence

It is no surprise that the air mass that moves along the flight deck becomes disturbed as it moves around equipment, parked aircraft and personnel. Jet engine exhaust velocities are ferocious while the aircraft is at full power just prior to catapult launch. Huge plates extend from the flight deck called JBDs (Jet Blast Deflectors) to push the exhaust gasses upward, away from equipment and personnel on the flight deck. The combined effect of all these disturbances result in constantly changing wind velocities and directions for a given location on the flight deck. Personnel have a difficult time remaining standing because turbulence is knocking them about

significantly. Since this turbulence remains fairly localized to the flight deck itself, the only effect on approaching aircraft is at the instant before touch down. Unpredictable variation in wing attitude at touch down is an effect that can be attributed to flight deck turbulence.

Angle Deck Up-wash

Air that is forced to move laterally around the hull of the ship experiences a slight rise in pressure. This pressure differential tends to cause the air mass to curl up and over the edge of the flight deck in the same way wing tip vortices curl upward. This occurs along the entire flight deck edge but affects aircraft only at the forward end of the landing area and can be visualized in figure I-2-14. The pilot will notice a slight but rapid 1° to 2° wing attitude change at the instant the aircraft rolls off the angle deck following a bolter. Direction of roll depends on recovery wind direction.

WIND EFFECT ON PILOT PERFORMANCE

There are many environmental factors that can not be controlled: there is little that can be done to change the phase of the moon or state of current sea swell condition. However, by

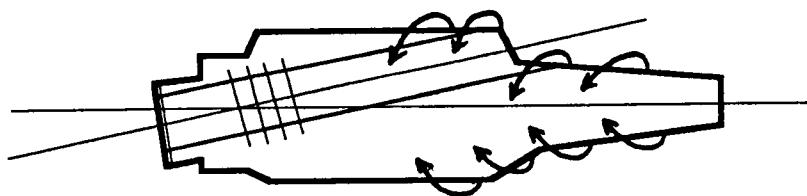


Figure I-2-14
ANGLE DECK UP-WASH

altering the ship's course through the water, consistent wind conditions can be achieved during each and every recovery to promote consistent pilot performance, just as basic angle was adjusted to provide consistent flight path angle. By doing so, the task remains unchanged, at least from the wind effect stand point and the pilot will be more able to successfully compensate when conditions are anticipated.

An example of the importance of consistent conditions during a task is illustrated when driving with a strong head wind. The driver will probably find himself slower than yesterday because his foot is accustomed to a particular position on the accelerator, which equates to a "no-wind" cruise speed. If today's drive were during the no-wind conditions, his foot would happily (and probably unconsciously) find the proper position. Having checked the speedometer, he readjusts his foot to speed up to the desired cruise speed. Chances are within a few moments he'll find himself slow again: current foot position, having fallen out of immediate awareness, returns to its "no-wind" accelerator position. So with a stronger than normal head wind, a driver must re-tune foot position for a new, "strong head wind" condition. After several miles, the driver's foot is re-trained and he proceeds down the road at the desired speed.

The same idea extends to the carrier pilot except he must control four limbs and maneuver his aircraft in three dimensions. He also has only 20 seconds on final to adjust his technique to ambient wind conditions. Clearly, pilot performance will be more consistent if the task were performed under similar wind conditions.

OPTIMUM RECOVERY WIND

Direction

It was determined long time ago during limited carrier wind tunnel tests that the airflow in the landing area is steadiest when the relative wind direction is parallel to angle deck centerline (Aircraft Recovery Bulletin No. 10-10C). Any experienced LSO or pilot will quickly agree: landing performance is better with winds right down the angle deck. With a constant recovery cross wind component, turbulent airflow increases as the angle between landing area centerline

and the relative wind increases. Simply put, the higher the cross wind angle, the more wind disturbance.

In addition to turbulence with increasing cross wind angles, the downwash moves closer to the ramp which equates to dramatically higher rates of decent crossing the ramp. Flight test with a seven kt cross wind component resulted in sink speed increases of 180 to 360 feet per minute. This represents a significant increase (50%) in nominal rates of decent. And the pilots were anticipating the need for extreme corrective action. The reader may imagine what these increased rates of decent would be if the pilot was not anticipating such adverse wind corrections. Obviously, landing performance will be degraded (causing reduced boarding rates) when operating with a cross wind. (Aircraft Recovery Bulletin No. 10-10C).

Velocity

As a result of flight tests conducted aboard four different carriers, the adverse effects of the burble were reduced by decreasing wind velocity. At 35 kts, the frequency of higher landing gear loads and random wing drop increased, which is undesirable. Test pilots concluded that 25 kts was the optimum wind velocity. The problem is that 25 kts cannot be utilized with certain carrier/aircraft combinations because of aircraft and arresting gear structural strength limitations, and operation considerations such as minimum ship's steerage speeds and the magnitude of prevailing winds. Again, consistency is far more desirable providing the ship is near this 25 kt optimum wind velocity. (Aircraft Recovery Bulletin No. 10-10C).

Chapter 3

Physiology

Understanding "the task" and "the environment" is only part of the whole story: the external part. Since the picture of the world provided by sensory input to the brain is not an exact reflection of the external world, understanding basic physiological mechanics is important.

This chapter summarizes the physiological factors that human beings use to interpret the world around us: specifically the nervous system, sight, equilibrium, and touch. An attempt has been made to discuss this rather large subject at the physiological level without regard to any psychological impact.

Throughout this discussion, the reader should keep separate two important physiological characteristics that occur before the brain gets the opportunity to evaluate the environment:

1. Stimulation is first detected.
2. Then the stimulation is coded and routed to the brain.

Every sensation starts with detection. Before the brain gets the opportunity to interpret the sensation, the nervous system must receive a signal. There are certain cells that are specialized for detection of certain kinds of energy, chemicals or motion. These cells, called receptor cells, must translate the incoming information into the language of the brain. On the basis of the incoming information, electrical activity is initiated that may in turn initiate a nerve pulse or affect a nearby nerve cell. Through an interpretive chain reaction in the nervous system, the brain is finally given the opportunity to size up the sensation. (Haber)

THE NERVOUS SYSTEM

The nervous system serves a person in the same way a highway serves a large city. The nervous can be separated into two separate systems: the central nervous system that consists of the spinal cord and the brain, and the peripheral nervous system that connects the central nervous system with the rest of the body. (Haber)

While brain signals involve both chemical and electrical events, often only the electrical events are studied. In some models of the nervous systems, the transmission and processing of electrical signals are the only events of interest. When speaking of circuits in the brain, physiologists mean connected groups of nerve cells in which electrical signals are generated, transmitted and analyzed. (Haber)

Nerve cells are unique in that they have the capacity to generate and conduct excited states, thus providing the signals that transmit and process information in the brain. These signals are transmitted along the nerve cell, and at its terminals (end of the axon) they produce changes that communicate some of the features of the nerve cell's excited state to other nerve cells. (Haber)

The states are complex physiological events. There are two principle classes of excited states in the nervous system: nerve impulses which can be thought of as digital information transmission and graded events which resemble analog interpretation of received digital information. (Haber)

NERVE IMPULSES

When a hot stove is touched, the receptor cells in the finger must signal sensation to the central nervous system for action. It does so via a nerve cell tentacle called the axon. This method of carrying information along a person's internal highway is called a nerve impulse. (Haber)

These pulse like events that last from 0.5 to 2.0 milliseconds resemble a chain reaction along the axon of the nerve cell. The speed of the pulse ranges from one meter per second to

over 100 meters per second depending on the size and structure of the axon. Once a portion of the axon transmits its pulse, several milliseconds elapse before it can fire again. This prevents the impulse from traveling back to the area that it has previously passed. Once started, the nerve impulse travels in one direction. (Haber)

The intensity of the stimulation is represented by repeated impulses, each of the same size, duration and amplitude. More intense stimulation increases the frequency of the impulses but not the magnitude. If stimulation is gradually decreased, a threshold is reached, below which the nerve impulse does not occur. (Haber)

GRADED EVENTS

When the nerve impulse reaches the end of the axon, it connects with another nerve cell at a junction called a synapse. The pulse transverses the synapse by either electrical or chemical means. Since the actual physiochemical explanation is rather complex, for the purposes of this discussion, it only matters that it does reach the connecting cell where graded events occur in the receiving cell. The received information is graded according to its magnitude and results in the local change in the magnitude of nerve cell's potential. When enough stimulation is received to exceed the receiving cell's threshold, a nerve impulse is triggered in the cell body and passes the information along. They are called graded because the size of the response is directly related to the size of the stimulus producing them. (Haber)

SIGHT

Gregory put the very familiar task of seeing into perspective. "We are so familiar with seeing, that it takes a leap of imagination to realize that there are problems to be solved. But consider it. We are given tiny distorted upside down images in the eyes, and we see separate solid objects in surrounding space. From the patterns of stimulation on the retinas we perceive the world of objects, and this is nothing short of a miracle."

"How is information from the eyes coded into neural terms, into the language of the brain, and reconstituted into the experience of surrounding objects?" Gregory explains that the task of the eye and brain is quite different from either a photographic or a television camera converting objects into images. "The temptation to say the eyes produce pictures in the brain suggests the need of some kind of internal eye to see it - but this would need a further eye to see *its* picture... and so on in an endless regress of eyes and pictures. This is absurd." The eyes feed the brain information coded into neural activity or chains of electrical impulses. By their code and patterns of brain activity, they represent objects. (Gregory)

Consider the images conjured up by the letters and words viewed on this page. They have a certain meaning to those who know the language. The images are received by the eyes, and a recognizable neurological impulse is supplied to the brain which is affected accordingly, but they are not pictures. When looking at something, the pattern of neural activity represents the object, and to the brain is the object. No internal pictures are involved. (Gregory)

Gestalt psychologists point out a problem in how the mosaic of retinal stimulation gives rise to perception of objects. They stress an essential problem with perception: the tendency to group things and 'organize' sensory data into objects. If the brain were not on the look out for objects, the cartoonist would have a difficult time. All he need do is present a few cleverly conjured lines and a face complete with expression is perceived. A few lines is all that is required for the eye, and the brain does the rest. Sometimes even objects that are not there can be seen: faces in the fire, or a man in the moon. Figure I-3-1 appears to the viewer as only a few lines without

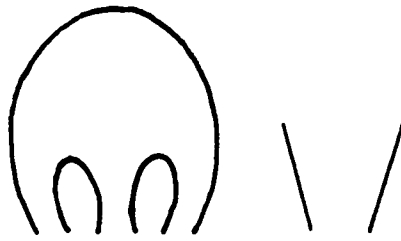


Figure I-3-1
LINES OR OBJECT?

Source: Adapted from Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton New Jersey, 1990.

meaning. As soon as the brain is supplied with a reasonable hint of what it should appear to be (a washer woman with her bucket), the brain instantly perceives the image. Viewing it again, the lines appear subtly different, almost solid, because now these meaningless lines are perceived as recognizable objects. (Gregory)

"Although we are concerned with how we see the world of objects, it is important to consider the sensory processes giving perception, what they are, how they work and when they fail to work properly. It is by coming to understand these underlying processes that we understand how we perceive objects." (Gregory)

The information that ultimately becomes available to the brain for interpretation is a subject worthy of discussion after a rudimentary understanding of the eye itself is achieved.

STRUCTURE OF THE EYE

The perfection of this optical instrument is a token of the importance of vision in the struggle of survival. Each part of the eye is an extremely specialized structure. Not only do the parts of the eye perform different functions, the tissues that compose each of them are specialized to the point of wonder (Gregory). Figure I-3-2 illustrates the structure of the human eye.

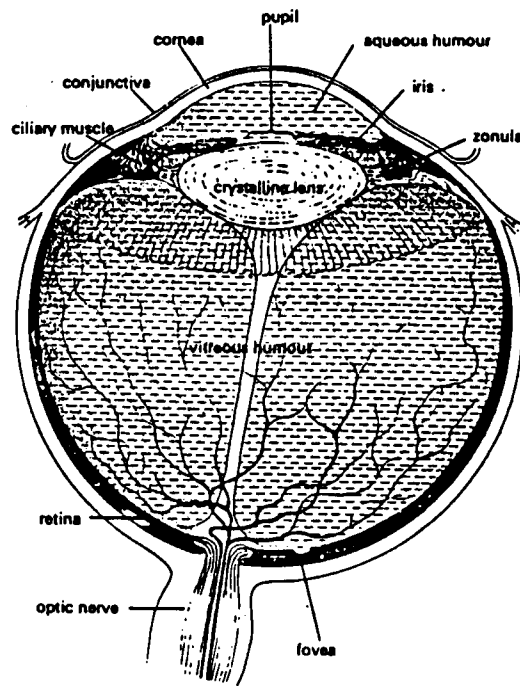


Figure I-3-2
THE HUMAN EYE

Source: Adapted from Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton, NJ, 1990.

The Cornea

The region where light is bent most to form an image on the retina is not the lens but the front surface of the cornea. The cornea separates two regions of different refractive index: air and the thick fluid contained in the aqueous humor. This difference combined with the rounded shape provides the initial optical focusing property before continuing to the lens located directly behind. The cornea is one of the few anatomical structures in the human body that has no blood supply. If it did, a person would have to see through an array of vessel structure. Blood vessels are avoided by obtaining nutriment from the fluid within the aqueous humor. The aqueous humor is continually secreted and absorbed so that it is renewed approximately once every four hours. (Gregory)

The Crystalline Lens

Although the lens is rather unimportant for forming the image on the back surface of the eye, it is important for accommodation. This is not achieved by changing the position of the lens (as with a fish or camera) but by changing its shape. The lens radius of curvature is reduced (becoming more round) for near vision thereby adding to the primary bending accomplished by the cornea. The lens itself is made of thin layers very much like an onion that allows its shape to be manipulated and is held in place by a membrane called the zonula. To accommodate for near vision, the ciliary muscles contract, releasing tension on the zonula and the lens springs to a more convex shape. (Gregory)

The Iris

The iris is the colored portion of the eye for a good reason. It must be pigmented so that it provides an effective aperture stop for the eye to control light that passes through the opening called the pupil. It is sometimes thought that the changes in pupil size are important in allowing the eye to work effectively over a wide range of light intensities. This could hardly be the primary function because its area changes over a ratio of 16:1, while the eye works efficiently over a range of intensity greater than 1,000,000:1. It would seem that the function of the pupil is to limit the passage of light to the central and optically best part of the lens except when full aperture is required for maximum sensitivity. It also closes for near vision which increases the depth of field. (Gregory)

The Retina

The name retina comes from the word meaning 'net' or 'cobweb tunic' from the appearance of its blood vessel network. The retina is a thin sheet of interconnected nerve cells that include light sensitive cells to convert light into electrical pulses: the language of the nervous system. Optically, the retina is inside out in that the photoreceptors are found at the back of the retina behind the blood vessels. This means that light must pass through the web of vascular structure,

a fine network of nerve fibers, three layers of cell bodies and a host of supporting cells before reaching the receptors. Given Mother Nature's original mistake, the situation is largely saved by cleverly routing the peripheral nerve fibers of the retina around the fovea (the central region of best acuity). (Gregory)

Rods and Cones

There are two kinds of light sensitive cells, rods and cones, named appropriately for their shape when viewed through a microscope. The retina contains about 120 million rods and seven million cones tightly packed together. "The number of cones is about the same as the population of Greater New York. If the whole population of the United States of America were made to stand on a postage stamp, they would represent the rods on a single retina" (Gregory). The tip of a sharp pin is larger than the area covered by 500 photoreceptors (Haber). The smallest photoreceptor is only about one micron or about the same size of two wavelengths of red light. This would seem to be Mother Nature's finest accomplishment; however the visual acuity of an eagle is four times better. (Gregory)

Cones are found everywhere in the retina but are most densely packed in a small area called the fovea. They function in daylight conditions and give us color vision. The cone density decreases as their distance from the fovea increases (Haber). It is interesting that although this region provides the best acuity and visual detail, it is less sensitive than the more primitive rod-region of the retina (Gregory). Cones cannot respond to the low light levels of night time.

The rods are found everywhere on the retina *except* the fovea and are primarily responsible for sight in low light levels. Therefore, rods are used for night vision whereas both rods and cones are used for normal to high light level. (Haber)

Rods are 'color-blind' in that all light, regardless of wavelength, produces only variations in intensity that is perceived as varying shades of gray. Cones occur in three different subtypes, each sensitive to different wavelengths. Stimulation arising from these three types allows discrimination of color which will be covered in some detail later. (Haber)

Neural Processing

The retina has been described by Gregory as 'an outgrowth of the brain'. It is a specialized part of the brain which has developed a sensitivity to light while retaining typical brain cell functionality. Although some of the processing for perception takes place in the receptors themselves, the electrical activity from the receptors is modified on the way to the optic nerve and ultimately the brain. (Gregory)

If each photoreceptor had its own private connection to the brain, there would be 127 million fibers leading to the optic nerve. Each photoreceptor would have a direct line to the brain and visual acuity would be simply a matter of knowing which nerve was active. In fact there are slightly less than one million such fibers. Nature's solution to minimizing nerve fibers in the retina is to connect more than ten thousand rods to the same nerve. The specific location of retinal stimulation becomes ambiguous because the nerve fiber has no way of knowing which of the ten thousand rods is active. The cones, especially the ones located in the center of the fovea, enjoy a much more private connection to the brain. Nearly half of the one million nerve fibers in the optic nerve service a single cone, thereby providing detailed information on the activity levels of the foveal cones. (Haber) Cones must receive enough light stimulation to exceed a particular threshold before they become 'active'. Once this threshold is exceeded, the cone alerts its connecting bipolar cell, illustrated in figure I-3-3. This bipolar cell also has a threshold that must be exceeded before it becomes 'active'. When the bipolar cell receives enough stimulation from either a single intensely stimulated cone or a number of moderated stimulated cones that feed a single bipolar cell, it will relay its activity message to the ganglion cell, and along the optic nerve and to the brain.

Rods do not need to absorb nearly as much light energy to become active. Since many rods connect with a single bipolar cell, very low light levels spread thinly over converging rods is enough to arouse their bipolar cell. Hence the rod's enhanced capability for night vision. (Haber)

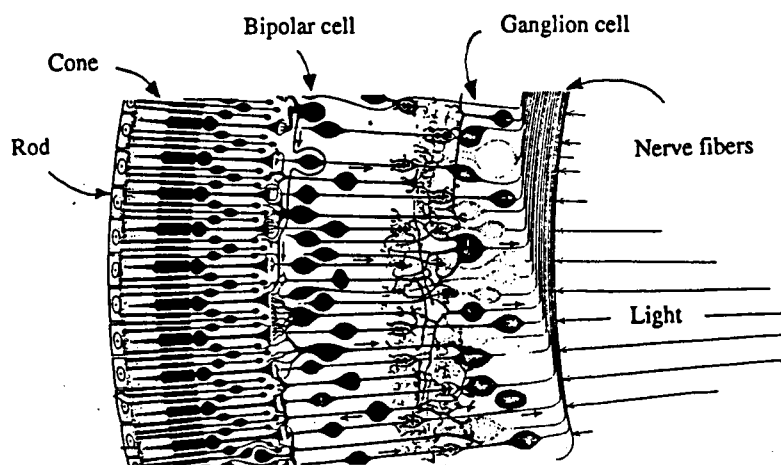


Figure I-3-3
NEURAL STRUCTURE OF THE RETINA

Source: Adapted from Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton NJ, 1990.

Not all transmission is 'excitatory'. When light levels reach normal room illumination, excitatory effects interact with inhibitory ones to permit some very sophisticated sensory coding of information on the part of ganglion cells. "Consider what the brain really needs to know about what is happening on the retina. If the entire retina were uniformly and intensely illuminated, such as when stimulated by an illuminated white wall or clear sky, a purely excitatory coding system would send many impulses to every fiber in the optic nerve, but the message on each would be the same. However, a single fiber can convey the same message by simply saying 'uniform' and using its activity level to convey the intensity of the stimulus. In an inhibitory system, the stimulated ganglion cells inhibit each other and neighboring ganglion cells. If all photoreceptors were equally stimulated, an area of uniform stimulation on the retina would signal lower than normal excitation to the brain. This combination of excitation and inhibition causes

the edge itself to stand out much more than it would in a solely excitatory system and ensures the brain is not bombarded with more signals than it needs." (Gregory)

EYE MOVEMENT

The eye is equipped with six extrinsic muscles, which hold the eye in its orbit and control rotation to follow moving objects or redirect the gaze. The eyes work together in that they are directed to the same object, converging for near objects. (Gregory)

The eyes are in continuous motion and they move in distinctly different ways. When searching for an object to fixate upon, they move in a series of rapid jerks, called *saccades* after the French word meaning 'flick of a sail'. "If you ever watch an individual read a book you have noticed that the eyes move jerkily across a line of print, stop at one fixation point, move quickly to a new one, and so on. Using precise measurement instruments, experimenters have shown saccadic movements to be very rapid: the eye generally moves from one point of fixation to the next in 0.025 to 0.1 seconds depending on the distance traveled by the eye. The fixations between each movement may last for only 0.2 seconds; they are typically around 0.25 to 0.3 seconds for reading and may last as long as one second for some types searching such as examining small objects." (Haber)

When the eyes follow a moving object, they do so smoothly and is called *pursuit*. These movements are so different from saccadic movements that evidence suggests that different brain control systems sub-serve each type of movement. (Haber)

A third type of eye movement is best described as a high frequency tremor or *drift*. It turns out that these tiny movements are essential to vision. It is possible to fix the image on the retina so that wherever the eye moves, the image moves with it so as to remain fixed on the retina. In this case, vision fades after only a few seconds. Part of the function of these eye movements is to continually sweep the image over the receptors so that they do not adapt and so cease to signal the brain to the presence of an image in the eye. (Gregory)

When looking at a sheet of white paper, the edges of the image of the paper will jitter about on the retina thereby renewing stimulation. In the center of the image, small movements of the eyes can have no effect because the region of brightness is substituted for another region of equal brightness. Therefore, no change in stimulation has taken place with these small eye movements, yet the middle of the paper does not fade away. This suggests that borders and outlines are important in perception. Physiologically speaking, large areas of constant intensity provide little information. They seem to be inferred from the signaled borders and the central visual system of the brain makes up the missing signals. (Gregory)

DEPTH PERCEPTION

Convergence

Depth perception is given in part by sensing the angle of convergence of the eyes as illustrated in figure I-3-4. The eyes converge on an object to bring the image to the fovea

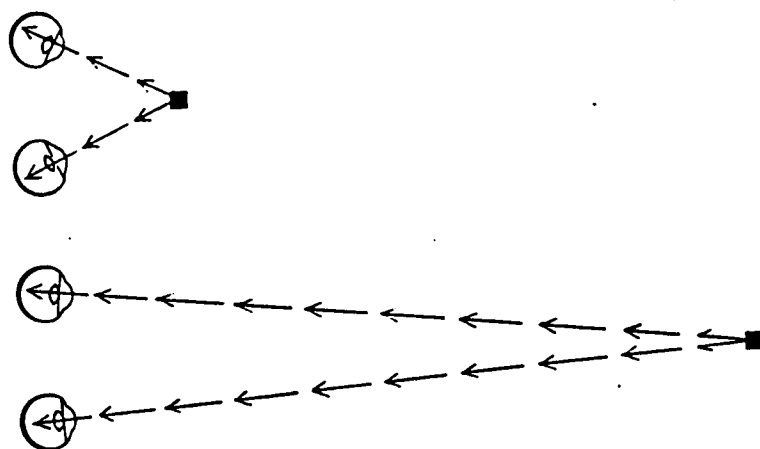


Figure I-3-4
DEPTH PERCEPTION FROM CONVERGENCE

Source: Adapted from Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton, NJ, 1990.

of both eyes. This angle of convergence is sensed by the brain as one indication of distance.

(Gregory)

There exists an inherent limitation to this technique. It only provides ranging to a single object at one time (Gregory). Saccade eye movement from one object to the next seems to be the obvious solution to sense relative distance between several objects, but this is not the case. Consider viewing a panoramic mountain range. The three-dimensional depth of the scenery is immediately sensed without having to sight every ridge and valley. To perceive the distance of many objects at one time, it is necessary to adopt a very different approach. Mother Nature has developed such a system, but it involves very elaborate computation for the brain. (Gregory)

Disparity Depth Perception

The eyes are horizontally separated by about 6.3 cm and so receive slightly different views. This can be demonstrated quickly by alternately closing and opening each eye. The closer objects appear to shift sideways in relation to more distant ones. This slight difference between images is known as *disparity*. It gives perception of depth by *stereoscopic vision*. "A great deal has been discovered over the last few years of how the brain combines the images of the two eyes, using the minute disparity differences to compute depth. We know that most cells in the visual cortex of the brain respond to stimulation from corresponding points of the two retina. These are called binocular cells. Presumably corresponding retinal points, as related by disparity to distance, are indicated by the firing of these binocular cells." (Gregory)

MOVEMENT DETECTION

The edge of the retina is sensitive only to movement. This may be demonstrated by getting someone to wave an object around at the side of the visual field, where only the edge of the retina is stimulated. Movement is perceived but identification is impossible. Once movement stops, the object becomes invisible. (Gregory)

The very extreme edge of the retina is even more primitive. When stimulated by movement nothing is experienced, but a reflex is initiated which directs the eye toward the object and brings the item into the central vision, for identification in the highly developed foveal region. The edge of the retina functions as an early warning device and is used to rotate the eyes to aim the sophisticated object-recognition part of the visual system onto objects. (Gregory)

There are two distinctly different movement signaling systems: the image/retinal system and the eye/head system. Both systems are capable of registering movement and work in collaboration with each other. Understanding each of these systems and how they depend on each other is important because when these two systems disagree, illusions are experienced that can be absolutely catastrophic in the carrier landing environment.

Image/Retinal System

As illustrated in figure I-3-5, when the eye remains stationary, the image of a moving object sweeps across the receptors which is interpreted as velocity signals or motion. Even when the eyes follow a moving object, the image of that object remains more or less stationary on the

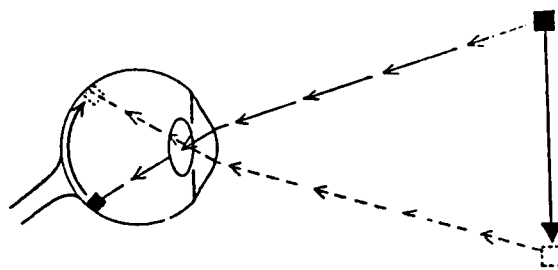


Figure I-3-5
THE IMAGE/RETINAL SYSTEM OF MOTION DETECTION

Source: Adapted from Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton, NJ, 1990.

retinas. The sense of motion comes from the background image sweeping across the retinas giving rise to a velocity signal. (Gregory)

Eye/Head System

The eye/head system of motion detection is illustrated in figure I-3-6. Movement is still perceived even when there is no visible background for comparison within the retina. This can be demonstrated by waving a lighted cigarette around slowly in a dark room and following it with the eyes. The movement of the cigarette is perceived fairly accurately although there is no background image moving across the retina to stimulate this. The movement of the eye is being somehow signaled to the brain and used to interpret the motion of external objects. (Gregory)

Two System Collaboration

"Why does the world remain stable when we move our eyes? The retinal images run across the receptors whenever we move our eyes, and yet we do not experience movement - the world does not usually spin around when we move our eyes. How can it remain stable?" (Gregory)

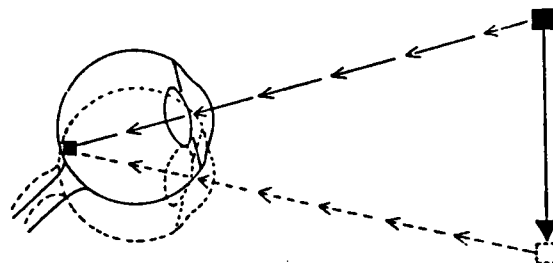


Figure I-3-6
THE EYE/HEAD SYSTEM OF MOTION DETECTION

Source: Adapted from Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton, NJ, 1990.

It seems that during normal eye movements, these two systems of motion detection cancel each other out to give stability to the visual world. Evidence favors the "outflow theory" developed by Helmholtz that suggest signals are canceled not by signals *received from the eye* muscles (inflow) but 'outflow' signals *received from the brain* commanding the eyes to move. (Gregory)

To demonstrate this, the reader can push gently on an eye with the finger while the other is closed. When the eye is rotated passively, the world would seem to swing around in the opposite direction of eye movement. Since the world swings round against the direction of the passive eye movements, it is evident that the image/retina system still works. It is the eye/head system which is not operating. This suggests that simply *sensing* eye movement (in the same fashion passive movement of the limbs are sensed) does not constitute grounds for the brain to cancel movement detection by the eye/retinal system. Helmholtz suggests that the eye/head system does not work by *actual eye movement* but rather by the *commands to move* them. (Gregory)

Another very strong piece of evidence to support this 'out flow' mechanization is revealed by noticing the results when all retina movement signals are stopped. This is achieved by creating an *after image* on the retina with a bright flash of light. This produces an area of fatigue much like a photograph glued to retinal surface that will move precisely with the eye (hence no movement detection by the image/retina system). If the after image is observed in darkness (to eliminate background image) and passive eye motion is induced by gently pushing on the eye, *the after image does not move*. It follows that if signals *from* the eye muscles were used in the eye/head system then motion of the after image would be perceived, which is not the case. When the eyes are moved voluntarily, the after image moves with the eyes. Wherever the eyes are voluntarily moved, so moves the after image because the head/eye system uses the signals *from the brain that directs* eye motion. (Gregory)

ILLUSIONS OF MOVEMENT

Everyone has experienced visual illusions at one time or another. Many examples of these effects have been experienced during daily activity: driving on a very dark road and a flashing light on a tower is mistaken for a moving aircraft; waiting at a stop light and nearly mashing the brake pedal through the floor because of an overwhelming sensation of rolling backward as the car in the adjacent lane pulled away; vivid motion depiction on the television.

Induced Movement

So far, the basic physiological mechanics of movement detection by the eye/head and image/retina systems have been considered. There is, however, far more to the perception of movement. While the perception of movement does not necessarily involve actual movement, it remains true that all movement is relative and a decision is always involved. The brain must still decide what is moving and what is stationary. As would be expected, this decision is sometimes made in error and causes illusions that can be catastrophic in aviation. (Gregory)

If an observer is walking, there is generally not much of a problem. He has a lot of information from his limbs that it is *he* who is moving and not the surrounding objects. But when he is carried along in an aircraft the situation is very different. With his feet off the ground his only source of information to decide the issue is through the eyes (in the absence of acceleration signals from the inner ear). In an aircraft there is little or no sensation of movement when flying very high. During landing it's a toss up whether the pilot sees himself moving or the carrier rushing up to meet him. Illusions and errors are frequent in this situation and pilots must learn to dispense with their normal perception of movement and rely on instruments and visual landing aids. (Gregory)

The phenomenon known as induced movement was thoroughly investigated by Gestalt psychologist K. Duncker. He devised several demonstrations which show the tendency to accept movement of smaller objects rather than movement of larger ones. A striking demonstration is when a small spot of light is projected on a large movable screen. When the screen is moved,

what is seen as moving is the spot of light, though in fact it is stationary. There actually is information available to the eye, for it is the image of the screen and not the spot which moves on the retina, but this information is not always sufficient to decide the issue. (Gregory)

Autokinetic Phenomenon

This phenomenon has been the subject of intense research, discussion and disagreement. A dozen theories have been offered to explain this mysterious visual illusion. This effect is best illustrated by placing a glowing ember on an ash tray in a completely dark room. When looking at it for more than a few seconds, it will appear to wander about the room, sometimes swooping one direction, sometimes oscillating to and fro. Its movement can be paradoxical in that it may appear to move yet not change position. (Gregory)

Gregory discusses the advantages and disadvantages of some of these theories in detail but ultimately concludes with the following explanation that falls back on the eye/head system of movement detection. "The wandering illusory movements of the autokinetic effect seem to be due to the command signals maintaining fixation in spite of spontaneous fluctuations in the efficiency of the muscles, which tend to make the eyes wander. It is not the eyes moving, but the corresponding signals applied to *prevent* them from moving which cause the spot of light to wander in the dark." (Gregory)

The Waterfall Effect

"The waterfall effect is a dramatic example of illusory movement caused by the adaptation of the image/retina system of movement detection. After looking at a waterfall, the bank or another fixed object will appear to move in the opposite direction as the water. Another example of this can be induced by looking at the center of a record spinning on a turn table for about 30 seconds. When the turn table is stopped suddenly, it will seem to spin in the opposite direction for a few seconds" (Gregory). An excellent demonstration of the power of this illusion is obtained when rotating a spiral like the one in figure 1-3-7. When it is rotated and the viewer

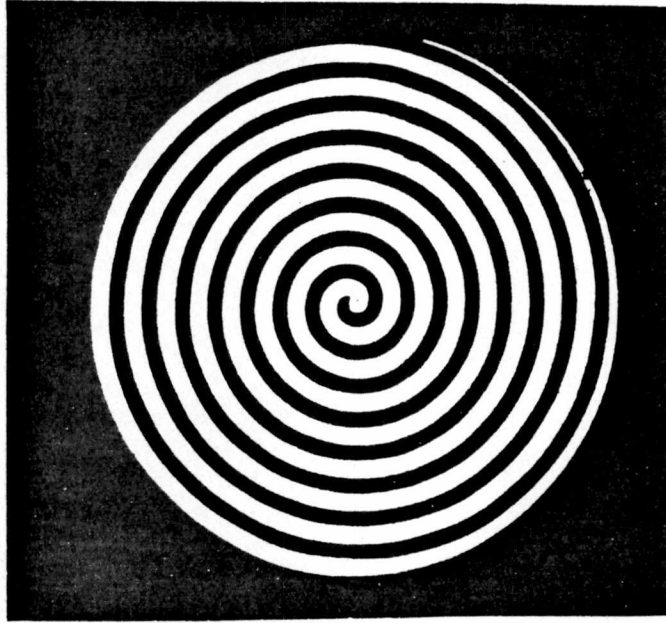


Figure I-3-7
A WATERFALL EFFECT INDUCING SPIRAL

Source: Adapted from Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton, NJ, 1990.

focuses on the center, it will appear to shrink or expand depending on the direction of rotation. When stopped, it appears to do the opposite: shrink if previously expanding, or vice versa. This illusory contraction or expansion when the spiral is stopped cannot be due to eye movement, for the eyes can move in only one direction at a time. The effect is a radial contraction or expansion occurring in all directions from the center *at the same time*. It remains a problem as to whether the adaptation takes place in the retina or the brain. (Gregory)

This illusory movement may be paradoxical: it may appear to expand and yet stay the same size. This seems like an impossibility: the higher thought processes should resolve any discrepancy. "But we must always remember that what holds true for real objects may not hold for perception once we suffer illusions. We can experience things which are logically impossible when we suffer from illusions" (Gregory). He goes on to suggest this stems from the fact that velocity and position signals are indicated by separate neural systems. Only the velocity system

is upset by continued viewing of the rotating spiral. "This is like a trial judge getting incompatible evidence from two witnesses and accepting both stories, at least for a time, before deciding that one is probably correct and dismissing the other as a pack of lies which can best be ignored. The perceptual system of the eye and brain has many channels, and many sources of information: the brain must serve as judge. Sometimes different sources of incompatible information are at least for a time accepted together, and then we experience a paradox - things that cannot possibly occur together." (Gregory)

Movement on Television

This is certainly the most persistently undetected illusion of movement. The viewer is presented with a series of still pictures and comfortably conjures continuous motion. Television relies on two distinct visual characteristics: persistence of vision and the phi phenomenon. (Gregory)

Persistence of Vision

This is the retina's failure to keep up with rapidly changing intensities. A light that is flashing at 50 Hz (cycles per second) is perceived as steady. Retinal neural structure can discern flash rates that exceed 100 Hz, with very bright light. Yet individual pictures that the cinema presents at 24 frames per second are not normally perceived because a three-bladed shutter triples the flicker rate to 72 flashes per second, three for each picture. British standard television presents 25 fresh pictures per second, each given twice to raise the flicker rate to 50 Hz. (Gregory)

On the other end of the flash rate spectrum, low frequency flash rates produce very odd effects on the normal observer. For flash rates of five to ten Hz, illusions of brilliant color and vivid objects, both moving and stationary can be experienced. "Their origin is obscure, but they probably arise from direct disturbances of the visual system of the brain, the massive repeated bursts of retinal activity overloading the system." (Gregory)

Phi Phenomenon

This is the ability for the perceptual "filling-in" of a change in scene. Provided that the new scene changes by the right amount and just enough time elapses between the two, perception becomes one of movement. The trade off between space and time to achieve the proper combination that is interpreted as movement is best described with an analogy. A key does not have to be exactly a certain shape to work the lock it was designed for. In fact, if the design is too exact, the key would fail to open the lock after a short time of wear. The lock must tolerate some deviation. Indeed, some tolerance is essential for otherwise any slight change in the lock or the key would prevent it working. The phi phenomenon illustrates that the eye/retinal system tolerates gaps so as to maintain visual continuity. (Gregory)

PERCEPTION OF BRIGHTNESS

Several important factors, in addition to the intensity of light, determine the magnitude of the sensation commonly called brightness. The most significant of these is the adaptation state of the eye: the adjustment to the prevailing level of light intensity. (Haber)

The visual system can function easily providing the light intensity of the viewed scene differs by less than 100 to one. When the ratio exceeds this threshold, only the detail in the lighter portion of the scene or the darker portion can be seen, but not both simultaneously. (Haber)

When walking into a dark room like a movie theater, the seats or isle can not be seen for several minutes. When walking outside again, momentary blindness caused by the intense ambient light difference occurs. Each of these are examples of the sensitivity adjustment process within the eye when the stimulus intensity suddenly shifts substantially. This change is called *dark adaptation* when the eye adjusts to the dark, and *light adaptation* when the eye adjusts to the light. These two processes, while not mirror images of each other, reveal important properties of the visual system. (Haber)

Dark Adaptation

Both cones and rods exhibit dark adaptation. Cones begin to gain sensitivity as soon as the lights go out and improve by a factor of ten within the first two minutes. No matter how long the eyes stay in the dark, after about four minutes, the cones will not become more sensitive. (Haber)

The rods do not begin to adapt to the dark until after five minutes. Their sensitivity increases beyond that of cones by a factor of 1000. Rod adaptation takes nearly 30 minutes before reaching their highest sensitivity. (Haber)

Light Adaptation

Walking out of the matinee may be uncomfortable because ambient lighting has possibly increased 10,000 fold. After squinting for a few seconds, the eyes function normally. The process by which sensitivity to light is reduced when moving from low to high light levels occurs very rapidly. Exactly how fast the eyes make this adjustment is somewhat dependent on how long they have been dark adapting. Most of the change takes place in less than a second and adaptation is complete within a minute or so. (Gregory)

Simultaneous Brightness Contrast

Another factor that affects how bright a particular light intensity will be perceived is the level of the surrounding light intensities. The brightness of an object will appear to increase as the intensity of background area decreases, and vice versa. This effect is called simultaneous brightness contrast and occurs even though the physical energy from the object itself does not change. (Haber)

In the case of a brighter background, the receptors that are stimulated by the intense surrounding area excite ganglion cells, which have inhibitory connections to other ganglion cells, some of which in turn are connected to the receptors under the object. Because these receptors are inhibited by the ganglion cells under the intense surroundings, the intensity of their response

to the object will not result in as much net excitation if the background area had been less intense. (Haber)

Successive Contrast

Contrasting effects also appear when the surfaces of a surrounding area are viewed successively rather than together. If a person looks at a bright wall and then at a gray patch, the patch will appear darker than it would if he looked at a dark wall first. Successive contrast works in the same way as simultaneous contrast except that the effects of inhibition occur over time as well as over space. When looking first at an intense surface, the neural activity created by the absorption of photons (including the inhibition generated) persists. When a second stimulus is presented, the activity it generates is reduced by the amount of the inhibition left over from the first stimulus. Because the eyes rarely look at total darkness, there is always some accumulated inhibition activity, but it varies from moment to moment, depending on the intensity of the most recent stimulus. Therefore, the contrast effects, along with adaptation, decrease the possibility that a simple proportional psychophysical relationship exists between intensity and brightness. (Haber)

COLOR VISION

"Color accounts for most of the affective connotations surrounding vision. It is also one of the most complex aspects of vision" (Haber). In general, color vision can be thought of as being composed of three color sensitive systems which respond uniquely to red, green and blue light. All external color is perceived by a mixture of these three systems. The eye goes through a great deal of signal processing before the signals reach the brain for further deciphering. The colored light that enters the eye is far from the perception of it.

It is important to understand what is meant by mixing colors. Everything learned in grade school art class has little to do with the mixing of light. The painter mixes yellow and blue to produce green. It vital to recognize that the eyes are absorbing green light not green paint. The

paint appears green because all light *except* green is absorbed by the these pigments and what is not, reaches the eye as green light. Mixing light is completely different. If green and red light are mixed, the result is yellow light.

Psychological Dimensions of Color

There are so many terms that are used to describe the symphony of colors the eyes can digest. Psychologists 'pair' light's physical attributes to their 'effect' upon us. The three most descriptive physical properties are *intensity*, *wavelength*, and *purity* and correspond to their psychological impact on the beholder as *hue*, *brightness*, and *saturation*. "These three psychological dimensions of color can be used together to describe our perception of light."
(Haber)

Hue and Wavelength

The physical dimension of wavelength determines the perceived hue, that is, what color is seen. Each wavelength has a unique hue even though the ability of the eye to discriminate between very subtle differences in wavelength is questionable (Haber).

Brightness and Intensity

Brightness is perceived from the variation in the number of photons absorbed by the photoreceptors. Generally, the perception of brightness increases as light intensity increases (contrast effects aside). Since intensity varies as a function of wavelength, some variation in perceived brightness will occur with a shift in wavelength or color. (Haber)

Saturation and Purity

Saturation of light is commonly called 'depth of color' and corresponds to the physical characteristic of purity. Red is a deeper color than pink, although both may be of the same hue

or wavelength (Gregory). The degree of saturation can be thought of as the amount of white light that must be added before the perception of color disappears completely. (Haber)

Color Coding

Around 1800, Thomas Young proposed an explanation of how hues are coded based on the observation that light can be mixed to make any hue from only three wavelengths. Measurements taken 150 years later substantiated parts of Young's postulation. He correctly believed that there were only three types of color receptors - one sensitive to long-wavelength light, one sensitive to middle-wavelength light, and one sensitive to short-wavelength light. He was partially correct that long wavelength light stimulates the long-wavelength cone (the "red" cone) a great deal and the "green" and "blue" cones very little. He wrongly assumed that when the output of all three systems is *mixed in the brain*, red light is perceived. Light near the middle of the spectrum stimulates the "red" and "green" cones, not the blue cones, and yellow light is perceived. White light is the simultaneous stimulation of all three cones and black is the absence of all stimulation. (Gregory)

Ewald Hering proposed the "opponent-coding" theory that involves complex inhibitory as well as excitatory behavior on the part of the ganglion cells in the retina. Hering took Young's ideas one step further by placing more emphasis on neural processing *in the retina* before the brain receives a signal. "Although some of the color-mixing information that Young used in his original theory is inherent in Hering's opponent-coding theory, Hering's theory is consistent with the manifestations of color contrast that confused Young." (Haber)

Color Contrast

Brightness of a surface is not simply a function of the intensity of light reflected from it, but is in part determined by the intensities reflected from the surrounding surfaces. Color contrast is related to brightness contrast. (Haber)

If a subject stares for half a minute or so at long-wavelength light (red) and then looks at a gray surface, it will appear green (afterimage of red). The reverse is also true; a gray wall looks red (afterimage of green) after staring at a green wall first. In fact, every hue has an after image hue, or complementary color that will be seen by staring at the first hue for a while and then looking at a neutral surface.

What is occurring in the eye is an effect called color contrast. When staring at middle-wavelength light for a while, the green cones are stimulated much more than the red and blue cones. Because of temporal inhibition, further stimulation results in a decreased sensitivity of the green cones (just as prolonged light stimulation will result in a lowering of receptor sensitivity). Then, by looking at a white wall, which contains equal quantities of all visible light wavelengths, the green cone excitation signal is inhibited from reaching the brain while the blue and red cones are permitted to signal their excitation. The result is the perception of a hue containing much blue and red, and little green. According to Young's theory, this stimulus condition should make gray look purple, but in fact, it looks red, as Hering's theory predicts. (Haber)

Hue Discrimination

Traffic lights, aircraft position lights, shipboard navigational lights, and automobile signal and brake lights all use red, yellow, green, and white light. It's curious why colors such as brown or purple are not used for these purposes. Intuitively the reason is because red, yellow and green lights are easy to tell apart. But the question remains, "How well can the eyes discriminate between small differences in wavelength?"

"A great deal of work has gone into defining the excitability of each of these systems with respect to wavelength variations, and this has proved surprisingly difficult" (Gregory). The complexities of exactly how color vision works can be avoided by simply understanding the perceptual result. The variability of the eye to discriminate color versus wavelength is illustrated by the hue-discrimination curve, figure I-3-8.

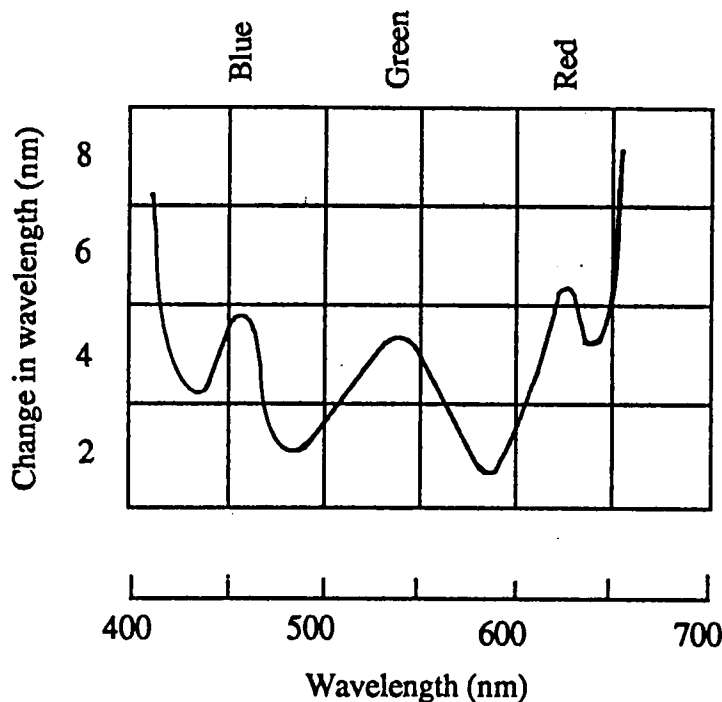


Figure I-3-8
THE HUE DISCRIMINATION CURVE

Source: Gregory, R. L., *Eye and Brain, The Psychology of Seeing*, Fourth edition, Princeton University Press, Princeton, NJ, 1990.

For the purposes of this discussion, this graph represents all that really needs to be understood about color vision. The curve suggests that perceived hue changes very little as wavelength varies from either end of the spectrum. The only physiological change that occurs is a gradual increase in the activity of the red or blue systems exclusively. This is perceived primarily as a change in brightness (rather than hue) even though it is indeed shifting wavelength. (Gregory)

As long-wavelength light shortens, dramatic changes in hue are perceived as the red system rapidly falls in activity and the green system rises. In this region, a small shift in wavelength produces a large shift in the relative activity of the red and green systems. This would suggest that hue discrimination is exceptional around yellow (between the red and green). Moving

farther left on the scale, sensitivity to subtle changes of green is reduced because only the green system is active and, once again, this is perceived as a change in brightness rather than hue.

EQUILIBRIUM

Information about a one's orientation and movement is available from the vestibular apparatus in the inner ear. The part of the system that mediates this information is composed of three fluid-filled semicircular canals located at right angles to each other. When the head moves, the fluid in one or more of these canals is set in motion and tiny internal hairs within each canal become disturbed and create a neural signal. (Haber)

ACCELERATION

It is important to understand that this system alerts a person to accelerations or *changes in motion* not the *presence of motion*. When a person accelerates in a car, the inner ear signals this initial change in motion. Once the car is established at a comfortable cruising speed, the fluid in the canals settle down and if the eyes were closed, it would be difficult to detect motion at all.

The inner ear can be easily fooled and provide intense misinformation about acceleration. If a subject were to close his eyes and spin in a stool, it would be easy to initially determine the direction of rotation. As the velocity of the internal fluid catches up to the rotational velocity of the subject, the sensation of motion decays. After just a short time, the subject no longer receives inner ear information regarding rotation. When the subject is gently stopped, the fluid essentially continues and he receives information that is interpreted as spinning the opposite direction.

ORIENTATION

In daily life, orientation of up and down is rarely difficult to keep straight. The brain keeps track of each little acceleration measured by the inner ear to develop a sense of orientation. When a person crosses a room in the dark, he is relying on the inner ear to provide a sense of orientation. Initially he is confident of his position. As he continues to operate in the dark, his orientation certainty gradually decreases to the point of groping for the light switch. The more time spent relying on interpreting the information from the inner ear, the less accurate the

estimation of orientation becomes. In this two dimensional case staying oriented is attempted by summing all the accelerations.

These same accelerations are present in aviation except in three dimensions instead of only two. Mother Nature did not envision humans operating high performance jet aircraft, so it should be no surprise that the inner ear rarely signals the correct orientation information while in flight. The accelerations experienced by the pilot may be interpreted accurately but may not necessarily be oriented properly. In a 60° angle of bank turn, the acceleration experienced in the cockpit is twice that of natural gravity even though the aircraft does not gain altitude. A nose up pitch rate can feel like the aircraft is entering a climb, performing a level turn or even beginning a dive if the aircraft is inverted: the inner ear sensation is the same.

TOUCH

Kinesthesia receptors are located in limb joints, muscles and tendons. They signal the changing position of these body parts and underlie the ability to make coordinated and skilled bodily movements. (Haber)

The sensation of touch, in the author's opinion, is one of the senses that is routinely ignored. Pilots are more likely to receive these signals as validation of motion rather than a direct measure of motion. As the reader is looking at this text, many tactile sensations are probably beyond immediate cognition: the sensations of the back of the legs on the seat, the shirt collar resting on the neck, shoes and socks, etc. Human beings are continually receiving these tactile signals but are typically not aware of them. Other than by choice, a tactile sensation must reach a certain threshold before it comes to a person's awareness.

In aviation, these tactile sensations become even more overlooked because the more engrossed or distracted the pilot becomes, the less attention paid to normal tactile sensations. The task of landing aboard a carrier is typically demanding and the personal threshold that will bring a tactile sensation to awareness increases. The signal from the muscles are being monitored but are not consciously considered.

Even though these sensations are not in the immediate awareness, they remain important. They tend to support, enhance or even contradict information available from the inner ear. Vertical acceleration are experienced by the pilot by getting heavier in the seat. The increased pressure on the back of the pilot's legs validates his acceleration sensation. Acceleration during take-off pushes the pilot back in the seat. Tactile sensations remain out of immediate awareness but have a large impact on the validity given to other senses.

Chapter 4

Psychology

PILOT TRAINING

THE "PIPE LINE"

The training command is a collective term that refers to all squadrons that are tasked with training flight students how to fly naval aircraft. It starts with about two months of ground school called Aviation Indoctrination that covers subjects like aerodynamics, engine design, physiology, and survival. Upon completion, the student is assigned to a "Primary" squadron where he will learn basic flight skills in the T-34C *MENTOR*, a single engine turboprop aircraft. Once complete, the student is funneled (depending class standing, individual preference and needs of the Navy) into one of three separate, more specialized pipe lines: Jets, Props or Helos.

If the student is selected for Jet training, he is assigned to one of several "Basic Jet" training squadrons where he learns basic jet aircraft flying skills in the T-2C *BUCKEYE*. The course includes familiarization, formation, instrument flight and aerial gunnery. Toward the end of this syllabus, the students has his first opportunity to land aboard a carrier, daytime only with a steady flight deck.

Successful completion of Basic Jet leads to further assignment to an "Advance Jet" squadron for more specialized training in the TA-4J *SKYHAWK* which includes familiarization, formation, air combat, section maneuvering, and weapons delivery. Once again, toward the end of this syllabus, the pilot must prove his ability to handle this more demanding aircraft at the ship (daytime only, steady deck). Finally after about one year of jet training (two years total) the student is designated "Naval Aviator."

Depending on the student's class standing, needs of the Navy and personal desires, the newly "winged" aviator is assigned an aircraft that he will continue to fly throughout his career. He is assigned to a Fleet Replacement Squadron (FRS) where he will learn in detail both the aircraft and the mission it is designed to carry out. Toward the end of this eight to twelve month syllabus, they once again must qualify at the ship, but this time, day and night and with "limited" deck motion.

A discussion on the training pipe line serves to illustrate a point that even the most experienced pilots tend to overlook. These students spent nearly two years of full time study and training to learn the coordination and intellectual skills necessary to fulfill their dream: fly high performance jet aircraft. Those that could not develop the skills rapidly enough were "washed out" from the flight program. During the author's student training, of all those people that started Aviation Indoctrination (some did not even make it that far) with the intention of completing the Jet pipe line, only 18% completed. Those who graduate have proven their aviation skills by completing all requirements: these graduates are not uncoordinated. The reader may ask, "Why then is the first night carrier experience delayed so long?"

Because they have to develop the "visual skills" to perceive deviations on an absurdly tiny VLA if there is any hope to correct for them, in an unforgiving environment that induces visual illusions, misleading physiological sensations, and tremendous psychological stress.

FCLP

During the student training program, the unique carrier landing style is practiced at the end of every flight. "Touch and go" landings are performed after every flight which are graded by the instructor in the aircraft. The more experience the student has in that particular aircraft, the higher the performance standards he is required to meet.

Prior to qualifying at the carrier, (Basic or Advanced) the student must complete the CQ phase or Carrier Qualification phase. The student flies Fleet Carrier Landing Practice (FCLP) periods where, under the guidance of a skilled LSO, he performs pass after pass, practicing and

improving his landing skills. Every tiny glide slope, airspeed and line-up deviation is recorded and discussed after each period. After about 13 FCLPs, and demonstration of the prerequisite skill, the student is considered "field qualified" and off to the ship they go for CQ.

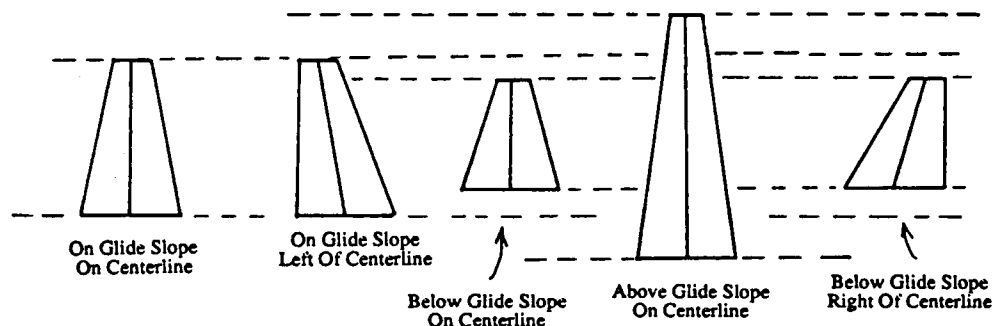
At the ship, the very same LSO who trained the student at the field and is intimately familiar with his tendencies, controls the student during his CQ period. Once again, every deviation is recorded and thoroughly discussed following the CQ period.

The FRS is more demanding for the simple fact that CQ is also conducted at night. Some FRSs require nearly two dozen FCLPs prior to CQ, most of which are flown at night. CQ lasts several days because more daytime arrestments are required before night CQ can be attempted. Many aviators and LSOs recognize that this is not the pinnacle of carrier landing skills. A pilot usually has 100 to 200 arrestments under his belt before his skills blossom as a carrier pilot.

ILLUSIONS FROM SHIP MOTION

During field approaches at nominal glide slopes, the pilot views the runway from the cockpit and receives some important information about his orientation. The perspective of the scene goes largely unnoticed on the conscious level, but still registers as an important input to determine relative position with respect to the landing area. At the far end of the runway, the runway edges appear to converge and are horizontally closer together. This is expected because from human experience, this convergence is appropriate for distant objects (perspective). On the two dimensional surface of the retina, the runway appears much like a trapezoid.

When the orientation between the aircraft and the landing strip changes, the scene also subtly changes as illustrated in figure I-4-1. The change in actual angle is extremely small, but it's perceived immediately. When the aircraft moves above glide slope, the angular distance



- Notes (1) Relative distance cueing comes from the angular width of the runway which is identical in each of these examples.
- (2) Glide slope perspective cueing comes from the angular distance from the near and far ends of the runway. Changes in glide slope change this dimension of our viewing scene. Two-dimensionally speaking, runway length shrinks and expands.
- (3) Line up perspective cueing emanates from the angular rotation of the runway edge lines and centerline.

Figure I-4-1
CHANGES IN LANDING AREA PERSPECTIVE

between both ends increases. Likewise, settling below glide slope makes the runway length shrink. Changes in the angle between the runway centerline and edge lines provide the pilot cueing to determine his line-up orientation.

As discussed in Chapter 3 of Part I, there is always a decision that must be made (unconsciously or consciously) to determine what is moving and what is stationary (Gregory). It's no surprise that during land based approaches, pilots correctly decide that the aircraft is changing position with respect to the runway and not vice versa: in all human experience, pilots have never seen an 8000 ft runway shrink on the earth surface. Thus, perspective change is used to control approach deviations.

This assumption is challenged in the carrier environment. The landing area can and does change orientation and the decision between what is moving and what is not, is sometimes impossible to make based purely on the visual scene (and that is the very reason for VLA).

It is true that tactile sensations are available to help sort this out. Under the tremendous stress of night carrier landings with no horizon, pitching deck and quite possibly ambiguous reflections off the surface of the ocean, these sensations are largely ignored. The full attention of the pilot is on VLA cueing that will keep him alive. There simply is not enough "human RAM" available to monitor tactile sensations. Two of the most disturbing manifestations of these dynamic illusions come from pitch and yaw of the ship.

PITCH MOTION PERCEIVED AS A CHANGE IN GLIDE SLOPE

During pitch motion of the ship, the angular distance between the ramp and the top of the angle deck is continuously changing, getting longer as the ramp pitches down and shorter as the ramp pitches up.

During daytime, pitching deck conditions, peripheral vision continuously picks up the natural horizon and trends to resolve conflicting information. At ranges of one to two nm, the ship subtends a small portion of the pilot's field of view. With the horizon subtending a larger portion of the pilot's vision (and he knows the horizon does not move), there is no surprise when

he decides that the ship must be moving, not the aircraft he is riding in. As the approach continues, the carrier grows in size to subtend a larger portion of his field of view and begins intruding on his peripheral vision. The pilot still tends to lean towards the "ship is moving" decision, but now the decision is becoming difficult to make. As the approach continues further, the peripheral cue of the pitching deck becomes dominant and the decision is a toss up, "Am I settling on to a number one wire or is the landing area coming up to me." This close to touch down, it makes little difference which is moving and which is stationary because the *relative* motion is the concern verses actual motion (flight deck impact angles, aircraft attitude at touch down, etc.) but it remains disconcerting for the pilot.

During night operations with an absence of the peripheral horizon cues, the perception of perspective goes largely unchallenged and landing area perspective is the only cue for glide slope. The problem is that the perspective change for "aircraft descending below glide slope" and "ramp moving up" is identical as depicted in figure I-4-2.

This is such a strong illusion, that LSOs must routinely re-focus the pilot's attention with voice calls to offset the disturbing visual effects of pitching deck motion. Any "peaking" at the pitching deck itself immediately leads to confusion and disorientation that does not subside rapidly.

YAW PERCEIVED AS A LINE UP DRIFT

Peripheral cueing of line-up drift can come from several sources. It can be observed by the sideways component of terrain movement. During approaches over land, the terrain has a sideways motion component when the aircraft drifts either side of centerline. At the ship, water texture is the same on the left side of the aircraft as it is on the right, which effectively eliminates this cueing.

In the absence of terrain texture at sea, some pilots use the wake of the ship to assist with initial centerline capture. In the case 1 pattern, the aircraft has to fly over the ship's course

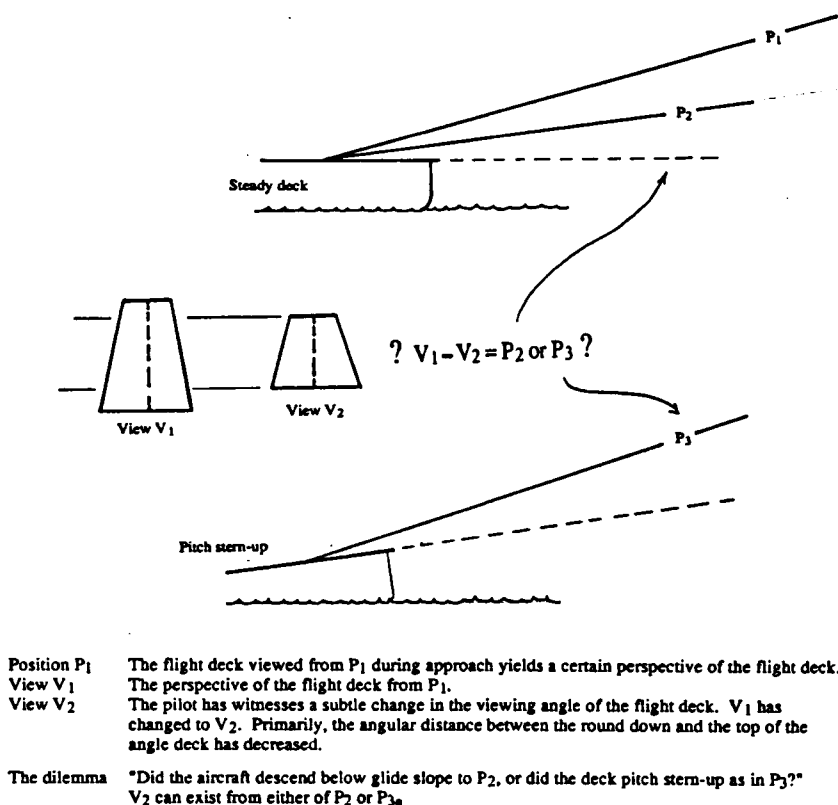


Figure I-4-2
PITCHING DECK OR GLIDE SLOPE CHANGE?

through the water to align with angle deck centerline. The speed of the wake's approach as the pilot rounds the corner provides a good rate-cue of approaching centerline. However, once established on centerline, the pilot can no longer see the wake because it's below the nose of the aircraft. While this cue is useful for capturing centerline, it is not available for maintaining it.

Surface wave motion often distorts the perception of line-up drift by playing on the pilot's expectation of terrain motion. This illusion comes from the perceived motion of the "wave peaks" in the same way that ripples in a pond appear to move away from the rock just thrown in. The water is not moving (wrong decision) the crest of the wave is moving.

Once again, the absence of good peripheral cues leaves angle deck geometry the only source of line-up information. The visual perspective of the landing area changes in exactly the same way for both ship yaw motion and line-up drift. The pilot notices a subtle angular shift between

the runway centerline and edge lines and without peripheral cueing to resolve this issue, he almost always (and wrongly) decides it's due to aircraft motion. This is such a powerful illusion it's often difficult to convince a pilot that a line-up deviation was due to ship motion not the pilot himself.

TENDENCY TO APPEAR HIGH

Ask any experienced aviator or LSO and they will agree, "It always looks like you are high, even when below optimum basic angle." This is a static illusion as opposed to a dynamic illusion associated with motion.

Perceptual geometry holds that the higher the pilot is above glide slope, the more parallel the edge lines will appear. The geometric "reality" of the carrier deck being so much smaller than a conventional runway leads the pilot to a faulty conclusion.

The best way to show the power of this illusion is through illustration. Figure I-4-3 is a geometrically correct depiction of a runway with the carrier deck superimposed on the touch

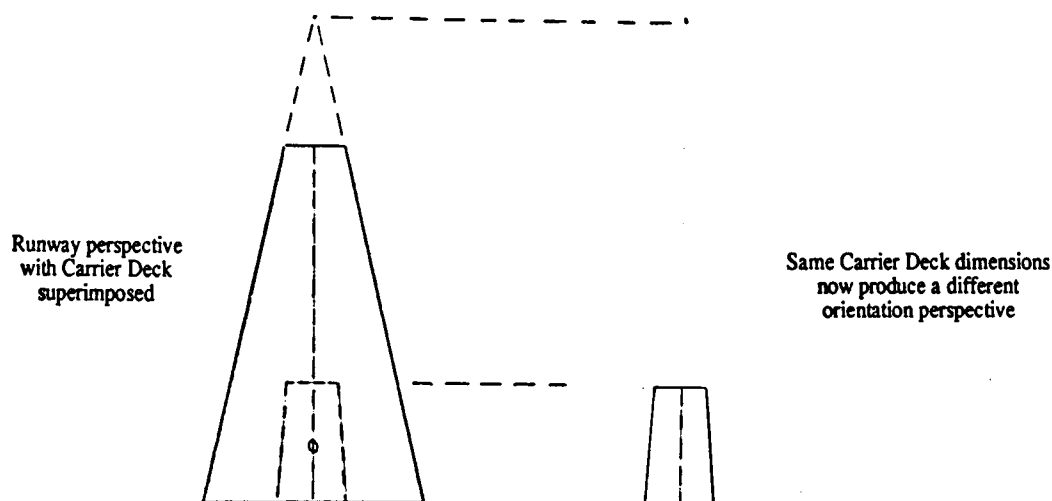


Figure I-4-3
TENDENCY TO APPEAR HIGH

down point. The angle of the runway edge lines yeild a sense of glide slope orientation. The perspective of carrier deck, while superimposed on the larger runway has noticeably different edge line angularity, but it matches the scene: perception does not detect anything unusual. But when the very same carrier deck is depicted by itself, with the same length, width and angles (the use of a ruler may be called for), perception results in a different orientation. The glide slope has not changed and neither has the touch down point and yet, the perceived glide slope orientation has changed dramatically.

PART II
CURRENT VLA SYSTEMS

Chapter 1

Glide Slope

The current VLA system for glide slope guidance is the Fresnel Lens Optical Landing System (FLOLS). The concept has roots in the Mirror Optical Landing System that is still operational at several Naval Air Stations. The FLOLS dimensions are roughly six ft high and twenty ft wide and designed to provide the pilot a space stabilized presentation of his current glide slope from about 3/4 nm to touch down. Total visual coverage is about 1.8° vertically and 40° horizontally. The system also provides basic angle adjustment and compensation for variation in aircraft H/E.

PADDLES

When the Navy first began flying from the decks of sea going warships many years ago, nobody understood quite what to expect or what might be required to do this effectively. How could they: it had never been attempted before. Since the visual presentation for a pilot approaching a ship is very different than when approaching an airfield, it became quickly apparent that the pilot needed some sort of assistance to pull it off.

The first carrier Visual Landing Aid was the Landing Signal Officer, or LSO. The LSO was a fellow aviator experienced in carrier aviation. He positioned himself near the aft end of the landing area during recovery operations and from this vantage point, the sight picture of an aircraft on approach to the ship was no different than it would be to an airfield. With some experience, the LSO could see aircraft attitude and glide slope and relay this information to the pilot by holding a "paddle" in each hand. He stood on a slightly raised platform at the port side of the landing area in front of a screen where his "paddles" would contrast against the neutral back drop. By "waving" his paddles about or holding them out at in a particular manner, the pilot would receive feedback on his glide slope and make appropriate adjustments. At night when ambient light is minimal, the LSO would wear a suit with light stripes as depicted in figure II-1-1. This approach seems almost comical now, but in its day, it proved very effective when relatively slow moving propeller aircraft were the Navy's airborne work horse.

Over the years, the role of Paddles has become an integral part of recovery operations. Although he no longer "waves" with a set of paddles, he remains responsible for "the safe expeditious recovery of aircraft" (NATOPS LSO). By virtue of his vantage point, Paddles remains located in the ideal position to verbally and visually supplement the pilot's ability to bring an aircraft aboard a moving vessel.

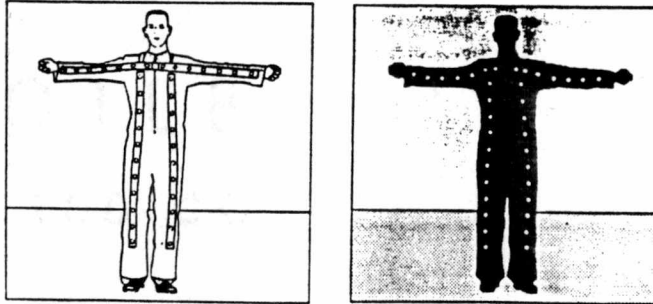


Figure II-1-1
THE LSO'S NIGHT RECOVERY UNIFORM

Source: *Visual Landing Aids, Design Standards, Ship board Installation.*, Washington D. C.: Chief of Naval Operations, 01 Jun 1974, (NAVAIR 51-50AAA-1).

MIRROR OPTICAL LANDING SYSTEM (MOLS)

The next attempt to provide a visual presentation of glide slope to the pilot was called the Mirror Optical Landing System or MOLS. This ingenious system was a huge leap in the right direction but lacked the durability and reparability the environment demands.

The MOLS was designed to provide a pitch stabilized visual presentation of glide slope, by which the pilot could control his approach to the carrier. The principle element of the MOLS was a large rectangular mirror as illustrated in figure II-1-2.

Its concave design allowed viewing of the landing aid when not directly lined up with angle deck centerline. The MOLS assembly was mounted on the left side of the landing area so that the mirror itself was nearly vertical, facing aft. Powerful "source" lights mounted aft of, and directed forward, towards the mirror assembly, created an image on the mirror which was viewed by the pilot during approach.

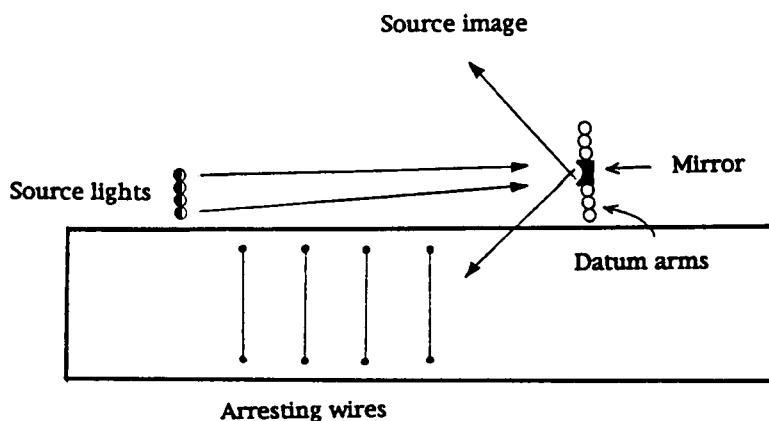


Figure II-1-2
MIRROR OPTICAL LANDING SYSTEM

Source: Adapted from Ross, A., *Analysis of a Mirror Deck Landing Aid*, Melbourne, Victoria, Australia.: Department of Defense, Aeronautical Research Laboratories, Feb 1986, (ARL-SYS-TM-86).

As illustrated in figure II-1-3, the vertical position of the image in relation to the a set of "datum" lights, mounted on the extended lateral center line of the mirror, provided the pilot with information about his present viewing position (present glide slope). If the aircraft was above glide slope, the image on the face of the mirror would lie above the datum arms. Conversely, if the image was below the datum arm, he knew his aircraft was below glide slope.

The MOLS is no longer in service aboard U. S. Navy carriers. There are a few still operational at some of the busier Naval Air Stations but are, by in large, no longer in use.

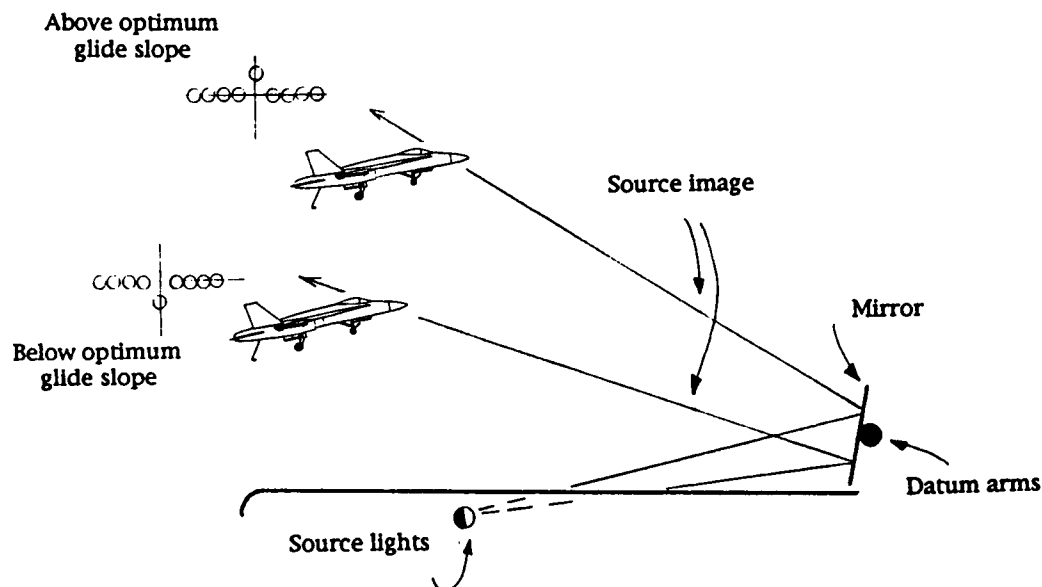


Figure II-1-3
MOLS GLIDE SLOPE PRESENTATION

Source: Adapted from Ross, A., Analysis of a Mirror Deck Landing Aid, Melbourne, Victoria, Australia.: Department of Defense, Aeronautical Research Laboratories, Feb 1986, (ARL-SYS-TM-86).

FRESNEL LENS OPTICAL LANDING SYSTEM (FLOLS)

The idea of the Fresnel lens concept as a replacement for the MOLS came in the early 1960's. The mirror's optical sensitivity to temperature, the reduced effectiveness in rain and propensity to breakage called for an improvement. The concept of "the meatball" floating above and below the datum arms to indicate the pilot's current glide slope was already working with some success. With the introduction of the Fresnel style optics in place of the mirror, many of the disadvantages were rectified and the meatball concept stayed afloat.

The FLOLS provides the pilot with essentially the same presentation as the MOLS. When the image or source is above the datum arms, the aircraft's glide slope is above optimum glide slope. When the meatball is below the datum, the aircraft is too low.

FLOLS GENERAL ARRANGEMENT

Like the MOLS, the entire apparatus is rather large standing nearly six ft high and twenty ft wide. The FLOLS is not mounted on the flight deck itself. The assembly stands on its own platform that lies to the left of the flight deck and several feet below flight deck level as illustrated in figure II-1-4. This allows launch operations from catapult number four (extreme left side of the angle deck) while the FLOLS remains configured for recovery. The FLOLS needs only to be turned on to be ready for use.

As illustrated in figure II-1-5, the Fresnel portion of the lens, called the "source," is composed of five separate lens box assemblies stacked vertically. Datum arms composed of six green lights each and extend horizontally on each side of the source. The five red lights mounted vertically on each side of the source are called the "wave-off" lights. The LSO can activate these with a hand held "pickle switch" when an approach to arrestment must be aborted. A single activation of the pickle switch turns the three inboard green datum lights off, and flashes the wave-off lights at about one cycle per second, visually indicating to the pilot that his approach must be discontinued. The wave-off lights remain on until the LSO actuates his pickle switch

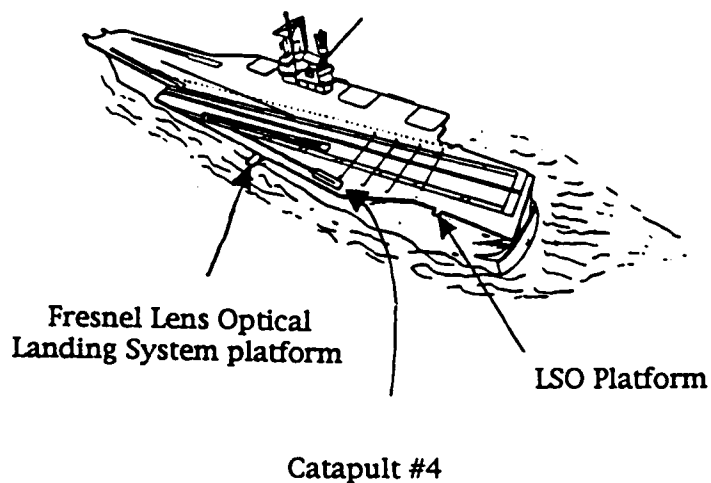


Figure II-1-4
FRESNEL LENS OPTICAL LANDING SYSTEM (FLOLS) LOCATION

Source: *Visual Landing Aids, Design Standards, Ship board Installation.*, Washington D. C.: Chief of Naval Operations, 01 Jun 1974, (NAVAIR 51-50AAA-1).

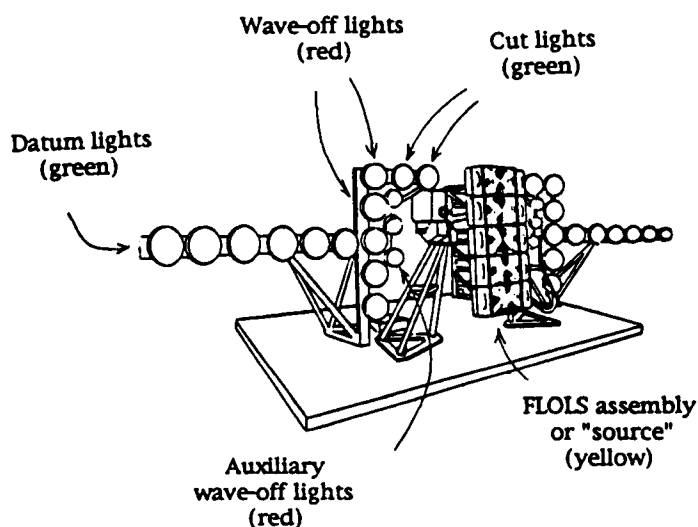


Figure II-1-5
FRESNEL LENS OPTICAL LANDING SYSTEM

Source: *Visual Landing Aids, Design Standards, Ship board Installation.*, Washington D. C.: Chief of Naval Operations, 01 Jun 1974, (NAVAIR 51-50AAA-1).

again. The four green lights mounted in a row above the assembly are called "cut lights." These are activated by a separate switch on the pickle and are designed to allow non-verbal communication to the pilot. When the LSO holds the switch down, the cut lights illuminate, and extinguish when released.

OPTICAL CHARACTERISTICS OF THE SOURCE

The central idea of this design was to provide a "light image" that appears to move depending on your viewing position. As your position moves so does the image. It must move smoothly and predictably for the pilot to interpret continuously, and do so while maintaining consistent brightness over the full range of visual coverage. To achieve this, the FLOLS source utilizes two types of lenses: a Fresnel lens and a lenticular lens. Since their optical result is similar to the characteristics of a plano-convex lens, it is worth a quick discussion.

Plano-Convex Lens

A plano-convex lens has a plane, or flat surface and a spherical convex surface. It is a collective lens in that it bends light to a focal point or image. If a person were to view a light through a plano-convex lens from several different positions the light would appear to move along the lens as depicted in figure II-1-6. That is, due to the light bending properties of refraction, the position of the light image on the lens itself is dependent upon a person's viewing position.

The equivalent circular radius of the spherical side of the lens is known as the radius of curvature. Specific optical characteristics can be achieved depending on the selection of this radius during production. The shorter this radius, the more curvature and the shorter the distance from the lens to the focal point as depicted in figure II-1-7.

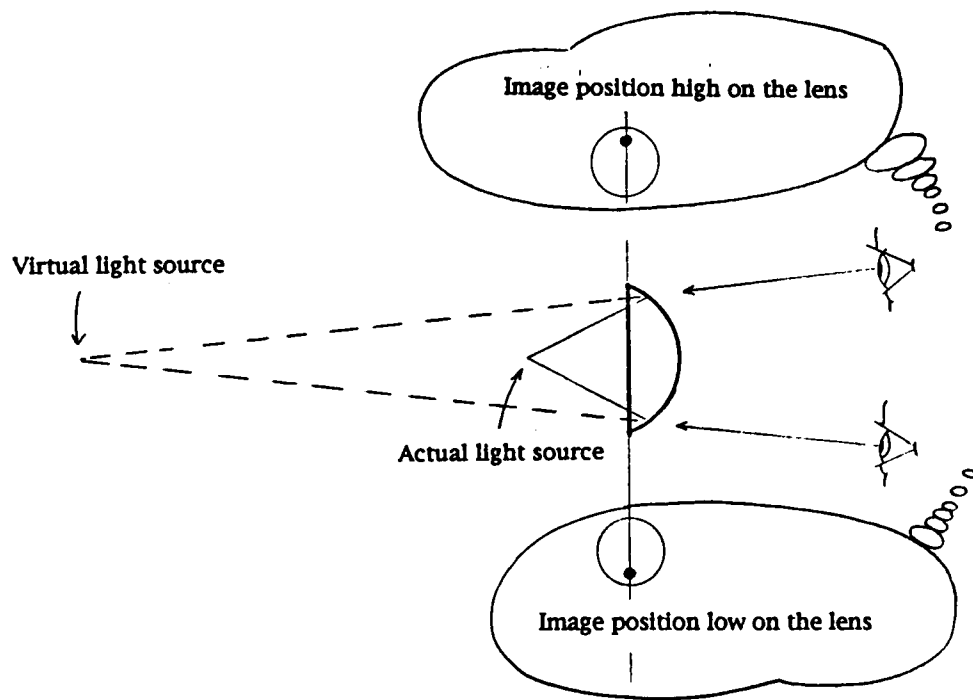
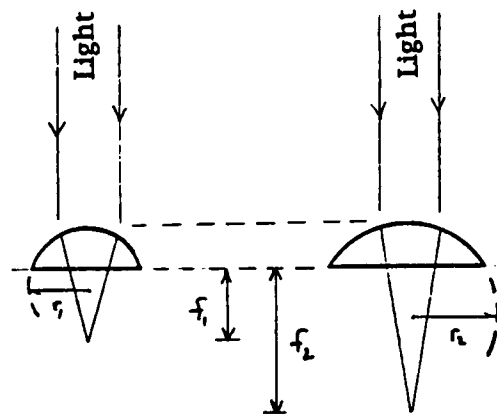


Figure II-1-6
REAL IMAGE VERSUS VIRTUAL IMAGE



If $r_1 < r_2$, then $f_1 < f_2$.

where: r is the radius of curvature.
 f is focal length.

Figure II-1-7
EFFECT OF RADIUS OF CURVATURE ON FOCAL PROPERTIES

An undesirable characteristic of the plano-convex lens is the change in focusing power toward the edge of the lens. As illustrated in figure II-1-8, when light, parallel to the principle axis of a convex spherical lens, passes through zones near the edge of the lens, the principal focus occurs at a point which is closer to the lens than the focal point of light passing through the lens near the principle axis.

Many things can degrade the focusing quality of a lens besides the effect of aberration. Uneven temperature deviation can distort the lens shape. Even a small film of oil on the surface can have a detrimental effect. Those who wear spectacles can attest to blurred vision from a dirty lens. These and any optical flaws introduced during production will degrade the lens' image.

Fresnel Lens

Desirable optical characteristics of any plano-convex lens can be reproduced with a Fresnel lens while eliminating some of the disadvantages of a plano-convex lens. The source is made of

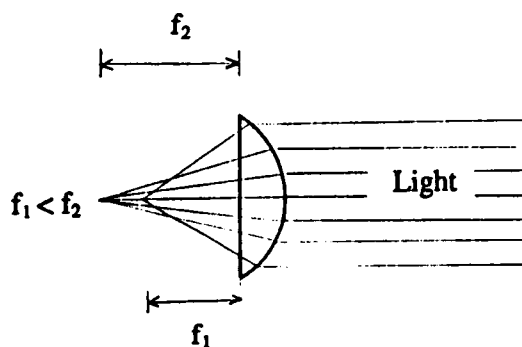


Figure II-1-8
EFFECT OF ABERRATION ON A PLANO-CONVEX LENS

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

a light weight and relatively thin sheet of transparent Lucite. The refraction of light by the Fresnel lens is collective like the plano-convex lens. One surface of the Fresnel lens consists of concentric grooves that extend from the center of the lens to the edge. As illustrated in figure II-1-9, the slope of each groove matches the slope of the convex side of the plano-convex lens. With this design, the scattering that occurs toward the fringes of the a plano-convex lens is avoided which allows the image to transition linearly from the edge to edge. Consistent focal length throughout the field of view results in a presentation that moves smoothly and predictably. (LSO Reference Manual)

Another obvious advantage of the Fresnel design is that it need not be as thick as a plano-convex lens and therefore is not as susceptible to breakage from rapid temperature changes or rough handling.

Lenticular Lens

The lenticular lens is a "fluted" lens placed on the front of each Fresnel lens. It consists of many, long convex cylindrical lenses aligned side by side as illustrated in figure II-1-10. Each

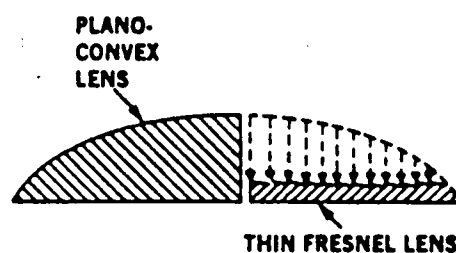


Figure II-1-9
GEOMETRY OF THE FRESNEL LENS

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

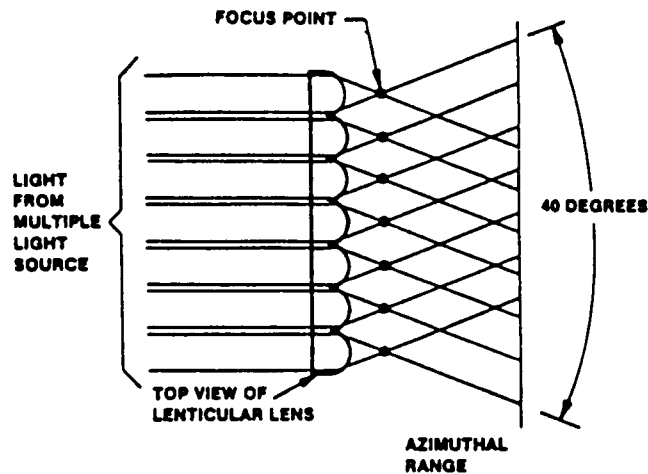


Figure II-1-10
GEOMETRY OF THE LENTICULAR LENS

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

cylinder is designed with the same, relatively short focal length. The viewing area of the source is horizontally expanded to $\pm 20^\circ$ azimuth. (LSO Reference Manual)

The lenticular lens also provides the amber color to the source (red for the very bottom cell) and is also designed to disperse sun light reflection from the face of the FLOLS. Because the optical grooves are exposed to the elements, it tends to collect salt, dirt and jet exhaust residue. These substances when sufficiently accumulated, decrease the definition of the principle focal point and therefore the surface must be cleaned frequently. (LSO Reference Manual)

FIELD OF VIEW (FOV)

The Fresnel lens, lenticular lens and the source light are assembled into a single lens box assembly or "cell." Each cell has an individual angular coverage of 0.023° . Five cells are mounted to the FLOLS in a vertical stack, as depicted in figure II-1-11 which yields a total

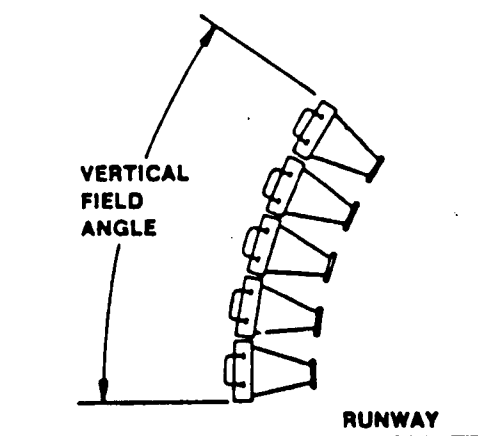


Figure II-1-11
FLOLS SOURCE VERTICAL FIELD OF VIEW

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

vertical FOV of 1.82°. Total vertical coverage is set by this arrangement while angular sensitively is determined by the optical qualities of the cell itself. Individual cell and total FLOLS coverage is listed in table II-1-1

Table II-1-1
FLOLS SOURCE VERTICAL FIELD OF VIEW

Distance from Virtual Image	Total Vertical Coverage (ft)	Vertical Coverage of Single Cell (ft)
375 ft	11.2	2.2
500 ft	14.9	3.0
1/4 nm	45.2	9.0
1/2 nm	90.4	18.1
3/4 nm	135.6	27.1
1 nm	180.8	36.2
2 nm	361.7	72.3

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

Vertical FOV

Total angular FOV for the entire FLOLS source is 1.82° . Chapter 1 of Part I discussed how all approach patterns put the aircraft at about $3/4$ nm from touch down, where the pilot should take over visually. The data in table I-II-1 show that total vertical coverage is 135.6 ft at the start of the pilot's visual approach. If the pilot reaches $3/4$ nm outside of this coverage, the source will not be visible. Furthermore, as distance to touch down decreases, the total angular coverage remains constant but actual vertical coverage (in feet) reduces significantly. By $1/4$ nm, it has reduced to 45 ft. The instant before touch down, total field of view is only 11.2 ft.

Horizontal FOV

Total horizontal FOV is $\pm 20^\circ$ either side of the FLOLS optical centerline. There are only two times when total horizontal coverage is a factor. In the case 1 pattern, the pilot is making a descending turn to angle deck centerline and the earlier the pilot can see the FLOLS, the better his approach performance will be. As designed, the aircraft penetrates the left side of horizontal coverage while passing through the 45° position (figure I-1-1). Even though the aircraft is laterally displaced many ft right of the FLOLS optical centerline at touch down, $\pm 20^\circ$ is sufficient to provide continued viewing (figure I-1-7).

SENSITIVITY

The virtual image of the source is 140 ft behind the FLOLS which equates to a sensitivity of 2.045 arcmin for every inch the image moves on the face of the FLOLS. For a single cell that is ten inches tall, the image covers about $1/3^\circ$ (20.45 arcmin per cell), but this does not mean much to the pilot trying to land his aircraft. The numbers listed in table II-1-1 are a bit easier to use in practical discussion.

For an aircraft at $3/4$ nm on glide slope, in a perfect world the pilot will see a centered ball. At this range, a glide slope change of 27.2 feet will move the source image ten inches, or the equivalent of a single cell. If the pilot has the visual acuity, he will now see the source is one cell

low, or "a ball low." At 1/4 nm, the sensitivity has increased substantial. Now, the pilot needs only to descend nine ft to see the same one-ball-low presentation. Just prior to touch down a single cell glide slope deviation is 2.2 ft. (LSO Reference Manual)

Pilots misunderstand "the 27 foot centered cell at the start" concept. Most believe this idea means that the image does not move until the aircraft deviates in excess of 27 ft. While it is true that the image may still be emanating from the middle cell, it does not mean the image itself is not moving within the cell. If an aircraft at the start descends ten ft, the source image has translated about three inches on the face of the FLOLS, in the same cell. Any pilot who can resolve three inches from 3/4 nm has super-human eyes and human physiology does not permit this.

Normal best-corrected visual acuity under daylight conditions is normally described as the ability to resolve one arcmin on the retina. Anybody with this ability is said to possess 20/20 vision. Using this standard, it means that the pilot at 1/2 nm must exceed 20 ft deviation before the image moves one arcmin and his 20/20 vision can perceive a change on the FLOLS. Actually, the story is not as dismal as it sounds. The alignment of a meatball between two datum arms requires a different visual judgment than discriminating letters at the eye clinic. (Temme)

Naval Aerospace Medical Research Laboratory conducted a study to determine the spatial dimensions of the visual stimulus which the FLOLS provides to the pilot. They made several conclusions that shed light on the systems sensitivity compared with the pilot's visual sensitivity. "The retinal image a pilot uses to evaluate and control approach early on glide slope is at the minimal limits of visual resolution at distances beyond about 0.5 nm" (Temme). When the pilot flies from 1/2 to 1/4 nm from the ramp, the angular separation between the source image and the inboard portion of the datum arms changes from 2.6 arcmin to 7.0 arcmin. Based on known retinal neurophysiology, the datum arm image can be expected to interfere with the retinal image of the source. The largest most rapid changes in stimulus size on the retina occurs within the last 1/4 nm, or about seven seconds from crossing the ramp. Up to that point, stimulus size changes very little. (Temme)

Combine this inherent limitation with a source that is too bright, pilot fatigue, poor visibility, and salt on the lens and it's suddenly no surprise that the FLOLS design has some serious limitations.

EFFECTS OF TEMPERATURE

The optical characteristics of the FLOLS varies appreciably with temperature changes. The lamps and lens of each cell assembly can be adjusted over the long term so that the image makes a smooth transition from one cell to another while operating at optimum temperature. On occasion when it is necessary to use the landing system prior to complete warm-up, smooth transition may not be assured. If the system is not evenly heated, the meatball may momentarily disappear as it transverses the junction between adjacent cells. Insulation and internal heaters are incorporated to reduce short term temperature variations. (LSO Reference Manual)

The system is designed to be operated at an internal temperature of $100\pm 3^{\circ}\text{F}$ and if allowed to operate outside of this range, three characteristics can be observed. The image will appear to change as it moves from lens center to the transition line between cell assemblies. If hotter than normal, the image will bloom as it moves toward the edge, and if colder the image will shrink approaching the edge. At extreme temperatures, it is possible to get blank areas or double images at or near the transition edge between cells. (LSO Reference Manual)

FLOLS SOURCE MOTION CAPABILITY

It would prove difficult to design and manufacture a rugged, reliable platform that could adjust position of the entire FLOLS assembly. A more practical approach is to program motion of the source itself. The source of the FLOLS is capable of motion to compensate for ship's motion (stabilization), adjust basic angle, and compensate for H/E variation between aircraft.

Pitch Angle

The source pitch angle can be adjusted to display the desired basic angle as depicted in figure II-1-12. This is also the method of "point" stabilizing the pitch axis. (LSO Reference Manual)

Roll Angle

The ability to adjust roll angle is by far the most ingenious design characteristic of the FLOLS. The source image is really a plane of light, covering $\pm 20^\circ$ either side of FLOLS optical centerline. When the source assembly is standing vertically, the light plane is level with the natural horizon. If the source is tilted (top rotated left or right) the light plane is also tilted by the same amount. If a person were standing in front of the FLOLS, to the right of optical centerline, and the source was tilted (top left) as in figure II-1-13, he would have to stand on a chair to view the same ball position because the plane of light on this side has rotated upward from its previous position. That is, the centered ball presentation is now above his current viewing position. The

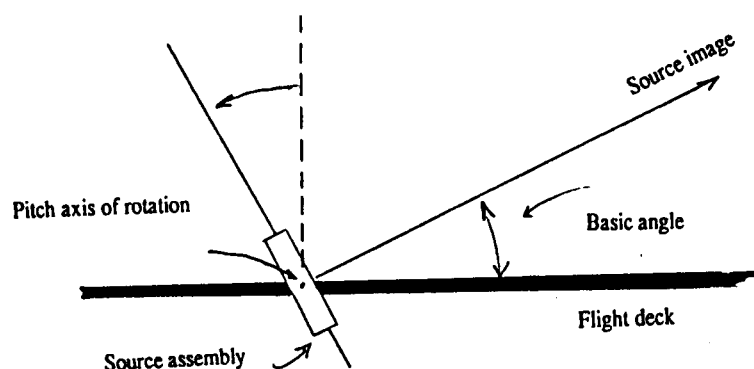


Figure II-1-12
SOURCE PITCH ANGLE FOR BASIC ANGLE ADJUSTMENT

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

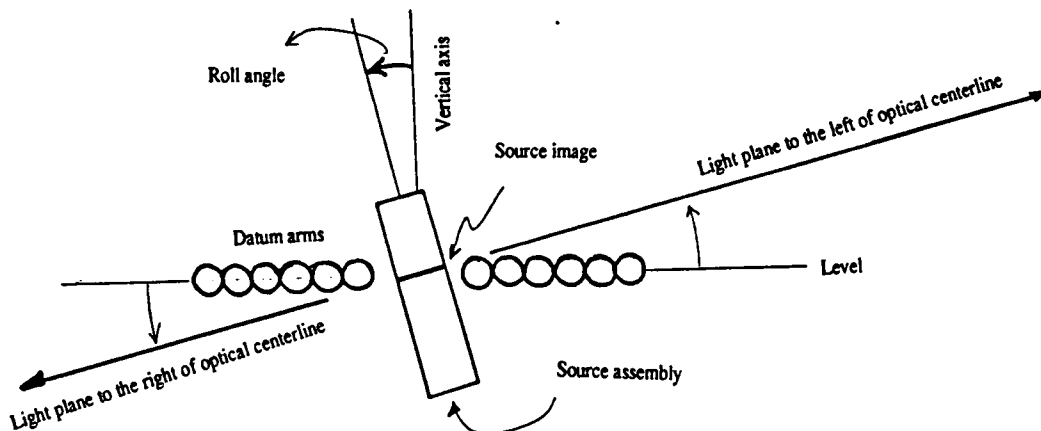


Figure II-1-13
SOURCE ROLL ANGLE FOR H/E ADJUSTMENT

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

glide slope angle of this plane of light is unchanged: FLOLS pitch angle is the same.

Roll angle can be used to compensate for differences in H/E such that hook glide path angle remains the same for each aircraft. The pilot's eye in an aircraft with a larger H/E value must fly a higher eye glide path than that of an aircraft with smaller H/E to keep the hook path the same. To achieve this, roll angle is increased so that the "on glide slope" presentation is now higher by the difference in H/E values between the two aircraft. Roll angle is also how the system achieves "line" stabilization of the glide slope presentation which will be discussed later in this Chapter.

STABILIZATION

Limits of Operation

The FLOLS stabilization system is designed to compensate for ship motion up to the limits listed table II-1-2. In addition, the system does not permit less than 1° between basic angle and the flight deck on a ramp-up pitch cycles. For example during operation with a $3\frac{1}{2}^\circ$ basic angle, minimum displayed basic angle is $2\frac{1}{2}^\circ$. (LSO Reference Manual)

Table II-1-2
FOLS STABILIZATION LIMITS

Stab Method	Pitch	Roll
Point	$\pm 6^\circ$	$\pm 6^\circ$
Line	$\pm 10^\circ$	$\pm 10^\circ$

Source: Adapted from *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

These limitations are certainly adequate to compensate for ship motion that typically does not exceed $\pm 1.5^\circ$ pitch or $\pm 2.2^\circ$ roll. However, most LSOs question if the system has the necessary velocity capability to keep up with rapid changes in deck position.

Line

Used during normal operations, roll angle adjustment allows stabilization of the optical glide slope along the vertical plane that runs through angle deck centerline as depicted in figure II-1-14. This provides a completely stabilized presentation for the pilot's eye all the way to touch down provided the aircraft is on extended angle deck centerline. The system does not compensate for heave. (LSO Reference Manual)

Point

Used as a back-up mode of operations, point stabilization provides an optical glide path which is stabilized at a fixed point on space 2,500 ft aft of the source in the same vertical plane with angle deck centerline. This is the only point along the optical glide path that is truly stabilized as depicted in figure II-1-15. When the aircraft is at the design point aft of the ship, the pilot will not perceive any presentation fluctuations from ship's pitch and roll. At any other position along the optical glide path, pitch and roll of the ship will cause deviations in the glide slope presentation. Movement of the lens pitch axis is rotated to perform point stabilization as previously depicted in figure II-1-12. (LSO Reference Manual)

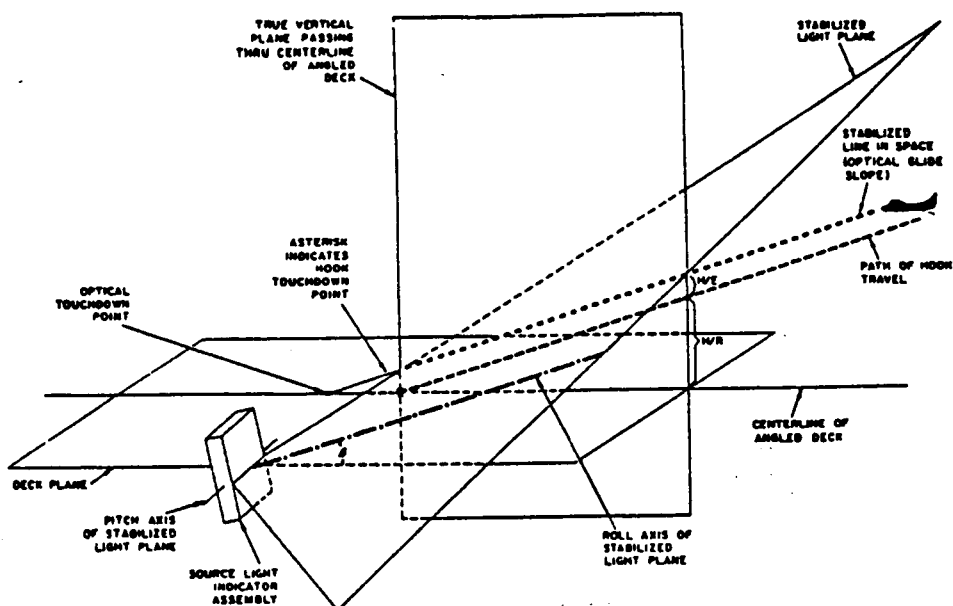


Figure II-1-14
LINE STABILIZATION OF BASIC ANGLE

Source: *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

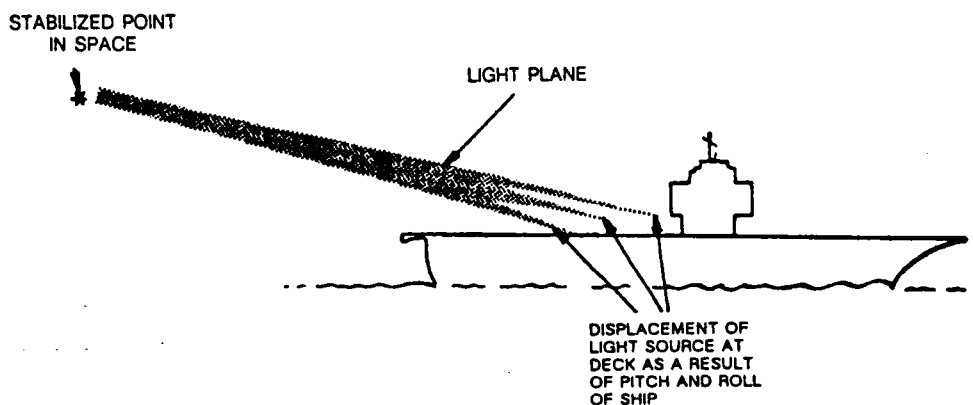


Figure II-1-15
POINT STABILIZATION OF BASIC ANGLE

Source: *LSO Reference Manual*, Virginia Beach: Virginia: U. S. Navy LSO School, Nov 1988.

Chapter 2

Line-up

Unfortunately for the pilot, there does not exist a "meat ball" counter-part to assist with line-up control. Outside of visual range, electronic landing aids provide glide slope and line-up guidance to about 3/4 nm. From here, the pilot must rely on simple observed flight deck geometry to keep his aircraft on extended centerline. The intent of landing area markings is to enhance the visual presentation during daytime flight operation. At night the landing area geometry is represented with a system of lights. Although these concepts seem simple enough and adequate for field operations, complications arise when applied to carrier operation that can easily be overlooked.

FLIGHT DECK MARKING

All flight deck marking has been standardized aboard all U. S. Navy aircraft carriers. Figure II-2-1 shows the flight deck markings configuration for *USS SARATOGA (CV-60)* that is still in service. Because carrier dimensions vary between classes, the dimensions of all flight deck markings for each carrier is described in detail in *Visual Landing Aids, Design Standards, Shipboard Installation*. This prevents "renegade" flight deck markings that may seem to provide improvement, but end up detracting from the pilot's ability to perform the task at hand. Those that have been chosen were flight tested when conceived and have been in use for nearly three decades.

NON-SKID

It should not surprise anyone that aircraft have a tendency to slip and slide around on the pitching deck of a sea going vessel. This is compounded by drippings of hydraulic fluid, oil and

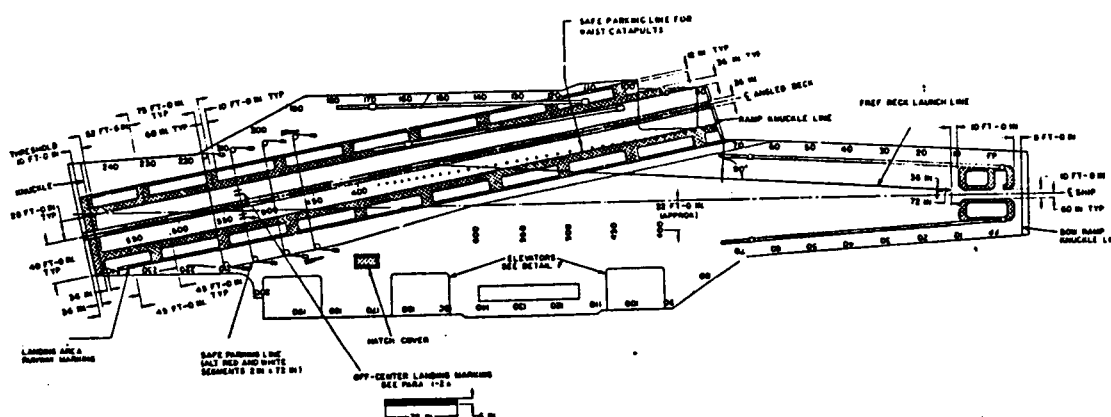


Figure II-2-1
USS SARATOGA (CV-60) FLIGHT DECK LANDING AREA MARKINGS

Source: Adapted from *Visual Landing Aids, Design Standards, Ship board Installation*, Washington D. C.: Chief of Naval Operations, 01 Jun 1974, (NAVAIR 51-50AAA-1).

grease that inevitably leak from aircraft that have to undergo the tremendous stresses and strains of continuous carrier operations. To compensate, the entire flight deck, except for the catapult tracks and the area that the arresting gear purchase cable slaps the deck during run out are covered with an extremely abrasive, durable non-skid compound.

The landing area itself is covered with a softer non-skid that does not wear down the arresting cable as rapidly when it is retracted following an arrested landing. Although this non-skid is equally craggy and rough, it tends to deteriorate and lose its roughness during a few months of continuous use.

Since painting over the non-skid tends to detract the abrasive quality of the surface, white or yellow colored non-skid compound is used to mark the landing area. Within a few months of deployment, the white and yellow non-skid become worn and saturated with hydraulic and oil drippings and lose their visual contrast. Combine this with a low sun angle near sunset or sunrise, reduced visibility from moisture in the atmosphere, and a sheen of salt residue on the windscreen of the aircraft and these markings become indiscernible.

Flight Deck Marking Maintenance

Non-skid replacement can only be done when in the ship yard because the curing process takes many days. For touch ups at sea, a durable paint-like color topping is used to touch up the colored non-skid. Its use must be judicious because continuous use will compromise the slip resistant property of the non-skid.

To insure these touch ups will adhere to the flight deck, the surface must be scrubbed and cleaned. For several reasons, this is an enormous task. First, the flight deck is immense (165,000 square ft) and scrubbing an area of this size represents a great deal of manpower. Second, the flight deck is covered from stern to bow with aircraft, tractors, fire trucks and maintenance gear. For a thorough cleaning, these articles must be moved out of the way very much like moving the furniture around the room to vacuum underneath. Once a small area has been cleaned, the area is filled with a few pieces of furniture to clear the next area for

vacuuming. The reader may imagine trying to scrub the floor of a tightly packed furniture store that covers several football fields. The carrier rarely has the luxury to take an entire day out of its busy schedule for this evolution. Eventually the flight deck becomes so dangerously slippery, the ship must take the time for a good scrubbing. As a bonus, some of the flight deck markings get a badly needed touch up.

RUNWAY CENTERLINE STRIPE

The centerline stripe is the pilot's main indicator of landing area geometry. The runway centerline stripe is 36 inches wide with alternating yellow and white segments. Each segment is 45 ft long. The pattern starts at the round down with yellow, and extends to the forward end of the landing area.

The centerline stripe is the only flight deck marking that uses yellow. The alternating yellow and white is designed to provide texture to the flight deck that will enhance the pilot's perception of closure. Unfortunately, the yellow is indiscernible from the cockpit during approach because the pilot's attention is absorbed with aircraft control. If a pilot ever took the time to perceive this color pattern, glide slope control would likely be degraded.

RUNWAY EDGE LADDER

Both runway edge "ladders" are composed of a fairly wide, white inboard stripes and a narrower outboard stripe that run the length of the landing area from the round down to the forward end of the angle deck. Tall horizontal stripes connect these vertical lines which give it the impression of a ladder. They look unusually tall if one were to stand near them much as words painted on the road appear distorted. When the word "STOP" is painted on a road, it appears disproportionately tall when not viewed from an approaching car. The shallow viewing angle of an approaching automobile depresses the vertical dimension, and the word "STOP" appears normal. During carrier approach, these horizontal lines appear roughly as high as they are wide.

The edge ladder design is a compromise between a presentation that appears narrow enough to call attention to deviation without over sensitizing the pilot to insignificant deviations. The inside stripe outlines a fairly narrow portion of the safe landing area. It accentuates slight deviations in line-up before they become extreme. Without it, larger line-up deviations would have to occur before recognition. The outboard stripe perceptually widens the landing area to prevent exaggeration of line-up deviations once they are recognized.

AFT ATHWARTSHIP STRIPE

The aft athwartship stripe is white and covers the round down at the very aft end of the angle deck. Although this cue provides another side of the "carrier box," it more importantly gives the pilot a very distinct indication for the proper point to begin his turn to final. With nominal wind conditions in the case 1 pattern, each pilot should commence the turn two to three seconds prior to being able to look right along the aft athwartship stripe. As discussed in Chapter 1 of Part I, this consistent interval is absolutely critical. A 45 second interval between arrestments is an ideal trade off between an expeditious recovery and enough time to prepare the flight deck for the next aircraft. This critical timing is controlled by the turn off the "abeam" position and the distinctive aft athwartship stripe provides the visual cue of this position.

DECK LIGHTING

Flight deck lighting is designed to give the pilot a visual presentation of the landing area during night recovery operations and provide ambient lighting to those that work on the flight deck. Those lighting systems that have an impact on the pilot's ability to land an aircraft aboard a carrier at night are illustrated in figure II-2-2. In addition, there are many areas on the flight deck that must be identified with distinctive lighting mounted in the flight deck of a carrier. Blue omni-directional lights mark the flight deck edge and red lights mark the transition from the flight deck to the landing area, to name only two.

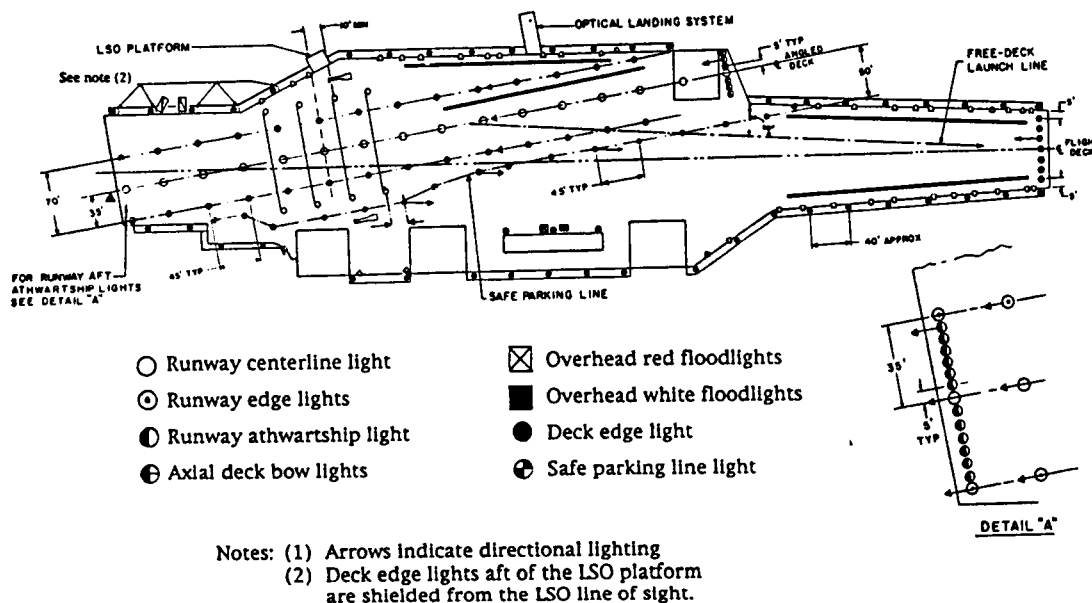


Figure II-2-2
FLIGHT DECK LIGHTING

Source: Adapted from *Visual Landing Aids, Design Standards, Ship board Installation.*, Washington D. C.: Chief of Naval Operations, 01 Jun 1974, (NAVAIR 51-50AAA-1).

All deck light intensity may be adjusted to suit the current weather conditions. Typically, once an intensity balance between all these lighting systems is achieved, rarely is the configuration changed with the exception of compensating for weather and visibility.

All flight deck lighting (as opposed to overhead floodlighting) is low profile in design to allow aircraft and tractors to roll over them. A 20° wedge in the light housing provides some degree of directionality by limiting the horizontal field of view to the approach corridor.

RUNWAY EDGE LIGHTS

The runway edge lights run the length of the angle deck, 35 ft either side of the centerline and each contain a 45 watt quartz lamp covered with a clear lens.

RUNWAY ATHWARTSHIP LIGHTS

Runway athwartship lights are installed on the fore and aft portions of the angle deck, perpendicular to centerline. They are spaced at five ft intervals with the same number of lights on each side of centerline. They are also unidirectional, white lights, rated at 100 watts, and appear identical to the runway centerline lights during approach.

Lights mounted at the round down horizontally connect each runway edge light. At the front of the angle deck, this is not possible because the forward left corner of the flight deck, on some carriers, is not square. With symmetry in mind, an equal number of lights are mounted on each side of centerline but do not run entirely to the edge lights.

At night, every aircraft flies a straight-in case 3 approach to the carrier. Unlike day time recoveries, the need to highlight the round down as a timing control cue is not necessary. Interval between aircraft is controlled by other methods. These lights provide a necessary part of the visual presentation by completing the "carrier box."

RUNWAY CENTERLINE LIGHTS

Runway centerline lights are low profile, white, unidirectional lights that use 100 watt quartz lamps. These fairly intense lights are flush mounted in the flight deck and built to withstand the landing forces exerted by a 54,000 lb F-14 *TOMCAT* even if the aircraft should land directly on top of one. They are located along the centerline of the landing area and run the length of the angle deck at 45 ft intervals.

The centerline lights provide a very necessary indication of landing area centerline. During simulation at NAWCAD Patuxent River MD, the pilot was far more attuned to small deviation from angle deck centerline with these illuminated. Without it, far greater line-up deviations occurred before sufficient visual cues alerted the pilot. (Nielsen, et al.)

Sequenced Flashing

All carriers have incorporated a sequence flashing control system for the centerline lights. The system provides the electronic circuitry for flashing the runway centerline lights in sequence from the ramp to bow of the angle deck. The sequence is capable of operating a maximum of 20 centerline lights with an adjustable sequence repetition interval from 0.2 to 2.0 seconds. As viewed from the cockpit during approach, the apparent speed of the flashing effect may varied from 100 kts to 600 kts; hence, a term that aviators have coined for this system, "the rabbit."

As the rabbit runs up the flight deck, the pilot is denied the strong tendency to fixate on the round down which invariably leads to the aircraft settling below optimum glide slope (sometimes dangerously below). The rabbit also enhances visual acquisition of the carrier without sacrificing long term retinal night adaptation. Flight deck lighting intensities are kept to a minimum to match the intensity of the FLOLS that must also be kept low to retain definition during the final ten seconds of the approach.

Combination Steady and Flashing

Any combination of sequenced flashing and steady illumination can be selected. Steady centerline lights without sequenced flashing results in shorter visual acquisition range and does not prevent the pilot from fixating on the round-down. Sequenced flashing without steady illumination between each sequence results in increased acquisition range but, between sequences, centerline is not illuminated. This produces an incredibly uncomfortable sensation of flying *through* the angle deck rather than *onto* the carrier and decreases pilot sensitivity to line-up deviations. Steady centerline light illumination between sequenced flashing is the preferred combination when configured with current VLA systems: increased visual acquisition range while minimizing round-down fixation tendencies. (Nielsen, et al.)

TUNNEL DECK LIGHTING

An interesting configuration that is worth discussing is "tunnel" lighting. Even though this configuration is no longer in use, it was an attempt to perceptually lengthen the flight deck of smaller carriers.

Because a flight deck is much shorter than a runway, the forward end of landing area lighting was toed-in so that the apparent width of the landing area was up to 50% smaller at the forward end than at the ramp. This would effectively lengthen the flight deck by playing on the pilot's perception of perspective. The percent of toe-in (determined by the ratio between the width of the forward and aft athwartship lights) ranged from 25% (CVA-43) to 50% (CVA-31).

As range to touch down decreases, the pilot's view of the flight deck is limited to the very forward portion of the landing area where the carrier box is most narrow (the rest of the flight deck is beneath the nose of the aircraft). It would seem that such a narrow presentation would demand a higher pilot attention: a given lateral deviation would appear larger in comparison with a more narrow presentation and would probably illicit a correction even if these smaller deviations are trivial.

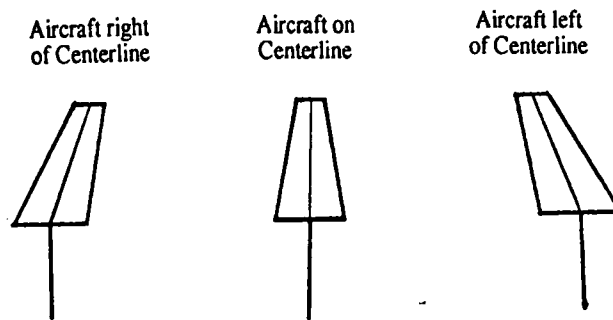
When larger aircraft carriers went into production, the perceptual complications of tunnel lighting were avoided by installing rectangular flight deck lighting. By the mid 1960's, roughly half of the west coast carriers were configured with tunnel lighting. The Navy recognized the need to standardize flight deck lighting and began to retrofit these carriers with rectangular lighting (Winterberg). Currently, all aircraft carriers have rectangular lighting systems and the presentation aboard each is standardized.

VERTICAL DROPLINE LIGHTS

Nine to fourteen, incandescent red lights are mounted vertically from the round down, below angle deck centerline. The lights are rated at 18 watts and have a total beam spread of 50° in azimuth and 25° elevation and are canted 4° above the horizon.

Dropline lights provide discrete line-up information. When the aircraft is on line-up, the centerline and dropline lights appear straight. If the aircraft is either side of centerline, this straight line presentation is broken, and hinges at the round down. The pilot perceives something resembling an arrow that points in the direction he needs to fly to re-capture centerline as illustrated in figure II-2-3. Line-up control without dropline lights is shaky at best. Simulation at Patuxent indicated that the pilot's ability to control centerline was better with the addition of dropline lights than it was without them. (Nielsen, et al.)

An undesirable characteristic of this presentation is the pronounced region of uncertainty near centerline. Line-up control must deteriorate significantly before the break becomes sufficiently pronounced for pilot recognition. Once attention is drawn to this break, the dropline light presentation exaggerates the deviation and the pilot will tend to over control his correction by over shooting centerline. It also tends to draw attention to the round down, which is undesirable. (Nielsen, et al.)



Notes: The angle between the Dropline and Centerline lights indicate magnitude and direction of line-up error.

Figure II-2-3
DROPLINE LIGHT PERSPECTIVE CUEING

An undesirable characteristic of this presentation is the pronounced region of uncertainty near centerline. Line-up control must deteriorate significantly before the break becomes sufficiently pronounced for pilot recognition. Once attention is drawn to this break, the dropline light presentation exaggerates the deviation and the pilot may tend to over control his correction by over shooting centerline. It also tends to draw attention to the round down, which is undesirable. (Nielsen, et al.)

OVERHEAD FLOODLIGHT ILLUMINATION

The purpose of overhead lighting is not to assist the pilot during his approach. Rather it is to provide a necessary source of ambient illumination for flight deck personnel to perform their jobs. Aircraft maintenance, ordnance reloading, and servicing of launch and recovery equipment need not be postponed if a usable source of illumination can be provided that does not interfere with the pilot's landing task.

Three standard systems of floodlight illumination are currently used aboard all U. S. Navy carriers. Yellow floodlights are typically used for ambient illumination during launch and recovery operations because they can be adjusted over their full range of intensity. The white and sodium floodlight systems provide flexibility and can serve as a back-up lighting source.

In 1971, Dunlap and associates in cooperation with Navy personnel attempted determine if there was any significant practical difference in night approach performance between the United Kingdom and United States lighting systems. United Kingdom deck lighting consisted of 80 narrow, medium and wide-beam spot lights, each aligned to illuminate a specific spot on the flight deck. Other deck lighting was kept consistent throughout the evaluation. The evaluators spent approximately two winter months aboard the *USS INDEPENDENCE* (CV-62) in the Mediterranean Sea collecting data for computation of boarding, bolter and wave-off rates, arresting wire frequencies, weighted landing performance scores, and approach deviations with a sample size of 2262 approaches. When all the data was reduced and statistical analysis complete, they concluded, "In summary, night final approach and landing performance under the United Kingdom lighting system was not found to be statistically or practically different from performance under the conventional American lighting system now in use fleet-wide." (Dunlap)

RED FLOODLIGHTS

These lights are mounted on the inboard island structure approximately 60 ft above flight deck level. The 300 watt, 120 volt sealed beam lamp assembly is equipped with a hood to limit stray light emissions. The preferred installation consists of four individual groups that light the axial bow, forward landing area, amidships landing area, and the aft portion of the landing area. Intensity can be varied from OFF to full brightness.

YELLOW FLOODLIGHTS

Yellow floodlights are designed to provide flight deck personnel adequate ambient illumination of the flight deck during recovery operations. They are grouped in four circuits and mounted about 60 ft above the flight deck. Each of the light fixtures is equipped with a 300 watt lamp and is adjustable (each fixture independently) from OFF to full brightness.

During approach, the illumination provided by these lights are not perceived by the pilot. As the aircraft approaches, the perceived brightness of the carrier box lighting over comes what floodlight illumination is not absorbed by the atmosphere. By the time the aircraft is close enough to perceive any floodlighting, his total concentration is on glide slope, line-up, and AOA control. For all practical purposes, the pilot in the aircraft does not perceive any yellow floodlighting at all. His total lighting presentation consists of a carrier box, dropline lights and a meatball.

WHITE FLOODLIGHTS

These 1000 watt lamps are mounted on the inboard side of the island at several different levels. Dimming is possible from full brightness to complete black out. Although, these lights are not typically used during recovery operations, they can provide very bright illumination between recovery cycles when required.

LOW PRESSURE SODIUM FLOODLIGHTS

Four banks of low pressure sodium floodlights are located on the island structure to provide another source of flight deck lighting. Each fixture has four lamps of different power (180 watt, 135 watt, 90 watt, and 55 watt) that allow discrete control of intensity. Each light can be turned ON and OFF individually to reach the desired overall illumination intensity. Because these lights require a warm up period, their real-time versatility is limited.

PART III
FUTURE VLA SYSTEMS

Chapter 1

Improved Carrier Optical Landing System (ICOLS)

The Improved Carrier Optical Landing System (ICOLS) was developed to improve glide slope information over that which is currently given by the FLOLS and carrier deck lighting. A demonstration of the various concepts was given at the Naval Air Engineering Center (NAVAIRENGCEN), Lakehurst, New Jersey in November of 1989. Following this demonstration, the ICOLS components were further developed for a detailed conceptual evaluation by NAWCAD Patuxent River, Maryland. The purpose of this effort was to evaluate the various line-up and glide slope concepts and determine which of these best provides long range line-up and long range glide slope alignment information. The Laser Centerline Localizer (now called Long Range Laser Line-up System) and the Laser Glide Slope Indicator (LGI) showed the most promise to fulfill the requirements of the next generation VLA and both were recommended for accelerated development. (Ciesielski)

LINE-UP SYSTEMS

CROSSBAR LONG RANGE LINE-UP SYSTEM (LRLUS)

System Description

Crossbar Concept

The system was composed of a series of light boxes located along the round down. An aircraft located along extended centerline would see a flashing amber light emanating from the center of the round down. If line-up deviation was to the right of centerline, the green light adjacent and to the right of the amber light would become visible (red if deviation to the left). As line-up deviation continued, the aircraft would penetrate the next adjacent light corridor and would then see three lights, one flashing amber and two green. More deviation and another green light would be visible and so on. Eventually when maximum deviation was reached, all colored lights, from centerline to the edge of the round down would be visible. (Ciesielski)

Five-Box and Three-Box System

This three-box system used three light sources (or light boxes) located along the round down spaced 12 ft apart. Total horizontal coverage was designed to be $\pm 10^\circ$, centered on the extended centerline. The five-box system used five lights either side of centerline, spaced ten ft apart for a 20° total horizontal coverage. The system was designed so that the pilot would no longer be able to see these line-up system cues once closer than about 1/3 nm. (Ciesielski)

Flight Test Results and Conclusions

System implementation was less than optimum due to improper sequencing and orientation of the lights and the low intensity of the green lights. The red lights (left deviations) were first visible at five to six nm compared to the green lights (right deviation) visible at 1.0 to 1.5 nm. The three-box and five-box Crossbar systems were evaluated during 73 approaches. The

flashing amber (centerline) was first visible at four to five nm, where the centerline strobe lights partially obscured the indication. The magnitude of line-up deviation was difficult to interpret from either Crossbar presentation which increased pilot scan requirements and workload inside of 1.5 nm. Small line-up deviations (one green or red light visible) were not easily recognized due partial obscuration by the flashing amber. Pilots concluded that neither configuration (three-box or five-box) improved their ability to acquire and maintain centerline position compared to current VLA. The evaluation recommended that the Crossbar LRLUS concept not be further developed. (Ciesielski)

LASER CENTERLINE LOCALIZER (LCL)

System Description

The LCL was located at the ramp along angle deck centerline and used color change and flash rate as line-up position cues. Solid amber indicated the aircraft was on centerline, red indicated left of centerline, and green indicated right of centerline. Within the red and green corridors, flash rate indicated the aircraft's distance from centerline, increasing as lateral distance increased. (Ciesielski)

Flight Test Results and Conclusions

This system was evaluated during 79 approaches and was found to provide useful information out to 12 nm (maximum range tested). The magnitude and direction of deviation from centerline was easy to determine from color and flash rate of the light presentation. Very small deviations inside of one nm were quickly recognized without dedicated scan of the LCL. Transition to the deck lights and centerline strobes was accomplished smoothly with the LCL cut-off set at approximately 1/2 nm. The pilots were unable to evaluate the LCL in conjunction with the dropline lights (field test site limitations) and were concerned with the possibility of confusion when using both systems or when transition from the LCL to the dropline lights occurred. Pilots' opinion indicated that their ability to acquire and maintain centerline position

was significantly improved compared to the current VLA without a significant increase in pilot workload. Pilots' comments concluded that the LCL is an enhancing system for line-up and was recommended for accelerated development. (Ciesielski)

An Advanced Development Model (pre-prototype development stage) was designed and built following this evaluation and Part III, Chapter 2 discusses the flight test program that evaluated this follow-on design.

COMBINED CROSSBAR LRLUS AND LCL

This concept was evaluated during 16 approaches using the combined presentation of the five-box Crossbar system and the LCL. Unfortunately the undesirable characteristics of the Crossbar concept eliminated any enhancing characteristics of the LCL and the combination was rapidly ruled out as a potential contender. (Ciesielski)

GLIDE SLOPE DISPLAY SYSTEMS

FORE AND AFT LONG RANGE GLIDE SLOPE INDICATOR (LRGSI)

This system was evaluated over the course of 28 approaches. The glide slope information presented was similar to the Visual Approach Slope Indicator (VASI) systems found around the country (red low, white high). The LRGSI was visible out to three nm and high and low deviations were easily recognizable. However the lack of positive feedback for an "on glide slope" indication resulted in a tendency to fly the upper or lower corridor edges or oscillate between corridors. When it came time to transition to the FLOLS, the pilot had to correct for being either high or low, thus increasing workload. Pilots felt that a self contained approach, monitoring descent rate while passing three, two and one nm altitude check points (which can hardly be considered precise), provided superior performance over the LRGSI. Needless to say this was not a contender. (Ciesielski)

LASER GLIDE SLOPE INDICATOR (LGI)

System Description

The LGI was designed to provide the pilot color and flash rate cue of current position relative to optimum glide slope and is illustrated in figure III-1-1. The system showed amber when on glide slope, green when above glide slope, and red when below glide slope. Solid color indicated slight deviation from optimum, while flashing indicated more significant deviation. Total vertical coverage of the system was 2.12° ($\pm 1.06^\circ$ either side of optimum) and total horizontal coverage was $\pm 16^\circ$ either side of optical centerline. Individual corridor coverage's are listed in table III-1-1. (Ciesielski)

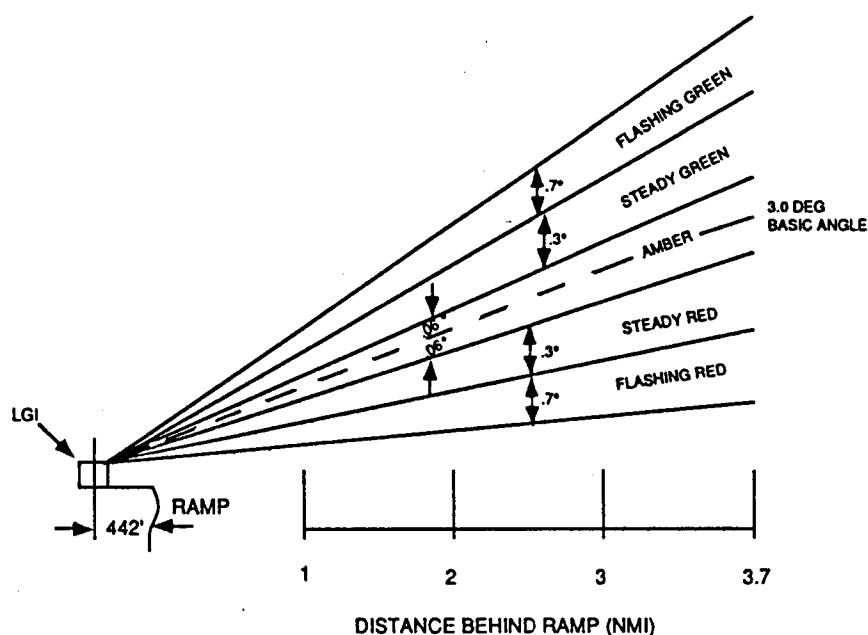


Figure III-1-1
LASER GLIDE SLOPE INDICATOR (LGI)

Source: Adapted from Ciesielski, Sonya, et al., *Improved Carrier Optical Landing System Evaluation*, Patuxent River, MD.: Naval Air Test Center, Strike Aircraft Test Directorate, 03 Oct 1990, (Report NO: SA-75R-90).

Table III-1-1
INDIVIDUAL VERTICAL COVERAGE'S OF LGI CORRIDORS

Distance (nm)	Amber (ft)	Steady Red and Green (ft)	Flashing Red and Green (ft)
1	13 1/2	34	79
2	26	65	152
3	39	97	225
4	47 1/2	119	277

Source: Adapted from Ciesielski, Sonya, et al., *Improved Carrier Optical Landing System Evaluation*, Patuxent River, MD.: Naval Air Test Center, Strike Aircraft Test Directorate, 03 Oct 1990, (Report NO: SA-75R-90).

Flight Test Result and Conclusions

The LGI was evaluated in two locations, on the left side of the landing area near the FLOLS and the right side of the landing area across from the FLOLS during a total of 40 approaches. The LGI was visible at 12 nm, (the maximum range tested) which was well beyond the required range of 3.5 to 4.0 nm. The extended range of the LGI could prolong pilot exposure to the lowest indication (flashing red), possibly causing confusion with the LCL during pitching deck operations. The location on the left side of the landing area caused confusion with the FLOLS, while location on the right side provided a clear and unambiguous presentation. Pilot comments indicated that precise interception of glide at three nm was easily accomplished without an increase in workload. Precise glide slope tracking from three nm to 1/2 nm was easily achieved. Very small deviation inside of one nm were quickly recognized even prior to recognition on the FLOLS. Transition to the FLOLS with a steady centered ball at 1/2 nm was easily accomplished. For all of these enhancing reasons, the evaluation concluded that the LGI showed the best potential for the next generation of glide slope VLA and was recommended for accelerated development. (Ciesielski)

As of January 1994, it appeared that the first Advanced Development Model of this system was nearly ready for flight test evaluation at Patuxent River.

Chapter 2

Long Range Laser Line-up System (LRLS) Continued Flight Test

Based on the favorable flight test results discussed in Chapter 1 of Part III, the LRLS was chosen for accelerated development to fulfill the lineup guidance mission of ICOLS. An LRLS Advanced Development Model (ADM) was created in a joint venture between NAWCAD Lakehurst and Humbug Mountain Research Laboratories (HMRL). HMRL designed the optical head and NAWCAD Lakehurst designed the stabilization platform. NAWCAD Patuxent River conducted the shore based flight tests at the Landing Systems Test Facility, simulation based flight tests, and shipboard testing aboard *USS THEODORE ROOSEVELT* (CVN-71) and *USS GEORGE WASHINGTON* (CVN-73). This chapter summarizes the entire test program that ran from March through July 1992.

This chapter is largely based on information contained in *Technical Evaluation of the Long Range Line-up System, Advanced Development Model*, which published the final test results, conclusions and recommendations. Although the author was intimately involved in this project as one of the primary test pilots, the contributions from each and every person involved with this program can not be overstated. Many of the concepts and conclusions that will be discussed and the majority of data analysis belongs to the collective mind of the entire test team.

LRLS TEST PROGRAM OVERVIEW

The Long Range Lineup System (LRLS) was evaluated to determine if it would satisfy the requirement for long range visual lineup cues for night case 3 carrier operations. In addition, the LRLS was evaluated for its compatibility with current carrier Visual Landing Aids (VLA) and Electronic Landing Aids (ELA).

To achieve these objectives, the program can be thought of in four separate phases (although they were intricately interwoven and overlapped one another): ground based analysis and laboratory evaluation, flight simulation, shore based flight test (99 night approaches, 20.4 flight hours), and shipboard flights (88 night approaches, 17.9 flight hours). Surprisingly, during the course of simulation and shore based flight test programs, the test team found some seemingly desirable characteristics that failed to meet their expectation during shipboard flight tests. Likewise, some characteristics that the test team thought would detract from the system's effectiveness at sea, turned out to the contrary.

Since this system was an "ADM," the test team realized that this was the last opportunity to change system design parameters prior to production of the first prototype, without incurring unacceptable expense. They were continually optimizing system variables during the test program to achieve the best possible performance and compatibility.

The improved guidance that this system provided for the pilot was astonishing. Having now been spoiled by a system with significantly improved VLA guidance, the author wonders how naval aviation ever operated without it.

The chapter is divided into sections that simplify understanding of the this complex test program: system description, description of test methods employed, instrumentation and data extraction, and test results.

LRLS SYSTEM DESCRIPTION

GENERAL

The LRLS is designed to provide night centerline line-up cues to the pilot at an increased range than what is available with the current aircraft carrier VLA and is designed to provide line-up information from at least five nm to 1/2 nm (from the ramp), at which point the pilot can transition from the LRLS to the normal carrier approach visual scan. The LRLS uses color change and flash rate as cues to the pilot for line-up position information. Amber indicates the aircraft is on centerline, red indicates left of centerline, and green indicates right of centerline. Within the red and green corridors, flash rate indicates the aircraft's distance from centerline, increasing as lateral distance from centerline increases.

LRLS OPTICAL DESIGN

The design horizontal visual coverage and flash rate of each individual corridor is given in table III-2-1. Total horizontal coverage of the system is designed to be $\pm 10.8^\circ$

Table III-2-1
DESIGN LRLS HORIZONTAL COVERAGE'S AND FLASH RATES

Corridor	Horizontal Coverage	Flash Rate
Steady Amber	0.4°	N/A
Steady Red and Green	0.6°	N/A
Slow Flashing Red and Green	4.0°	55 cyc/min
Rapid Flashing Red and Green	6.0°	115 cyc/min

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

either side of angle deck centerline. LRLS horizontal coverage is illustrated in figure III-2-1. The wider edge corridors are designed to provide turn-in guidance to assist the pilot with initial centerline capture. Once established on centerline, the smaller coverage's of the interior corridors are designed to indicate any small deviations to assist with maintaining centerline.

Total vertical coverage is designed to be 5.0° ranging from 0.5° to 5.5° degrees above the horizon. The vertical coverage lower limit was chosen to prevent ocean surface reflection. The vertical coverage upper limit represents a tradeoff between providing adequate coverage above optimum glide path and cut-off (the point where the aircraft exits the top of coverage shortly before touchdown). Vertical coverage shown in figure III-2-2, depicts

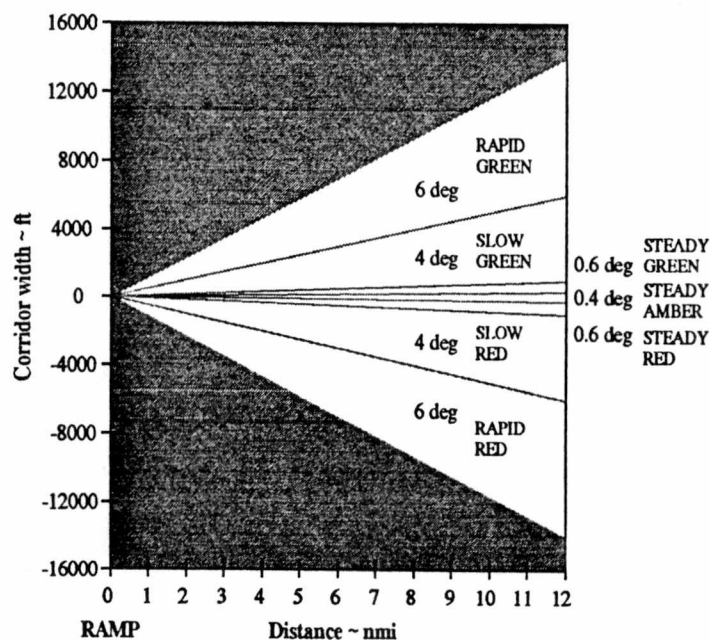


Figure III-2-1
LRLS HORIZONTAL COVERAGE

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

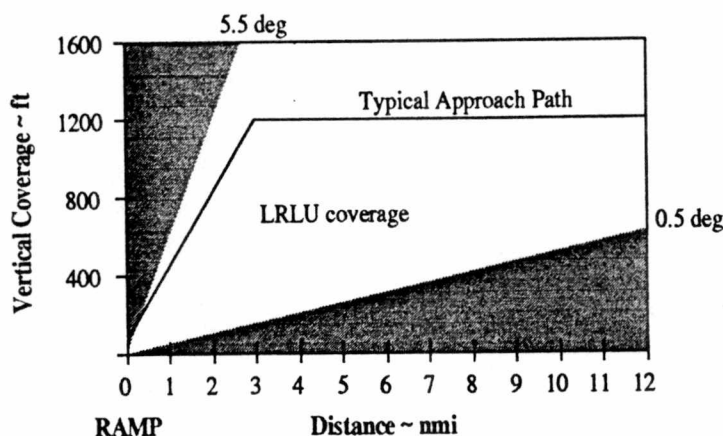


Figure III-2-2
LRLS VERTICAL COVERAGE

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

a 1/2 nm cut-off point. Once the aircraft is passed this point, the pilot should no longer receive LRLS visual information.

Figure III-2-3 is a photograph of the LRLS optical head. Its size is surprisingly small: about the same as a large VCR player. The fins on the top of the box allow for cooling and the two bars running across the face plate allow for lower limit coverage adjustment to avoid ocean surface reflection. The LRLS houses a total of eighteen lenses broken down as described in table III-2-2. One class III helium neon laser for each corridor (or lens) is projected through a series of prisms for presentation control as shown in figure III-2-4.

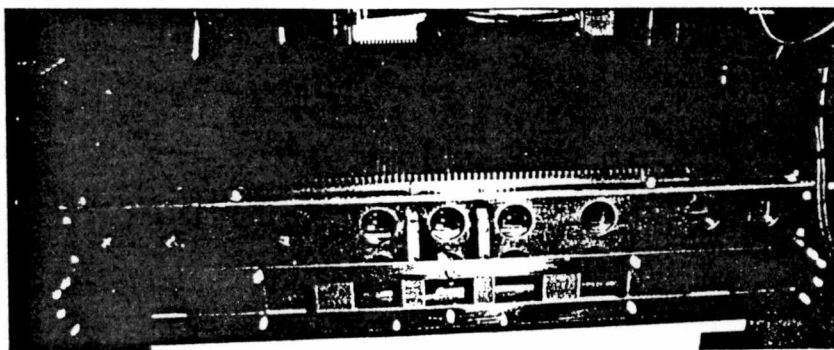


Figure III-2-3
LRLS OPTICAL HEAD

Source: Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

Table III-2-2
LRLS LASER CONFIGURATION IN EACH CORRIDOR

Corridor	Number of Lasers
Fast Flashing Red	4
Slow Flashing Red	2
Steady Red	2
Amber	2
Steady Green	2
Slow Flashing Green	2
Fast Flashing Green	4

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

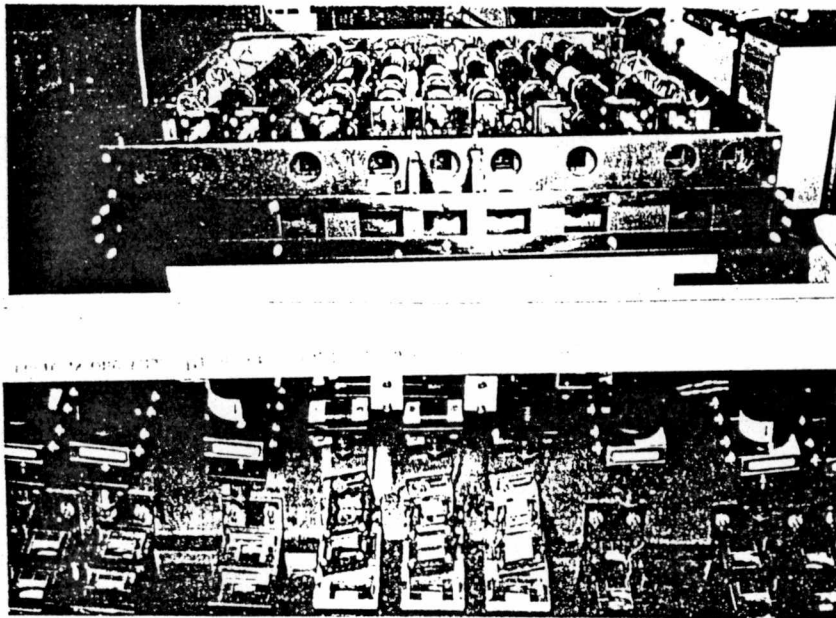


Figure III-2-4
LRLS HELIUM NEON LASERS AND PRISM ARRANGEMENT

Source: Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

LRLS STABILIZATION

Design Requirements

The LRLS stabilization platform is designed to compensate for ship motions up to sea state six and was designed and built by NAWCAD, Lakehurst. The optical head is attached to the platform and moves according to programmed platform position. Table III-2-3 lists the ship motion design criteria that it should be expected to compensate for. Real time ship motion and position information received from the Ship's Inertial Navigation System

Table III-2-3
LRLS DESIGN SHIP MOTIONS AND VELOCITIES FOR STABILIZATION

Ship motion	Design Motion Compensation	Maximum Velocity
Pitch	2.5° in a 10 sec period	1.57°/sec
Roll	12.0° in a 19 sec period	3.97°/sec
Yaw	2.0° in a 17 sec period	0.74°/sec
Sway	8.0 ft in a 17 sec period	2.96 ft/sec

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

(SINS) or MK-19 gyros, are input to the LRLS processor which determines the required pitch, roll, and yaw compensation. The processor signal is sent to the LRLS stabilization platform, which translates this electrical signal into mechanical platform motion. The pitch and roll stabilization is a one to one, input to output ratio. The system is designed to simply stay level with the horizon. More complex stabilization is required for yaw motion because this is a line-up VLA system.

Stabilization Methods

Two yaw stabilization methods were considered: point stabilization combined with yaw compensation, and yaw compensation alone that is currently used on with ICLS (Instrument Carrier Landing System discussed in the Instrumentation and Data Extraction section of this chapter). One of the goals of the LRLS simulation tests was to provide insight on the best yaw stabilization method and associated selection of time constants for the LRLS yaw stabilization algorithm.

Yaw Stabilization

The LRLS yaw stabilization implements an alpha filter similar to the current ICLS yaw stabilization. Ship yaw data is processed through an alpha filter with an internal limiter as presented in figure III-2-5. The filtered yaw error is then subtracted from the current ship yaw position. The alpha filter creates a lag in the LRLS yaw response to actual ship motion, thus filtering out yaw motion due to sea state conditions while still following ship turns. The limiter sets the maximum number of degrees that the LRLS centerline will lag behind the actual angle deck centerline. The response of the LRLS to ship yaw is primarily a function of the filter time constant. During large magnitude high rate ship turns, the limiter can be reached and will affect the LRLS stabilization response time.

Yaw with Point Stabilization

A second stabilization method proposed was the alpha filter with the addition of point stabilization as illustrated in figure III-2-6. In pure point stabilization, the object is to

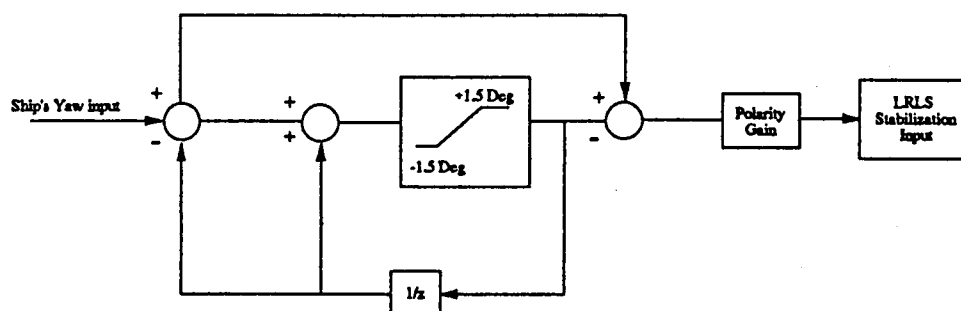
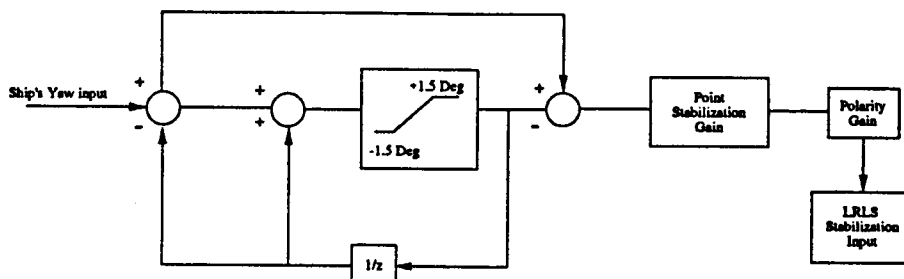


Figure III-2-5
LRLS YAW ALPHA FILTER STABILIZATION

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).



$$\text{Point Stabilization Gain} = \tan^{-1} \left| \frac{\sin(\Psi) D_L}{D_r} \right|$$

Where:

Ψ = Yaw angle.

D_L = Distance to the LRLS along ship centerline.

D_r = Distance to the stabilized point in space along approach.

Figure III-2-6
LRLS YAW WITH POINT STABILIZATION

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

"direct" the LRLS amber corridor to a stationary point in space such that the presentation, when viewed from this stabilized position, would appear fixed regardless of the ship motion. At ranges other than the point stabilized range, the corridor would be over-stabilized or under-stabilized depending on range.

LRLS TEST INSTALLATION

Shore Based

The goal of the shore based installation was to create the exact, relative dimensions of the flight deck visual presentation that would be encountered during shipboard flight tests.

The carrier box lights, shipboard version of the FLOLS and the LRLS was arranged as illustrated in figure III-2-7.

The LRLS optical head was installed by NAWCAD Lakehurst at Patuxent River on the centerline of the runway, 260 ft forward of the round-down of the simulated carrier deck. The simulated carrier deck consisted of centerline strobe lights, edge line lights, and fore and aft athwart ship lights that were very representative of current shipboard lighting configurations. The FLOLS was installed in a carrier-representative position on the left side of the carrier box, 100 ft left of centerline and 493 ft forward of the round-down. The entire presentation was "geometrically correct" when viewed from a 3.5° basic angle (F/A-18 H/E value was used in calculation)

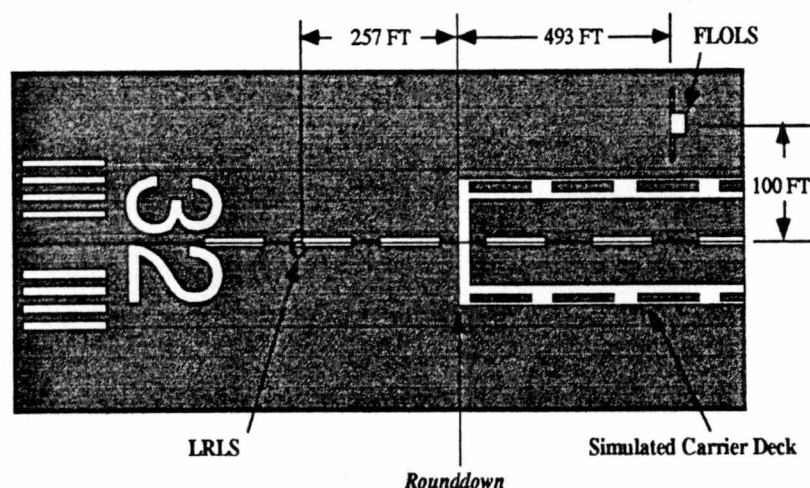


Figure III-2-7
SHORE BASED LRLS TEST INSTALLATION

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

The LRLS was placed on a mounting bracket that allowed for fine adjustments in alignment. The mounting bracket was first secured to the runway prior to each flight period in the identical surveyed position for repeatability, then the optical head was placed on top and secured. "Pole checks" were conducted to check the alignment of the LRLS optical presentation prior to each night's flight operations. Following completion of that evening's flight tests, the mounting bracket and optical head was removed to clear the runway to non-project air traffic.

Shipboard

Figure III-2-8 shows the shipboard LRLS location. The shipboard test installation consisted of the LRLS optical head mounted on the NAWCAD Lakehurst stabilization platform. The LRLS ADM was installed on the *USS THEODORE ROOSEVELT* (CVN-71) and the *USS GEORGE WASHINGTON* (CVN-73) and inspected by Lakehurst personnel. The LRLS was installed directly below angle deck centerline, coincident with the dropline lights, approximately 27 ft below the round-down.

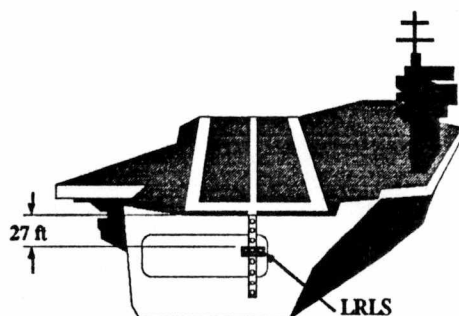


Figure III-2-8
SHIPBOARD LRLS TEST INSTALLATION

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

DESCRIPTION OF TESTS

This section contains a description of each of four test phases: Ground Tests, Simulation, Shore Based Flight Tests, and Shipboard Flight Tests.

GROUND TESTS

System Acceptance

Ground acceptance laboratory tests were performed by NAWCAD Lakehurst engineers to quantify system optical performance for comparison to design specification. These verified actual total horizontal and vertical coverage's, individual corridor horizontal coverage's, flash rates, and intensity.

Optical Performance Tests

Optical performance tests were conducted to evaluate the following categories:

1. Corridor spacing.
2. Existence of visual coverage dead zones.
3. Existence of overlapping corridors.
4. Orthogonality of corridors.
5. Existence of intensity variations.
6. Optical power of the system.
7. Wavelength of each laser.

Stabilization Tests

Stabilization tests were performed in the laboratory at NAWCAD Lakehurst facilities to evaluate the stabilization platform performance with the optical head attached. Simulated motion was input to the platform and the resulting motion was documented for later comparison to actual shipboard motion response.

SIMULATION TESTS

Simulation tests were conducted for a preemptive examination of those characteristics and maneuvers that would be evaluated during flight test. These objectives included:

1. Familiarize the pilots.
2. Validate the LRLS test scenarios.
3. Optimize the shipboard stabilization algorithm.
4. Optimize the LRLS presentation.
5. Evaluate the characteristics of both proposed stabilization schemes.
6. Optimize the stabilization time constant selection.
7. Evaluate the characteristics of various cut-off point distances.
8. Quantify maximum useful range.

Since some performance characteristics could not be altered on the ADM system, simulation was the only way to investigate degraded modes and failures. These objectives included examination of:

1. Degraded modes of operations.
2. Impact of ship environment on corridor widths selection.
3. Loss of corridors.
4. Stabilization failure, back-up modes.

Simulation was accomplished with the aid of the F-14 cockpit in the Patuxent River Manned Flight Simulator (MFS) and the MATLAB program on the Apple Macintosh personal computer. Fixed wing pilots participated in the simulation tests for a total of 78 simulated approaches and approximately 16 hours of flight simulation.

Literally hundreds of combinations of sea states, ship turns (performed at various distances from touch down), approach profiles and tasks were examined. The range of variables that were evaluated are listed in table III-2-4.

LRLS yaw stabilization time constants were evaluated for acceptable correlation between the LRLS and the shipboard landing systems by incorporating sinusoidal wave

Table III-2-4
SIMULATION SCOPE OF TEST

Time constants (sec)	10, 7, 5, 0
Sea state	Nominal, 5, 6
Ship's turn rate (°/sec)	0.1 to 0.2
Aircraft distance from touchdown (nm)	6 to 1 nm
Ship turn magnitude (°)	5 to 20

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

motion as well as ship turn maneuvers. Approaches were started between six to ten nm aft of the ship at 1200 ft altitude on final bearing. The pilot had PALS or ICLS needle information available on several approaches. The PALS or ICLS (described in the Instrumentation and Data Extraction section of this chapter) was yaw stabilized using a ten second time constant for the majority of the approaches. For several special test events the ICLS yaw stabilization time constant was set to five seconds. The LRLS was yaw stabilized using a first-order alpha filter with time constants ranging from five to ten seconds.

The three sea state conditions tested, presented in table III-2-5, were modeled by single sinusoidal yaw motion.

Table III-2-5
SEA STATE CONDITIONS

Sea State	Amplitude (°)	Frequency (cycles/second)
6	± 1.32	0.060
5	± 0.48	0.071
nominal	± 0.30	0.020

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

Ship turns consisted of right and left 10° turns at 0.1°/sec starting between 6.0 and 4.5 nm, right and left 20° turns at 0.2°/sec starting between 5.5 and 5.0 nm, and random ship turns within $\pm 5^\circ$ at 0.2°/sec activated from six into one nm. Various combinations of pure wave motion (no turns), pure turns (no wave motion) and combined wave motion and turns were evaluated.

FLIGHT TESTS

The test methods employed during both the shore based and shipboard portion of the test program were fairly detailed and lengthy. Each individual approach had specific objectives, approach profiles, and tasks. To make accurate comparisons, most of these tests were conducted with the LRLS ON and OFF for a given combination of profile, task and objective.

The approach profiles were basically the same as discussed in Part I, Chapter 1 (case 3 and bolter patterns). They were sometimes modified with ship turns during approach, ELA radiation and usage, and variations in deck lighting configuration. The tasks ranged from centerline capture to performing intentional deviations and re-corrections. The individual objectives were very detailed. "Determine the impact of current FLOLS presentation sensitivity on LRLS upper vertical coverage limit" is an example of one. These objectives fell into one of five basic categories:

1. System performance
2. Compatibility with ELA
3. Compatibility with VLA
4. Visual utility
5. Human Factors

Shore Based

Shore based tests were conducted to evaluate the optical presentation and provide a pilot buildup to the shipboard tests. A total of four fixed wing pilots and two rotary wing pilots were dedicated to the evaluation. These pilots accumulated a total of 99 night approaches during 20.4 flight hours. To expand the sample of pilot opinion and performance, fixed wing pilots from U. S. Naval Test Pilot School also participated in the shore based evaluation. These participatory pilots accumulated a total of 48 night approaches during 9.7 flight hours. In addition, familiarization flights for the test team personnel were conducted in a C-12 aircraft which flew a total of eight night approaches during 2.0 flight hours. Table III-2-6 lists the variety of aircraft and approach profile combinations.

Shipboard

Shipboard tests were conducted to evaluate the stabilized LRLS presentation, compatibility with current carrier visual and electronic landing aids, and validate

Table III-2-6
LRLS SHORE BASED SCOPE OF TESTS

Type of Approach	Number of Approaches				
	F/A-18	F-14	SH-60	A-6	Participatory A/C T-2, F/A-18, C-12
Without ELA assistance					
LRLS On	6	7	4	6	48
LRLS Off	7	8	—	2	10
Intentional Deviations	4	6	—	—	—
With ELA assistance					
LRLS On	11	13	—	—	—
LRLS Off	4	3	—	—	—
Intentional Deviations	6	—	6	—	—

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

conclusions drawn during shore based flight test. Only two test pilots (one flying an F/A-18 *HORNET* and the other an F-14 *TOMCAT*) were permitted to participate in the shipboard evaluation. These pilots accumulated a total of 88 night approaches and 17.9 flight hours during the shipboard evaluation. A shipboard 'scope of test' matrix is presented in table III-2-7. SH-3 and SH-60 helicopters were used initially to verify general operation before fixed wing flight test commenced.

Table III-2-7
LRLS SHIPBOARD SCOPE OF TESTS

Type of Approach	Number of Approaches			
	F/A-18	F-14	SH-3	SH-60
Without ELA assistance				
LRLS On	5	6	4	—
LRLS Off	—	2	—	—
Turns	—	—	—	3
Intentional Deviations	—	—	6	1
With ELA assistance				
LRLS On	17	19	—	—
LRLS Off	2	2	—	—
Ship Turns	8	8	—	—
Intentional Deviations- LRLS On	2	2	—	—
Intentional Deviations- LRLS Off	1	1	—	—

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

INSTRUMENTATION AND DATA EXTRACTION

PALS INSTRUMENTATION

One Electronic Landing Aid (ELA) at the pilot's disposal is the Instrument Carrier Landing System or ICLS (Navy designation: AN/SPN-41 for the shipboard version and AN/TRN-28 for the shore based version). It is very much like the civilian ILS. Azimuth and glide slope signals are radiated from antennas located on the ship. These signals are received by the aircraft, interpreted and displayed to the pilot as "needles" depicting the aircraft's relative position from optimum glide slope and centerline. If the aircraft is above glide slope and left of centerline, the needle position calls for "fly down, fly left." The ICLS system is stabilized in pitch, roll, and yaw to compensate for ship motion.

Another ELA system is the Precision Approach Landing Systems (PALS) which is basically a more precise ICLS. The Navy designation for the system is AN/SPN-42 (analog internal processing) or AN/SPN-46 (digital processing). From the pilot's perspective, both the SPN-42 and SPN-46 systems operate the identically. They are composed of a shipboard or shore-based, closed-loop radar tracking system and two-way electronic data-link system (ship-to-aircraft and aircraft-to-ship electronic communication). The radar system on the ship tracks the approaching aircraft's radar beacon in azimuth, elevation and range. Position data is up-linked to the aircraft, where it is electronically interpreted, and displayed to the pilot in the form of elevation and azimuth needles (aircraft high and left, needles display "fly down and right"). A unique characteristic of the PALS is that stabilization gain takes into account aircraft range. As aircraft range decreases, tolerable deviation from optimum decreases and needle presentation sensitivity increases. Very precise spatial information about the aircraft position can be attained from recording certain PALS parameters (providing ship motion effects, programmed glide slope, and programmed centerline are normalized).

The reader should keep in mind the basic difference between these two systems: ICLS is a passive, one-way ELA system and PALS is an active, two-way, very precise system. PALS and ICLS systems are located on every aircraft carrier and most major Naval Air Stations and are used extensively. During the test program, the test team instrumented the PALS systems with a PC based data acquisition system to record a variety of parameters to include actual aircraft position. Table III-2-8 lists those PALS and ship motion parameters measured during each flight phase of testing.

Aviators distinguish between the two systems by calling ICLS "bullseye" and PALS "needles." Since vast differences exist between the two, their names cannot be used

Table III-2-8
PALS AND STABILIZATION INSTRUMENTATION PARAMETERS

PALS		Shipboard Stabilization Parameters
Shore based	Shipboard	
Range (X)	Range (X)	LRLS pitch from the SINS
Lateral Position (Y)	Lateral Position (Y)	LRLS roll from the SINS
Lateral Error (Ye)	Lateral Error (Ye)	LRLS yaw from the SINS
Altitude (Z)	Altitude (Z)	LRLS pitch
Altitude Error (Ze)	Altitude Error (Ze)	LRLS roll
Elevation Summation	Heave of HTDP (Z11)	LRLS yaw
Azimuth Summation	DSS Pitch Angle	LRLS synchro outputs
	DSS Roll Angle	
	Ship Yaw	
	Centerline Yaw	
	Discrete Word 2	
	Discrete Word 3	
	Discrete Word 4	
	Elevation Summation	
	Azimuth Summation	

Source: Adapted from Honors, Owen P., et al., *Long Range Lineup System (LRLS) evaluation, Project Test Plan*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 2 Mar 1992, (Test Plan NO: 1246).

interchangeably. For clarity, throughout this discussion, "PALS" refers to the two-way data link precision approach system ("needles" provide the guidance) and ICLS refers to the passive (one-way) instrument approach system ("bullseye" provides the guidance).

SIMULATOR DATA EXTRACTION

A list of recorded simulation parameters is presented in table III-2-9.

Table III-2-9
RECORDED SIMULATION PARAMETERS

Ship Parameters	Aircraft Parameters	X, Y, and Z Positions
Heading	Pitch angle	X, Y, and Z position of pilots eye with respect to the touchdown point
Change in heading	Bank angle	X, Y, and Z position of pilots eye with respect to the LRLS
	Roll angle	X, Y, and Z position to a stabilized touchdown point
	Altitude	X, Y, and Z position to the ICLS elevation antenna
	Longitudinal stick position	X, Y, and Z position to the ICLS azimuth antenna
	Lateral stick position	X and Y position to CG of ship
	ICLS elevation needle	
	ICLS azimuth needle	
	Elevation to LRLS	
	Azimuth to LRLS	

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

AIRCRAFT INSTRUMENTATION

Aircraft were instrumented to record longitudinal and lateral stick position and throttle position for analysis of amplitude and frequency versus time. This data was also used to calculate a Frequency-Weighted Task Complexity Index, a measure of pilot workload. The intent of this data manipulation was to compare quantified pilot work, with and without the LRLS.

TEST RESULTS AND CONCLUSIONS

COMPATIBILITY WITH VISUAL LANDING AIDS (VLA)

Dropline Lights

LRLS compatibility with the aircraft carrier dropline lights was evaluated during standard carrier approaches aboard CVN-71 and CVN-73. During CVN-71 approaches by the SH-60F helicopter, pilots requested that the dropline light intensity be lowered so they could see the LRLS more clearly. The dropline configurations evaluated by fixed wing aircraft aboard CVN-73 are presented in table III-2-10. With the dropline lights ON, the LRLS was obscured by the dropline lights at all ranges eliminating its effective usage. By masking the first dropline light above and below the LRLS to provide separation between dropline lighting and LRLS presentation did not noticeably improvement the situation. Pilots reported no significant approach degradation when the dropline lights were turned OFF with the LRLS ON. In fact LRLS cueing of the LRLS was far superior to that offered

Table III-2-10
DROPLINE LIGHT CONFIGURATIONS TESTED ABOARD CVN-73

	Configuration
1	30% intensity
2	30% intensity with the first light above and below the LRLS masked
3	Off

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

by the dropline lights. Once this was determined, all test conditions that called for LRLS ON, dropline lights were OFF and those for LRLS OFF, drop lights were ON. The test team envisioned dropline light usage limited to only complete failures of the LRLS, fulfilling the back-up roll for line-up VLA cueing.

Another interesting characteristic of eliminated the dropline lights in favor of the LRLS was a reduction in the pilot's current perception of being above glide slope when really on glide slope. This can be partially attributed to the reduction in the apparent landing area elongation the dropline lights introduce. The landing area vertically subtends far less with the dropline lights OFF, which perspective cueing tells the pilot he is high.

Centerline Lights

LRLS compatibility with the centerline lights was evaluated during standard carrier approaches both shore based and shipboard. Centerline light configurations and test locations are presented in table III-2-11. During shore based flight periods nine and ten, the centerline strobe lights perceptually appeared to be originating from the same location as the LRLS while aircraft were at range. This characteristic obscured the LRLS at the beginning of the flashing sequence but was not evident as the strobe continued up the angle deck. Pilots felt that shore based approaches without the centerline strobes were easier than approaches with the centerline strobes.

During shipboard flight tests, helicopter pilots reported that the amber LRLS corridor blended in with the centerline strobe lights. However, during fixed wing flight tests, whether the centerline lights were steady or strobing had no effect on the pilot's ability to use the LRLS. Turning the first or the first and second centerline strobe lights OFF provided no significant difference from having all the lights ON. Pilots were able to receive useful information from the LRLS whether the centerline lights were steady or strobing

Table III-2-11
CENTERLINE LIGHT CONFIGURATION AND TEST LOCATION

Configuration	Test Location
Steady	Shore based flight periods 1-8 Shipboard (CVN-73)
Strobing	Shore based flight periods 9 and 10 Shipboard (CVN-71, CVN-73 flight periods 1-5)
Strobing with the first centerline light near the round-down turned off	Shipboard (CVN-73 flight period 2)
Strobing with the first and second centerline lights near the round-down turned off	Shipboard (CVN-73 flight period 2)

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

even though individual preference between the two configurations was divided. The test team concluded LRLS compatibility with centerline lights was satisfactory and left the strobing issue to individual Airwing preference. Since strobing provides a strong deterrent to pilot visual fixation on the round-down, strobing was recommended as the optimum configuration.

FLOLS and Remaining VLA

LRLS compatibility with the FLOLS and remaining VLA was evaluated during standard carrier approaches both shore based and shipboard. The FLOLS and remaining VLA were operated in their standard configuration with intensities adjusted to each pilot's preference. The LRLS was easily distinguishable from the carrier box lights and the FLOLS due to the brilliant color saturation of the LRLS corridors and the differences in location. For these reasons, the red low cell on the FLOLS could never be mistaken for the

red corridor of the LRLS, or vice versa. LRLS compatibility with the FLOLS and remaining VLA was satisfactory for night case 3 carrier operations.

VISUAL UTILITY

Visual utility of the LRLS was evaluated by flying approaches with and without the LRLS. Line-up acquisition, line-up performance and glide slope performance tasks were evaluated during visual and instrument approaches with the LRLS ON versus LRLS OFF. In all cases (with the exception of the F-14 shore based visual approaches), the LRLS improved lineup performance significantly. The higher percentage of time outside the amber corridor for the F-14 shore based visual approaches correlated with the FWTCI results and can be attributed to pilot adaptability and learning curve. The improved centerline acquisition and lineup performance of the LRLS, over that provided with current VLA, is an extremely enhancing characteristic.

OPTICAL SYSTEM PERFORMANCE

Flash Rates

LRLS laboratory flash rate test results are presented in table III-2-12. Transition between the fast flashing and slow flashing corridors (both red and green) was not easily distinguishable and required significant pilot attention to determine correct corridor position. It took a few flash cycles before the pilot could positively determine that corridor transition had occurred. Any delay in recognition resulted in delayed corrective action which was not optimal. The slightly ambiguous flash rate difference between slow and fast flashing corridors (both red and green) was an undesirable characteristic.

Table III-2-12
LRLS ADM LABORATORY DETERMINED FLASH RATES

CORRIDOR	Flash Rates (flashes/min)	
	Designed	Measured
Rapid Flashing Red	115	120
Slow Flashing Red	55	57
Slow Flashing Green	55	55
Rapid Flashing Green	115	126

Source: Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

Flash Patterns

Flash patterns (rate and coding) of the LRLS corridors were evaluated during all shipboard approaches. Both pilots misinterpreted the ship's helicopter anti-collision light for a flashing red LRLS corridor on a number of occasions before actually flying into the LRLS coverage. Spatial disorientation and confusion occurred initially when both a flashing red corridor and the ship's helicopter anti-collision light were in view ("which red light am I supposed to follow?"). Under the right condition, disorientation from this ambiguity could lead to loss of aircraft and crew. The test team felt this was a serious safety related problem that needed correction.

Following the conclusion of this test program, an assortment of alternate flash patterns were investigated in the simulator, by "flash-coding" each corridor separately (ie: three faster flashes, long pause, three faster flashes, short pause, etc.) which was effective in reducing this ambiguity. Given that the original flash pattern was not an option, preferred flash pattern was largely a matter of personal preference. The simplest way to eliminate confusion would be to change the color of the helicopter anti-collision light. A-6 *INTRUDERs* configured as tankers (airborne fueling stations) use green anti-collision lights

to distinguish themselves from other traffic. Perhaps a blue anti-collision light on the helicopter would solve the problem.

Intensity

Only the intensity of the solid corridors (red, amber, and green) were adjustable at discrete settings of 30%, 50%, 80%, and 100% intensity. Both green and red flashing corridors incorporated no intensity adjustment provision. Green corridor intensities were too dim for ranges outside of four nm during all shore based flights and during CVN-73 periods two, three, and four. Adjusting the flashing green corridor intensities prior to CVN-73 period five required opening the LRLS optical head and removing the tapered neutral density filters. This resulted in improved acquisition range, but was now far too intense at close ranges (the function of the neutral density filters). As discussed in Part I, environmental factors like moisture affect absorption and the "brightness" perceived by the pilot is not necessarily directly related to intensity of the source. The best way around these difficulties is to allow separate analog intensity control. By doing so, each individual corridor intensity, regardless of frequency or flash rate can be optimized individually. Inadequate provision for adjustment of each individual corridor intensity level reduced the effectiveness of the system.

Acquisition Range

Acquisition range of the LRLS was evaluated during all approaches (shore based and shipboard) by correlating pilot comments with range information. Acquisition range and meteorological conditions for each flight period are presented in table III-2-13. Acquisition range varied from 1.5 nm to 15 nm during shore based tests, and 8.5 nm to 20 nm during shipboard tests. The large variation in acquisition range was due to inherent laser

Table III-2-13
METEOROLOGICAL CONDITIONS AND LRLS ACQUISITION RANGES

Test Phase	Flight Period	Sky Condition (x100 ft)	Visibility (nm)	Rel. Humidity (%)	Acquisition Range (nm)
Shore	1, 2	10 SCT, 17 OVC	4 Fog	93	4.5
	3	7 SCT, 10 OVC	4 Fog/Haze	93	4.5
	4	7 SCT, 10 OVC	4 Fog/Haze Ground Fog	93	1.5
	5	20 SCT, 45 BKN	7 +	78	12-15
	6, 7	240 SCT	7 +	77	12-15
	8 - 10	30 BKN, 70 BKN	7 +	62	12-15
Ship	2	25 SCT, 80 BKN	7	95	9
	3	15 SCT, 25 SCT, 8 BKN	6 Fog/Haze	81	8.5
	4	10 SCT	3-5 Haze	No data	8.5
	5	CLR	7 +	No data	20

Notes: CLR - Clear (0% cloud coverage), SCT - Scattered (1-50% cloud coverage), BKN - Broken (51-99% cloud coverage), OVC - Overcast (100% coverage).

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

characteristics and environmental conditions. Laser light is easily defracted by haze and fog and does not penetrate moisture well. Higher ambient lighting during shore based flight tests in poor visibility (less than six nm in fog and haze) resulted in carrier VLA acquisition prior to LRLS acquisition. During shipboard flight tests (poor visibility included), the LRLS was consistently seen prior to other carrier VLA. During Visual Meteorological Conditions (VMC), the LRLS was acquired at ranges equal to the weather-reported visibility. In general, the LRLS allowed visual acquisition of the carrier at farther ranges than conventional VLA, which is a desirable characteristic for night case 3 carrier operations.

Total Horizontal Coverage

Design and actual horizontal coverage (measured by NAWCAD Lakehurst) are presented in table III-2-14. Pilots flew into the LRLS coverage after completing the turn to base in the bolter pattern. Individual corridor coverage's was wide enough to provide good feedback to the pilots of approaching centerline during turns to final and intentional offset corrections. Once inside the LRLS coverage, the pilots only exited the coverage intentionally to achieve a specific approach objective. In fact, pilot' anticipation of visually acquiring the system was so high that each began searching for it even before the turn to base leg was complete.

Amber Corridor Horizontal Coverage

Desirable amber corridor width was a compromise between sensitivity and performance. If width is too wide, the system provides no increased assistance with line-up control and lets the pilot deviate significantly before alerting him (under-sensitive, poor task performance). If it is too narrow, the pilot must neglect other tasks to maintain

Table III-2-14
DESIGN AND ACTUAL HORIZONTAL COVERAGE

CORRIDOR	Coverage (degrees)	
	Designed	Measured
Rapid Flashing Red	6.0	6.140
Slow Flashing Red	4.0	3.742
Steady Red	0.6	0.598
Amber	0.4	0.437
Steady Green	0.6	0.777
Slow Flashing Green	4.0	3.960
Rapid Flashing Green	6.0	5.930

Source: Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

unreasonably strict performance criteria (over sensitive, task over-performance).

Somewhere between "too narrow" and "too wide" is a width that balances good sensitivity to reasonable performance deviations.

During shore based flights, amber corridor width appeared satisfactory: once outside the amber corridor, pilots made rapid corrections back to centerline and considered work load versus performance acceptable.

Significantly higher pilot gain and sensitivity to smaller approach deviations during shipboard tests affected acceptable amber corridor width significantly. As shipboard flight tests continued and the pilots gained a level of confidence with the system, their reactive sensitivities to the visual presentation also changed. As soon as the aircraft moved outside of the amber corridor (saw amber changed to red or green), pilot attention was immediately given to correcting line-up deviation. Actual position registered by the PALS system instrumentation, although measurable, was very small and certainly not significant.

The system was doing a dramatic job eliciting a response from the pilots (good sensitivity) but for unrealistically small deviations (task over-performance). The LRLS was causing the pilots to overreact to insignificant line-up deviations that increased overall pilot workload. A slightly wider corridor would reduce frequency of pilot reaction without significantly degrading line-up performance, thereby reducing workload. The narrow horizontal coverage of the amber corridor degraded the system's effectiveness by increasing pilot workload to achieve unnecessarily precise line-up performance.

Following the completion of the test program, follow-on simulation tests were conducted to determine just how much to widen the corridor. Since simulation did not reveal this deficiency in the first place, it was unlikely the test team could determine the answer with confidence. From these simulation tests it was estimated that increasing the width by about 30% should achieve the desired work load reduction without a significant degradation in line-up performance.

Vertical Coverage

Design and actual vertical coverage (measured by NAWCAD Lakehurst) are presented in table III-2-15. Actual vertical coverage was within 6% of the design coverage. During shipboard EMCON approaches, inbound at 2400 ft, the aircraft flew out of the LRLS vertical coverage at approximately four nm, about the same time the aircraft nose blocks the ship from the pilot's view. During standard carrier approaches, the aircraft consistently remained within the LRLS vertical coverage during normally encountered deviations in glide slope. Reflections off the water were not observed during shipboard tests. The vertical coverage of the LRLS provided adequate boundaries above and below the glide slope and was considered satisfactory for night case 3 carrier operations.

Table III-2-15
DESIGN AND ACTUAL VERTICAL COVERAGE

CORRIDOR	Coverage (degrees)	
	Designed	Measured
Rapid Flashing Red	5.0	4.99
Slow Flashing Red	5.0	5.00
Steady Red	5.0	5.12
Amber	5.0	4.86
Steady Green	5.0	5.07
Slow Flashing Green	5.0	4.69
Rapid Flashing Green	5.0	5.17

Source: Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

Color Transition

The LRLS was evaluated for distinct color transition between the amber/steady red and the amber/steady green corridors. During shore based periods one and two, the amber/steady green corridors blended together at range (corridor overlap). During shore based period five and shipboard tests, the amber/steady red corridor blending was observed only at range. Transition between the amber/steady red and amber/steady green corridors was not distinct when blending occurred. Blending of amber/steady red and amber/steady green corridors slightly delayed the pilot's recognition of corridor transition and subsequent correction. Indistinct corridor transition was annoying when observed should be avoided in follow-on designs.

Coverage Continuity

The LRLS corridors were evaluated for continuous coverage during all approaches. During shore based period five, a dead zone (or gap) existed between the rapid flashing red and the slow flashing red corridors at approximately six nm. During shipboard tests, a dead zone existed between the steady red and amber corridors at range. Dead zones in LRLS corridors affected the pilots more than blending zones. The pilot's first inclination was, "The LRLS is no longer ON," followed by, "Have I flown completely out of the horizontal coverage?" These dead zones were not large but illustrated the possible confusion and hesitation when encountered. Discontinuity of LRLS corridors should be eliminated in future designs.

Reduced Intensity

Reduced intensity of the LRLS was observed during CVN-73 period four. Prior to period four, the LRLS 12 V AC power supply failed. A back-up power supply was not incorporated in the LRLS design. A 12 V/300 amp-hr lead acid cell battery from the ship's

supply was used to provide power to the LRLS during period four. The ship's battery was not fully charged resulting in a failure of one of the four fast flashing red lasers, one of the two slow flashing red lasers, and two of the four fast flashing green lasers. The laser failures resulted in reduced intensity of the fast flashing red, slow flashing red, and fast flashing green corridors respectively. Redundant lasers in each corridor helped to limit the loss of the entire corridor but still, pilots perceived degraded system presentation with diminishing battery power. This resulted in indistinct corridor transitions and left the pilots, once again doubting their position.

Corridor Blanking

The issue of corridor blanking is different than dead zones, in that the entire corridor is no longer illuminating as opposed to a gap in coverage. The same cause for reduced intensity eventually led to the entire corridor to shut down: the ship's battery was not fully charged resulting in a total loss of the slow flashing green corridor. Loss of this corridor was incorrectly interpreted by the pilots as flying completely out of the LRLS coverage. The pilot, having made an aggressive correction, overshot approach centerline more confused than when the correction was initiated. Confusion is the last thing that a pilot can tolerate in such a demanding environment and can possibly result in the loss of aircraft and crew. Having only evaluated a particular corridor, it cannot be confidently determined that the loss of a different corridor would have the same effect. If system design does not permit single corridor blanking (perhaps by complete system shut down with a single corridor failure), the issue becomes one of reliability instead of safety. Suffice to say, corridor blanking was a serious, safety related design deficiency that needed to be corrected.

Cut-off

LRLS cut-off distances between 0.25 and 0.70 nm were evaluated for optimum position and compatibility with current VLA during shipboard and shore based flight tests. LRLS cut-off as close as 0.25 nm provided peripheral lineup information inside the "ball call" and did not detract from the pilots normal VLA scan pattern.

Significantly higher pilot gain and sensitivity to smaller approach deviations during shipboard testing affected acceptable cut-off position significantly. Continued LRLS illumination inside the "ball call" competed with other VLA for the pilot's attention. Color change inside 1/2 nm were common with acceptable lateral deviations (narrowing corridor widths) and dangerously drew the pilot's attention to the round-down. Cut-off ranges outside 0.65 nm prematurely removed useful information. Optimum cut-off during at sea testing was 0.60 nm to 0.65 nm and resulted in cut-off shortly after the pilot's "ball call."

It should be pointed out that if basic angle is changed to compensate for higher than normal recovery wind conditions, cut-off distance will change also. Moving from 3.5° to 4.0° will cause the pilot to fly out of the top coverage earlier (which is considerably better) than later.

Residual Lighting After Cut-off

Actual cut-off was distinct and clear as was anticipated. As the approach continued a few seconds inside the cut-off range, the pilot could see residual lighting from all of the corridors simultaneously. The conglomeration of red, amber, and green lights blinking in the pilot's field of view was very distracting and borderline dangerous. At this point in the approach, this is the last place the pilot should be looking. The residual lighting was perceived as more intense and far more distracting during the shipboard testing than it was shore based. All pilots strongly objected to the residual lighting after cut-off as it competed

for pilot attention that must be reserved for other VLA. Residual lighting after cut-off was a serious design deficiency that needed correction.

STABILIZATION SYSTEM PERFORMANCE

Computer Analysis

The alpha filter yaw compensation algorithm and the same alpha filter yaw compensation algorithm with the addition of point stabilization were evaluated for stabilization compensation using the "MATLAB" computer program. A sinusoidal input corresponding to the three sea state conditions (nominal, five and six) was used with the response of the modeled yaw filters as output. To determine which filter best compensated for yaw motion, the percentage of time that the LRLS did not display amber when the pilot was on centerline was calculated. The results of these calculations are presented in table III-2-16. The percentage of time that the LRLS did not display amber while the pilot was on

Table III-2-16
COMPUTER ANALYSIS OF STABILIZATION PERFORMANCE

Sea State	Constant Time (sec)	Percentage of time LRLS not displaying amber while pilot is on center line	
		Yaw Filter	Yaw Filter + Point
6	10	60.0	59.7
6	7	73.6	73.6
6	5	79.8	77.7
5	10	0	0
5	7	0.3	0
5	5	6.7	0.9
nominal	10	1.3	1.4
nominal	7	32.1	33.8
nominal	5	43.7	43.5

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

centerline was slightly higher for the yaw filter with the addition of point stabilization than it was for the yaw filter alone. Ship turns were input into the modeled yaw filters to determine response time. The yaw filter with the addition of point stabilization had a greater response time than the yaw filter alone. The addition of point stabilization to the alpha filter yaw compensation degraded the performance of the alpha filter. The alpha filter yaw compensation algorithm currently used in the ICLS system showed the best potential for night case 3 carrier operations.

Flight Simulation

Flight simulation confirmed computer analysis that straight alpha filter yaw stabilization was the preferred compensation algorithm. Three time constants were evaluated using the F-14 cockpit: ten, seven, and five seconds. The ten and five second yaw stabilization time constants were evaluated in sea state six, sea state five, and nominal sea state while the seven second time constant was evaluated in sea state five only.

Sea State Six

The LRLS yaw stabilization was evaluated for its operational effectiveness during sea state six with two time constants: ten and five seconds. The LRLS presentation alternated between the amber, red, and green corridors for all time constants evaluated when there was no associated aircraft lateral deviation from centerline. Although the LRLS provided a point light source indicating the ship's general direction, the pilot found the alternating color presentation annoying. The pilot preferred the lower time constants in close, once the carrier deck was in view, because the LRLS more closely matched the ship's approach centerline. However, the rapid corridor changes seen during sea state six caused the LRLS to be un-flyable, giving only an indication that deck motion was present. A larger time constant with its associated increased lag of the LRLS presentation to the ship's approach

centerline, or a wider amber corridor would be required to dampen out the rapid corridor changes in sea state six. Pilot comments indicated that sea state six was an unrealistic design target based on the tradeoffs which would have to be made to make the system usable in sea state six. The LRLS system as currently configured, could not be satisfactorily stabilized during sea state six conditions. The test team recommend the LRLS not be operated during sea state six conditions.

Sea State Five and Nominal

The LRLS yaw stabilization was evaluated for its operational effectiveness during sea state five and nominal sea state conditions. In sea state five, the LRLS presentation appeared steady outside of four nm for the ten and seven second time constants. A slight bouncing effect of the LRLS corridors was seen outside of four nm for the five second time constant in sea state five. In this situation, pilot compensation in the form of mentally averaging the presentation was required to determine line-up position, but the LRLS was usable. In the nominal sea state conditions, all time constants evaluated provided a steady LRLS presentation outside of four nm. Inside of four nm, when the carrier deck was in view, the LRLS lagged the ship's approach centerline in all sea states evaluated for the seven and ten second time constants. The five second time constant provided satisfactory correlation between the LRLS and the ship's approach centerline. Although a smaller time constant would more closely match the carrier deck presentation, the resulting increased rate of alternating LRLS corridors would be objectionable. The five second time constant was viewed as the best compromise between long range stability while maintaining acceptable correlation, and showed the best potential for optimum at sea performance.

Compatibility with ELA

Compatibility between the LRLS and the ICLS needle presentations was evaluated in the simulator by flying approaches with and without ship motion. A ten second and five second time constant were used for the ICLS. Approaches with a ten, seven, and five second yaw stabilization time constant were evaluated. Additionally, approaches were flown with the LRLS caged to the deck (0 second time constant). Pilots flew the LRLS presentation, and cross-checked with the bullseye. When the same time constant was used for the LRLS and ICLS yaw stabilization, deviations from centerline were first noted by LRLS color change, with the ICLS bullseye providing useful rate information. When the ICLS time constant was slower than that of the LRLS, conflicting guidance information was given. A graph showing the effect of the ICLS with a time constant of ten seconds and the LRLS with a time constant of five seconds after the completion of a $0.2^\circ/\text{sec}$ turn is presented in figure III-2-9.

With the aircraft positioned as shown in figure III-2-10, the LRLS gives a "fly left" presentation, while the needle presentation indicates "fly right." The actual pilot action should be to fly left. The conflicting guidance information given when the ICLS time constant was slower than the LRLS time constant was an annoying characteristic. Conflicting guidance information caused confusion and loss of actual centerline position awareness. Additionally, pilots initiated the wrong correction, more than once, resulting in excessive, unacceptably large corrections close to touch down.

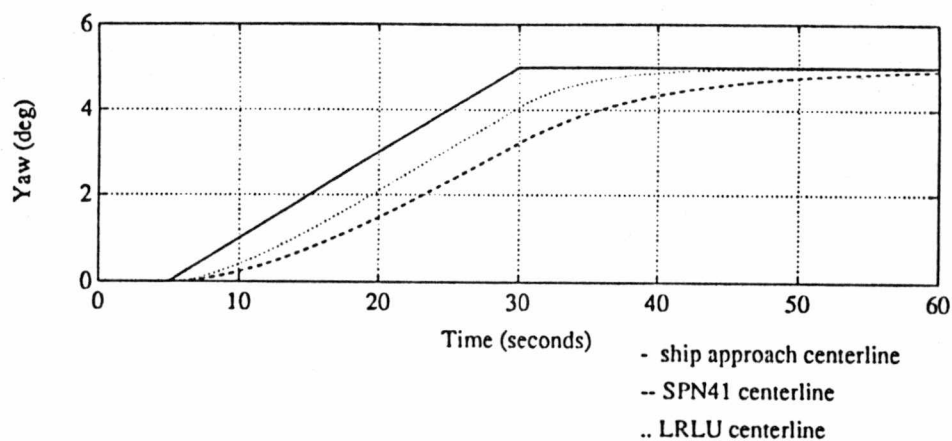


Figure II-2-9
ICLS AND LRLS RESPONSE TO SHIP TURNS

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

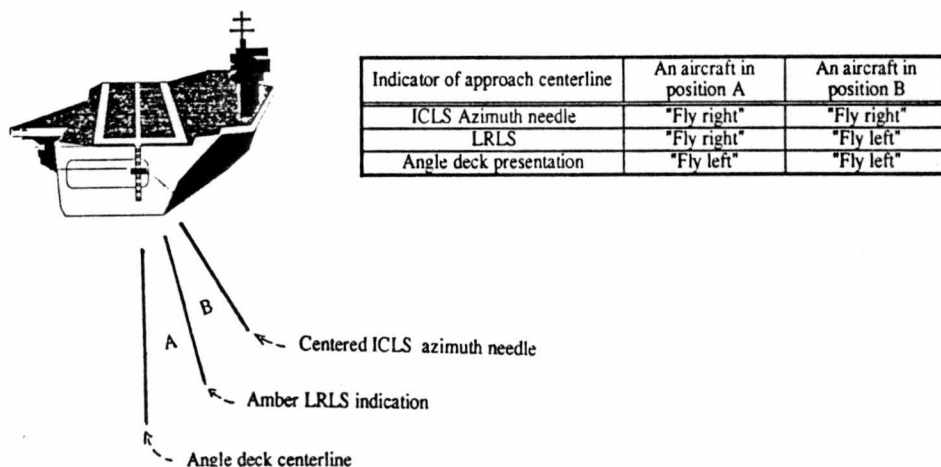


Figure III-2-10
CONFLICTING LRLS AND ICLS GUIDANCE INFORMATION

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

The reader might think that the visual presentation of the carrier deck would settle the question, "Where is centerline?" As discussed in Part I, Chapter 3, when conflicting information is presented, a perceptual decision has to be made, and this decision is sometimes made in error (Gregory). Data indicated that "visual" presentation is always believed over "electronic" presentation. Furthermore, when several conflicting "visual" cues are available, the decision as to which is correct, is disconcerting, difficult to make and is sometimes made in error. Large guidance disparities between two VLA systems are neither tolerable nor easily reconcilable.

Shipboard Flight Tests

Back-up Mode of Operation

The LRLS yaw stabilization back-up mode of operation was evaluated during *USS ROOSEVELT* (CVN-71) SH-60 flight tests. The stabilization failed prior to flight tests resulting in temporary caged operation (LRLS fixed to the carrier deck). A graph of the LRLS yaw synchro output compared to the theoretical yaw output during this failure is graphically illustrated in figure III-2-11. The stabilization failure occurred because the LRLS software did not take the $\pm 5.0^\circ$ yaw synchro input limits into account. Average ship motion during caged operation was 0.31° pitch, 0.15° roll, and 0.19° yaw. CVN-71 SH-60 flights consisted of approaches against the LRLS while the ship conducted turns. The ship conducted left and right 10° turns at $0.2^\circ/\text{sec}$ once the helicopter was established on centerline. Turns were stopped prior to the aircraft reaching one nm from touchdown. Helicopter pilots were able to use the LRLS outside of two nm without accurate yaw stabilization. Inside of two nm, difficulty keeping up with the LRLS presentation became impossible as corridor transition occurred frequently. Without proper stabilization, even though the utility of the LRLS was degraded, its use at range was still desirable. The

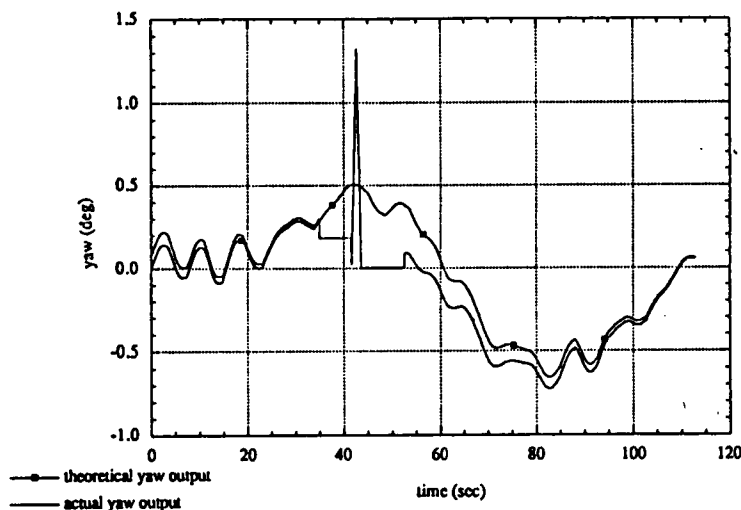


Figure III-2-11
YAW STABILIZATION FAILURE PERFORMANCE

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

software error was corrected prior to CVN-73 flight tests and stabilization errors were not encountered during fixed wing flight tests. Although simulation indicated LRLS usage with a caged presentation was possible during nominal sea state conditions, it was inconclusive if the yaw stabilization back-up mode of operation is satisfactory for fixed wing night case 3 carrier operations.

Pitch and Roll Compensation

The LRLS pitch and roll stabilization performance was evaluated during CVN-73 flight tests. Graphs of actual LRLS output versus input for pitch and roll platform motion are presented in figure III-2-12 and III-2-13 respectively.

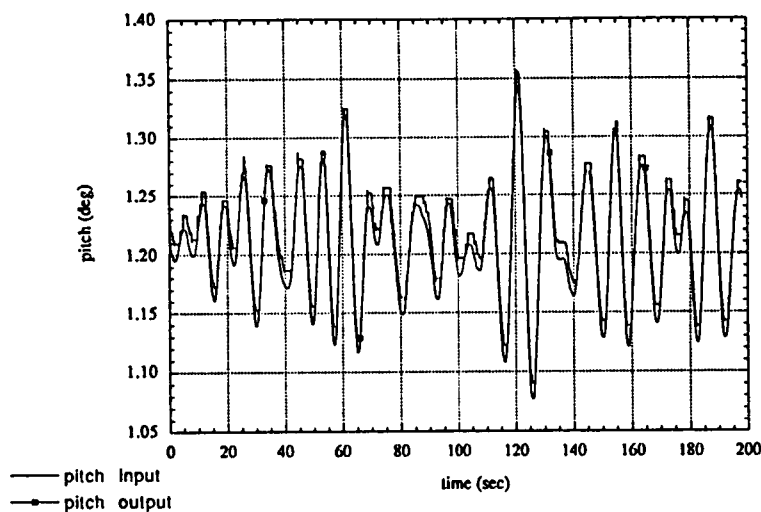


Figure III-2-12
PITCH STABILIZATION PLATFORM PERFORMANCE

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

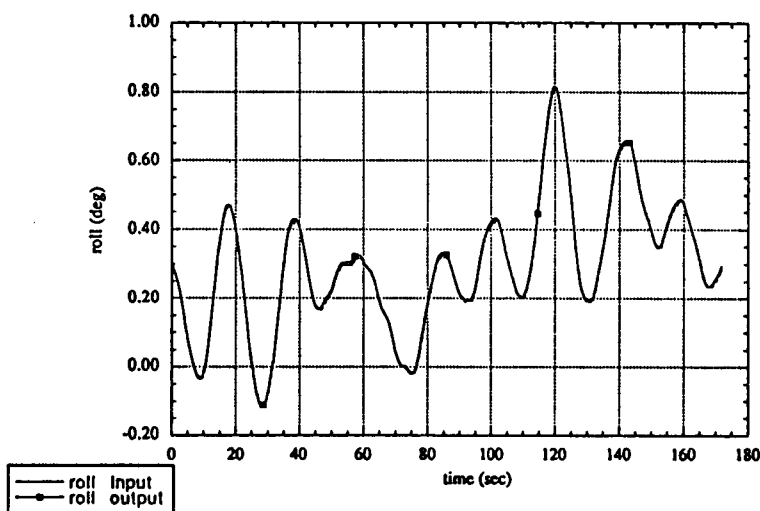


Figure III-2-13
ROLL STABILIZATION PLATFORM PERFORMANCE

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

The LRLS pitch and roll stabilization performed correctly during the entire CVN-73 at sea period and provided an LRLS presentation unaffected by pitch and roll motion, which was considered satisfactory for night case 3 carrier operations.

Yaw Compensation

As a result of simulation tests, the CVN-73 tests evaluated the ten, seven, and five second yaw stabilization time constants by conducting left and right 10° ship turns at 0.2°/sec. Ship turns were initiated when the aircraft was inbound on final bearing at four to six nm and again at eight to ten nm. Actual yaw output versus theoretical yaw output for each yaw stabilization time constant evaluated was nearly identical and performed as predicted by simulation tests. The ten second time constant caused the LRLS to lag the ICLS bullseye when the ship came out of a turn. The seven second time constant seemed to match the bullseye, and the five second time constant seemed to lead the bullseye when the ship came out of a turn. As predicted by simulation tests, the lag between the ICLS bullseye and the LRLS when using the ten second time constant was disconcerting to the pilots. Both the seven second and the five second time constant needle correlation, although not ideal, were acceptable during ship turns. The LRLS yaw stabilization filtered out yaw motion and allowed the pilot to follow the ship through a turn.

Visual correlation with the carrier deck was most closely matched with the five second time constant. Actual sea state during flight test was significantly less than those examined in the simulator which did not allow evaluation of large disparities between the LRLS and deck presentation (two competing and conflicting VLA presentations). The LRLS yaw stabilization using a five second time constant was considered satisfactory under the sea state conditions tested and the test team recommend the five second time constant be used in the LRLS yaw stabilization algorithm.

COMPATIBILITY WITH ELECTRONIC LANDING AIDS (ELA)

F-14 TOMCAT

Compatibility with ELA was evaluated during shore based and shipboard instrument approaches by flying "head-up" and "head-down" approaches using the LRLS, ICLS, and PALS. The LRLS was preferred over bullseye or needles for centerline acquisition especially at long range. The LRLS was very effective in the turn to base leg by assisting the pilot with initial centerline capture. However, the scan between the LRLS and the bullseye was difficult because the F-14 TOMCAT does not have primary attitude information on the "Head-Up Display," or HUD. The pilot had to go head-down for glide slope information (located in the cockpit) and head-up for LRLS lineup cues. As shown in figure III-2-14, the pilot was able to stay within the amber corridor region better without

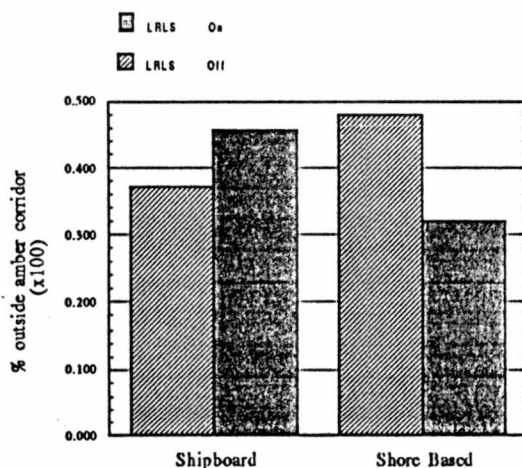


Figure III-2-14
PERCENTAGE OF TIME F-14 OUTSIDE AMBER CORRIDOR DURING
INSTRUMENT APPROACHES

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

the LRLS than with the LRLS during shipboard instrument approaches because scan time was divided between significantly different locations.

Widening the amber corridor may provide some workload reduction in maintaining line-up by allowing more pilot attention to glide slope control (see Amber Corridor Width discussion). Providing an adequate long range glide slope VLA system would also eliminate the need for inside-outside scan complications. With the exception of the F/A-18 *HORNET*, all presently operational aircraft display ELA guidance information "head down." Re-configuring all naval aircraft with a HUD is not a practical solution for obvious reasons. The high workload, caused by significantly different scan locations of the LRLS and the ELA glide slope indicator, detracted from compatibility.

F/A-18 *HORNET*

Compatibility with ELA was evaluated during shore based and shipboard instrument approaches by flying head-up and head-down approaches using the LRLS, ICLS, and PALS. The F/A-18 has primary attitude information on the HUD so ELA glide slope information was collocated with LRLS line-up information. As shown in figure III-2-15, line-up performance was significantly better during instrument approaches with the LRLS than for instrument approaches without the LRLS. The same results were obtained for the F/A-18 as were obtained for the F-14 when restricted to head-down ELA scan: overall approach performance degraded when scan location was significantly different. LRLS compatibility with ELA for HUD equipped aircraft was acceptable.

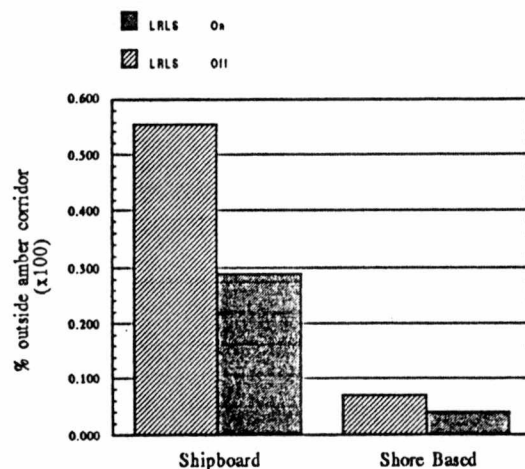


Figure III-2-15
PERCENTAGE OF TIME F/A-18 OUTSIDE AMBER CORRIDOR DURING
INSTRUMENT APPROACHES

Source: Adapted from Nielsen, Wesley S., et al., *Technical Evaluation of the Long Range Line Up System Advanced Development Model*, Patuxent River, MD.: Flight Test and Engineering Group, Strike Aircraft Test Directorate, 25 Apr 1993, (Report NO: SA-7R-93).

CREW COORDINATION

Crew coordination while flying with the LRLS was evaluated during shore based visual approaches with the A-6 *INTRUDER*, which is a side-by-side cockpit arrangement (F/A-18 is single seat and the F-14 is tandem seating). Air crew found that during their approaches with the LRLS, the normal division of cockpit duties changed. Normally the pilot monitors altitude, Angle of Attack (AOA) and line-up while the Bomber/Navigator (B/N) concentrates on line-up, scans the flight instruments and calls any significant deviations or unrecognized trends. During the level leg portion of approaches with the LRLS, the pilot concentrated on maintaining altitude and airspeed while re-configuring the airplane for landing, while the B/N issued line-up corrections. After glide slope intercept,

the air crew found it easier for the pilot to concentrate on lineup control while the B/N provided descent speed and glide slope calls. This division of cockpit duties is very different from the currently accepted method. Due to scheduling and funding constraints, the test team was unable to evaluate this issue during at sea tests. The test team recommended that the next phase of flight testing for the follow-on LRLS design include an aircraft with side-by-side seating to investigate this issue more thoroughly.

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VITA

Wesley Scott Nielsen was born in the Northern California, San Francisco Bay Area on March 23, 1961. He attained his Private Pilot license in Venture California at the age of 18 and graduated from Beuna Vista High School the following month in 1979. He attended Jacksonville University in Florida under a full NROTC scholarship, and graduated in April 1983 with a dual Bachelor of Science degree in Physics and Psychology, with minors in Mathematics and Naval Science.

He received a commissioned in the United States Naval Service and after two years of flight training, earned his "wings of gold" in July 1985. His first assignment was as a Basic Jet flight instructor in VT-26 flying the T-2C *BUCKEYE*. In April 1986 he joined the "Strike-Fighter" community in Lemoore California flying the newest naval aircraft, the F/A-18 *HORNET*. While assigned to VFA-113, he made two Western Pacific/Indian Ocean deployments and participated in operation Desert Shield. In January 1991, he attended the U. S. Naval Test Pilot School in Patuxent River, Maryland. Following completion, he was assigned to the Strike Aircraft Test Directorate where his flight test area of expertise was Carrier Suitability.

Wes has logged over 2420 total flight hours, 2260 of high performance jet time and over 1110 in F/A-18 *HORNETS*. He has flown more than 28 different aircraft including dual and four engine propeller aircraft, Gliders, Biplanes and Helicopters. He has operated from the flight deck of 13 different carriers, logged more than 670 carrier landings and is an Airwing qualified LSO. Wesley Nielsen is a member of the international Society of Experimental Test Pilots and has recently been selected as a finalist for the NASA space shuttle program.