DOT/FAA/AM-21/20
Aviation Safety
Office of Aerospace Medicine
Washington, DC 20591

Approach Lighting Systems in the U.S. National Airspace System and Flight Performance During Low Visibility Instrument Approach and Landing Operations: A Literature Review

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July 2021

This project is funded by the FAA NextGen Human Factors Division (ANG-C1) in support of the FAA Office of Aviation Safety (AVS), Flight Standards Service (AFS-400).

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-21/20		

4. Title and Subtitle	5. Report Date
Approach Lighting Systems in the U.S. National Airspace System and Flight Performance During Low Visibility Instrument Approach and Landing Operations: A Literature Review	July 2021
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Kelene A. Fercho	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Civil Aerospace Medical Institute, FAA	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Approach lighting systems provide the bridge for the transition from instrument flight to visual see-to-land operations, and are critical to safety. However, they are expensive to install and maintain, and may not feasible for all runways due to terrain restrictions or the availability of undeveloped land. This report provides a review of the approach lighting systems in the U.S. National Airspace System, approach lighting system components, and desired visual guidance. Additionally, research on approach lighting systems conducted by the FAA and others is summarized. Major themes of this research include investigating the effects of modifying characteristics such as the pattern, size, lighting density, and individual lighting components on safety and flight performance. More recently, there has been a focus on in-cockpit technologies, such as head-up displays or advanced vision technologies, and their ability to supplement the visual cues provided by an approach lighting system during low visibility flight operations.

17. Key Words	18. Distribution Statement
Approach lighting systems, Instrument procedures, Approaches, Landings, Low-visibility operations, Airfield lighting, Pilot performance	Document is available to the public through the Internet: (http://www.faa.gov/go/oamtechreports/)

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	70	

Acknowledgements

The author wishes to acknowledge and thank the sponsors of this research, Matt Harmon, Doug Dixon, James Tittinger, Chris Hope, and Janet Greenwood, and the program manager, Dr. Chuck Perala, for their helpful feedback. The author also wishes to thank Terry King, Mark Humphreys, Janine King, Dr. Peter Hu, Dr. Jeff Dressel, Dr. Tom Nesthus, and Dr. Carla Hackworth for their excellent feedback on previous versions of this document.

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List of Abbreviations

Abbreviation	Term
ALS	Approach Lighting System
ALSF-1	Approach Lighting System with Sequenced Flashing Lights configuration 1
ALSF-2	Approach Lighting System with Sequenced Flashing Lights configuration 2
ASALS	All-Strobe Approach Lighting System
BALS	Basic Approach Lighting System
CAT I	Category I Operation
CAT II	Category II Operation
CAT III	Category III Operation
CFIT	Controlled Flight Into Terrain
CL	Centerline Lights
DA	Decision Altitude
DH	Decision Height
EFVS	Enhanced Flight Vision System
FAA	Federal Aviation Administration
FALS	Full Approach Lighting System
GS	Glideslope
H	Height
HDD	Heads-Down Display
HIRL	High Intensity Runway Lights
HUD	Head-up Display
IALS	Intermediate Approach Lighting System

Abbreviation	Term
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
JFK	John F. Kennedy International Airport
LDIN	Lead-in Light System
LIRL	Low Intensity Runway Lights
LOC	Localizer
MALS	Medium Intensity Approach Lighting System
MALSF	Medium Intensity Approach Lighting System with Sequenced Flashers
MALSR	Medium Intensity Approach Lighting System with Runway Alignment Indicator Lights
MDA	Minimum Descent Altitude
MIRL	Medium Intensity Runway Lights
MSO	Missoula International Airport
NALS	No Approach Lighting System
NAS	National Airspace System
ODALS	Omni-Directional Approach Lighting System
PAPI	Precision Approach Path Indicator
RAIL	Runway Alignment Indicator Lights
REIL	Runway End Identifier Lights
RVR	Runway Visual Range
SA	Special Authorization
SALS	Short Approach Lighting System

Abbreviation	Term
SALSF	Short Approach Lighting System with Sequenced Flashers
SPALS	Shortened Precision Approach Lighting System
SSALF	Simplified Short Approach Lighting System with Sequenced Flashers
SSALR	Simplified Short Approach Lighting System with Runway Alignment Indicator Lights
SSALS	Simplified Short Approach Lighting System
SVS	Synthetic Vision System
TDZ	Touchdown Zone
TDZL	Touchdown Zone Lights
U.S.	United States
VASI	Visual Approach Slope Indicator
VFR	Visual Flight Rules

1. Introduction

It is generally accepted that flight in Instrument Flight Rules (IFR) conditions is associated with increased pilot fatigue and workload (Wilson & Hankins, 1994), and the phase of flight most affected by fatigue is approach and landing (Rosekind et al., 2000). In particular, IFR approaches are especially risky during low or restricted visibility conditions, such as operations at night or with obscuring media such as fog (Bennett & Schwirzke, 1992). Further, more than half of controlled collisions during instrument approaches occur within two miles of the airport, suggesting problems with the transition from instrument flight to a visual landing (Bennett & Schwirzke, 1992). In an analysis of accidents that occurred between 2008 and 2017 involving worldwide commercial jet airplanes heavier than 60,000 pounds maximum gross, Boeing (2017) reported that 49% of all fatal accidents occurred during the final approach and landing phase of flight, even though this phase accounts for only 4% of flight time exposure.

The increased risk associated with low visibility approach and landing operations suggests a need for ongoing research into the role that both in-cockpit technology and airport infrastructure, such as Approach Lighting Systems (ALSs) and runway lighting, play in flight performance and safety. ALSs, in particular, provide the bridge for the transition from instrument flight to visual see-to-land operations, and are critical to safety. However, ALSs are expensive to both install and maintain, and are not feasible at all airports due to the required real estate, environmental concerns, or terrain restrictions. The Federal Aviation Administration (FAA) has an interest in evaluating the role that ALSs play in safety and performance during low-visibility approach-to-land operations, particularly as recent developments in advanced vision technologies—which may provide similar or additional visual guidance—increasingly become available.

Currently, regardless of approach category (i.e., Category I, II, or III), low visibility approach and landing operations require significant runway and airport infrastructure, which limit low visibility operations to those airports which have the requisite infrastructure. For example, for fixed wing aircraft, to perform a Category I (CAT I) approach below Decision Height (DH), one of the following ten visual references for the intended runway to land are required (see 14 CFR 91.175):

- The approach light system, except that the pilot may not descend below 100 feet above the touchdown zone elevation using the approach lights as a reference unless the red terminating bars or the red side row bars are also distinctly visible and identifiable.
- The threshold.
- The threshold markings.
- The threshold lights.
- The runway end identifier lights.
- The visual glideslope indicator.
- The touchdown zone or touchdown zone markings.
- The touchdown zone lights.
- The runway or runway markings.
- The runway lights.

It is noteworthy that out of the 10 visual references required for CAT I IFR approach and landing, the approach lights are the only reference located within the approach zone; the remainder of the visual references are located at or beyond the runway threshold. ALSs extend visual cues out into the approach zone, placing the lights much closer to the pilot at their Decision Altitude (DA) or DH than visual cues located on the runway side of the threshold. For this reason, lower straight-in visibility minima may be established for runways that have ALSs installed (Table 1.1).

Table 1.1
Approach categories and visibility minima.

Approach Category	Minimum Visibility	Exceptions
CAT I	200 Feet DH / 2400 Feet RVR	RVR 1800 feet with touchdown zone and centerline lighting; or RVR 1800 feet with autopilot, flight director, or HUD.
SA CAT I	150 Feet DH / 1400 Feet RVR	HUD to DH
CAT II	100 Feet DH / 1200 Feet RVR	RVR 1000 feet with autoland or HUD to touchdown as noted on authorization.
SA CAT II	100 Feet DH / 1200 Feet RVR	SA Category II approach to runways without centerline lighting, touchdown zone lighting, or ALSF-2 are permitted with autoland or HUD to touchdown, as noted on authorization.
CAT III	No DH or DH below 100 feet or less than 1000 Feet RVR	

Note. Category II and III operations require special authorization and equipment (see AC 120-118). DH = decision height; RVR = runway visual range; HUD = heads-up display; SA = special authorization.

2. A Brief Historical Perspective on ALSs

The need for effective aids to guide low visibility landings was first recognized in World War I (Charnley, 1989). During this time, the Royal Naval Air Service made some of the first attempts at landings at night and in fog using an aircraft height indicator (Charnley, 1989). This device, referred to as a 'ground proximiter', consisted of a weight attached to a cord, which hung underneath the aircraft. When the weight touched the ground, a red light would turn-on in the cockpit, indicating that it was time to start to flare for landing.

In terms of approach lighting, one of the first installations was at Royal Air Force Drem, Scotland, in 1940 (Calvert, 1948). The Drem system consisted of six lights arranged in a 90° v-shape, along with a flood light that was placed near the end of the runway. The flood light would be switched on for the landing aircraft and then quickly switched off after touchdown. Later, a circle of lights was installed around the perimeter of airfield so that the airfield was easier to find, and to provide a visual cue for aircraft to line up for spacing before landing.

In the United States, the Bartow system was one of the first ALSs to use high intensity lighting (Pearson & Gilbert, 1947). Bartow system lamps were movable through use of miniature synchronous motors, so that the beam of light could be rotated around the vertical axis of the unit. These approach lights provided two parallel rows of lights that could be adjusted in fog; the heavier the fog, the more the beams would be turned in toward the centerline. The Bartow system never gained widespread usage; however, during World War II, a modified version that did not include the moveable beam feature was used by the U.S. Army and Navy. Although the modified Bartow system supported a number of low visibility landings at airfields around the world, there were also reports of pilots missing the ALS entirely, suggesting that more work needed to be done (Pearson & Gilbert, 1947).

ALSs have continued to evolve over time, with much of the research underlying these modifications discussed in this report. In particular, research dating to the 1940s and 1950s had tremendous influence on modern ALSs. Several types of ALSs were flight tested in the 1940s and 1950s, including parallel row light systems, multiple row light systems, a slope-line system, and the Calvert system (Vaughan et al., 1962). In the United States, the Landing Aids Experiment Station was set up in Arcata, California, with the purpose of having a method of evaluating new patterns of ALSs in full scale, under conditions of low visibility (Calvert, 1950). However, the results of these tests were often scrutinized, as it was difficult to control visibility conditions, and the highly skilled test pilots used in the evaluations were not representative of the regular airline pilot.

The most effective ALSs were thought to be the slope-line and the Calvert systems, which were similar in many respects but with one significant difference (Garbell, 1951, as cited in Lybrand et al., 1959). The slope-line system was preferred by pilots who felt more comfortable flying down a dark lane of lights with an alignment of lights on either flank of the lane. In contrast, the Calvert transverse-bar system was preferred by pilots who felt more comfortable flying down a centerline of lights. The slope-line system was very expensive and required a significant amount of real-estate, and was not feasible for installation at some of the largest airports, including LaGuardia.

A centerline approach system was eventually adopted in 1958, and became what was known as the U.S. Standard (see section 7.1.1 in this report for a description and research utilizing the U.S. Standard system). Calvert (1954) pointed out the benefits of the U.S. Standard system, with its Centerline Lights (CL) and "stub bars", though Calvert stated that it was apparently not adopted in the United Kingdom due to the cost of installation. The United Kingdom eventually adopted the Calvert line-and-bar system, which has undergone refinements and modifications over time, but is still used in parts of the world outside of the U.S. today (Ferguson & Mainwaring, 1971). Today, all modern ALSs continue to use a pattern in which the runway centerline is extended into the approach zone—though many evolutions and modifications to size and lighting density of the ALS have taken place since the adoption of the U.S. Standard system. This report documents the research which underlies the evolution in the modern ALSs.

An effective ALS must be easily recognizable with signals that are quickly and accurately interpreted. Calvert can be credited with focusing on a coherent theory as to how pilots make judgements, as opposed to simply flight testing every new lighting pattern to determine efficacy. As Calvert (1950, p. 186) pointed out, "…new patterns can be invented as quickly as the old ones can be evaluated." Calvert (1950) believed that a successful ALS must be both geometrically sufficient as well as psychologically acceptable to a pilot traveling at a high speed in challenging visibility conditions. In particular, research on ALSs focused on the judgements that a pilot needed to make in order to land (Calvert, 1948; 1954). These judgments include alignment to the runway and approach slope, all the while taking into consideration that the aircraft has six degrees-of-freedom, making these judgments more difficult particularly in conditions of poor visibility.

Using perspective analysis, Calvert demonstrated that a pilot in a free moving aircraft cannot judge lateral deviations simply by looking at the ground. Rather, the pilot requires a picture of a horizon or patterns on the ground that are transverse to the desired track to derive alignment cues (Calvert, 1948; 1954; 1957). All modern ALSs in the U.S. National Airspace System (NAS) that support precision approaches utilize this principle, by providing at least one decision bar that is transverse to the extended runway centerline. It is noteworthy that the modern Calvert ALS also utilizes this principle by utilizing multiple transverse bars of graduated width that are transverse to the path of travel. To prevent errors in directional indications as a result of aircraft height, the approach lighting line must be straddled by the aircraft. The International Civil Aviation Organization (ICAO) standard at the time included both a CL and a crossbar pattern (Calvert, 1954). Some of the early ALSs used a pattern to provide directional cues to the runway, such as parallel lines, v-shapes, and funnels (Pearson & Gilbert, 1947). However, these systems are ineffective at low visibilities, as less and less of the pattern is visible, and the mental calculation required to determine the vanishing point become progressively more difficult (Calvert, 1948).

Calvert (1954) argued that important visual cues included the plane of the ground to provide horizon cues, and objects of a known size on the surface for distance and rate cues. Horizontal and vertical lines can provide a reference frame by which the pilot can derive these elements. Rectangular lines, such as those used in the slope-line ALS previously mentioned, can induce a visual illusion in which the pilot perceives the approach path as sloping downhill to the threshold. In poor visibility, the pilot may perceive the point at which the lines converge as the horizon, and believe that the aircraft is flying level when in fact, it is descending over converging lines. Calvert (1954) pointed out that the slope-line system was deemed successful when evaluated by test pilots who grew accustomed to interpreting cues from the two rows of lights, but would not be a viable ALS for regular pilots who make very few low visibility approaches in a year and may be more susceptible to visual illusions.

Additionally, the slope line system did not provide any indication of distance or rate. Since the individual lights appeared to be the same size, the mental process of comparing far objects to objects of a known size to indicate distance, or using the texture of the foreground, was not possible. Without depth cues, the pilot may lose his or her ground plane, and have a strong tendency to pull up (Calvert, 1950).

To provide texture cues, the Calvert ALS included transverse bars of varying length, with the thought that if these transverse bars are a constant distance from one another, the visual angle of the light and spaces would provide additional depth cues to the observer and produce the impression of a plane (Calvert, 1950). The slope line system was also susceptible to misinterpreted height estimations. The distance between the rows of parallel lights would depend on the size of the runway, so that a runway that is 75 feet in width is viewed as a scale model of a runway that is 150 feet in width. Judgements of height would require the pilot to remember the pattern that he or she is landing on—otherwise, an error in judgement is likely, particularly if texture information from the ground is not available (Calvert, 1948). However, regardless of the pattern utilized for the ALS, pilot estimates of the height of the aircraft above the ground cannot be fully accomplished by the guidance provided by ALSs, and require supplementation from additional runway infrastructure (e.g., Instrument Landing System [ILS] system or visual glide slope indicator; Calvert, 1959; Ferguson & Mainwaring, 1971).

Modern ALSs continue to utilize some of the same principles of visual guidance originally outlined by Calvert (1948, 1950, 1957). For example, ALSs that support precision instrument approaches continue to include an extended runway centerline, in which the correct track is for the aircraft to straddle the line. This approach minimizes the possibility of making judgment errors due to misinterpreted directional indications. Additionally, modern ALSs also include at least one decision bar, which not only provides distance information, but also serves as an artificial horizon on the ground providing lateral deviation and banking cues. Since the 1950s, much work by the FAA on ALSs has focused on the effect of modifications to both size and density of lighting, with the goal of increasing the amount of airports in the U.S. NAS that can support low visibility operations, while at the same time controlling for costs.

3. Approach Lighting System Categories

A major factor in expanding instrument capability to new runways or airports has been the installation of ALSs. ALSs provide the basic means to transition from instrument flight to visual flight for landing. Operational credit has been authorized for certain conditions, based on the visual guidance available through airport and runway infrastructure. For example, with no visual approach aid, non-precision (no vertical guidance) approach minima are typically limited to a 250 foot Minimum Descent Altitude (MDA) or Height (H) and 1 mile visibility. For precision approaches (vertical guidance provided) without approach lights, the DA (H) is reduced to 200 foot with ¾ mile visibility. Approach lights such as Medium Intensity Approach Lighting System with Runway Alignment Indicator Lights (MALSR), Simplified Short Approach Lighting System with Runway Alignment Indicator Lights (SSALR), or Approach Lighting System with Sequenced Flashing Lights Configuration 1 (ALSF-1) reduce the visibility minimum to 2400 foot Runway Visual Range (RVR), and to 1800 foot RVR when standard high intensity runway Centerline (CL) and Touchdown Zone (TDZ) lighting systems are provided. The brightest and most expansive ALS, the Approach Lighting System with Sequenced Flashing Lights Configuration 2 (ALSF-2), allow for CAT III operations. In general, increasing the runway or ALS infrastructure allows for operations in lower visibility conditions (see Table 3.1).

Table 3.1
Category of ALS and associated visibility reduction credit.

Categories of ALSs

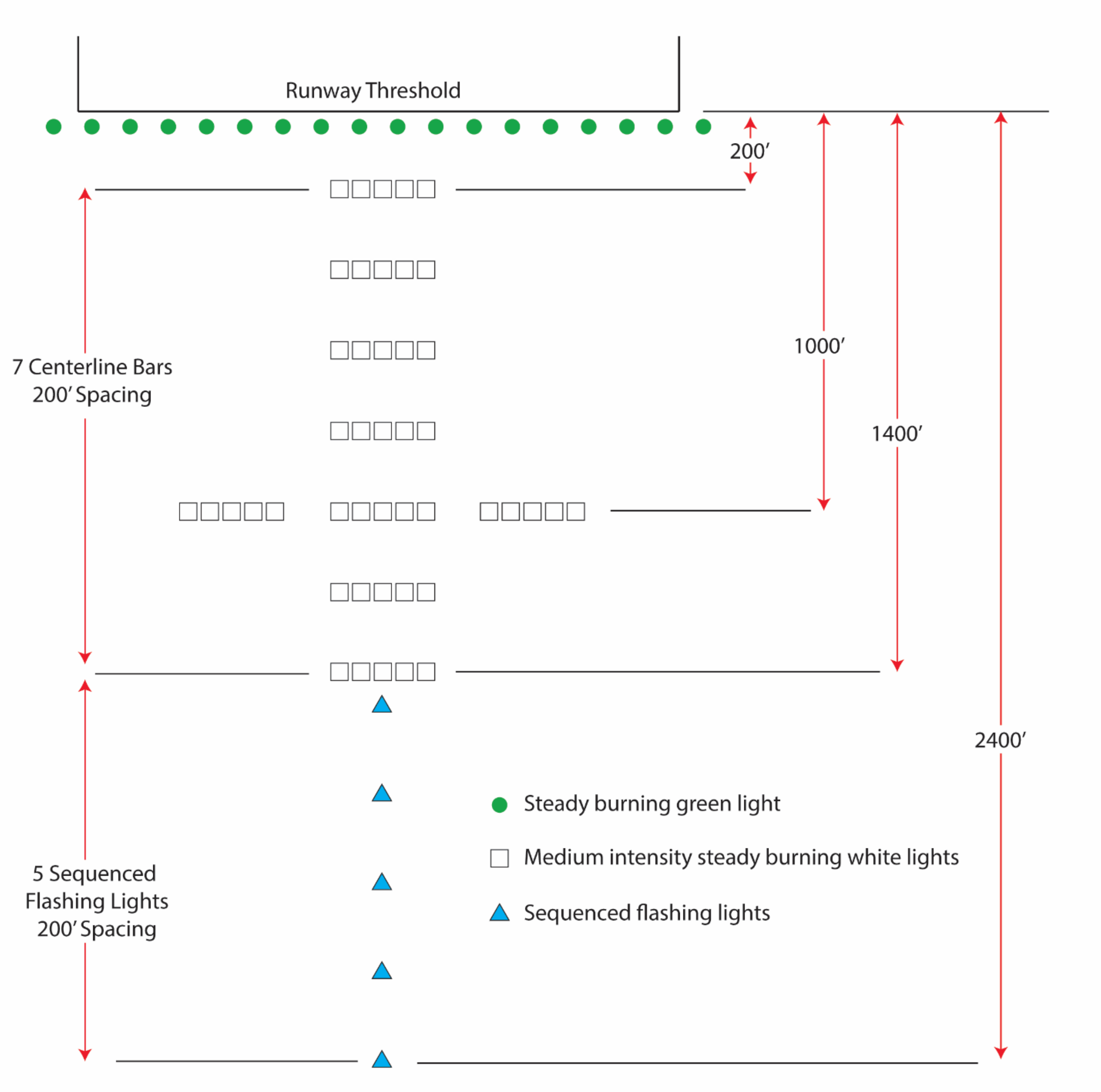
ALS Category	ALS Configuration	ALS Length in Feet	DA (H) in Feet	TDZ RVR in Feet	Visibility in Statute Miles
NALS	No Lights	–	200	4000	3/4
BALS	ODALS	≥ 700 – 1399	200	4000	3/4
IALS	MALSF, MALS, SSALF, SSALS, SALS/SALSF	≥ 1400 – 2399	200	4000	3/4
FALS	MALSR, SSALR, ALSF-1, or ALSF-2	≥ 2400	200	1800	1/2
FALS + TDZL & CL	MALSR, SSALR, ALSF-1, ALSF-2 with TDZL & CL lighting	≥ 2400	200	1800	1/2

Note. Values are based on a DA (H) equal to 200 feet (FAA Order 8260.3D, United States Standard for Terminal Instrument Procedures.) NALS = No ALS; BALS = Basic ALS, IALS = Intermediate ALS, FALS = Full ALS; TDZL = Touchdown zone lights, CL = Centerline lights.

3.1 MALSR-type

For CAT I precision approaches, MALSR (or better) provide planned approach visibility at 1800 feet to ½ mile, with a DH of 200 feet (Federal Aviation Administration, 2019b). The MALSR configuration consists of a Medium Intensity Approach Lighting System (MALS) type approach light with Runway Alignment Indicator Lights (RAIL) in the outer segment. Specifically, MALSR lighting structures consist of a combination of green threshold lamps, medium intensity steady burning light barrettes, and sequenced flashing lights (Figure 2.1). A typical MALSR uses 18 green lamps along the runway threshold spaced 10 feet apart; 9 steady burning light barrettes each with 5 medium intensity white lights, and a separation of 200 feet between barrettes; and 5 sequenced flashing lights also separated every 200 feet. At the 1000 foot location, there are three light barrettes (15 lamps total) for added visual reference for distance and roll guidance to the pilot on final approach. Sequenced flashing lights in the outer 1000 foot segment provide added visual guidance down the runway centerline path. In total MALSR lights extend over 2400 feet (nearly ½ mile) from the runway threshold. MALSR lights require an expanse of land that is at least 2600 feet long by 400 feet wide (FAA Order 6850.2B). Currently, there are approximately 900 MALSR facilities in the U.S. NAS (Federal Aviation Administration, 2019b).

Figure 3.1
MALSR layout.



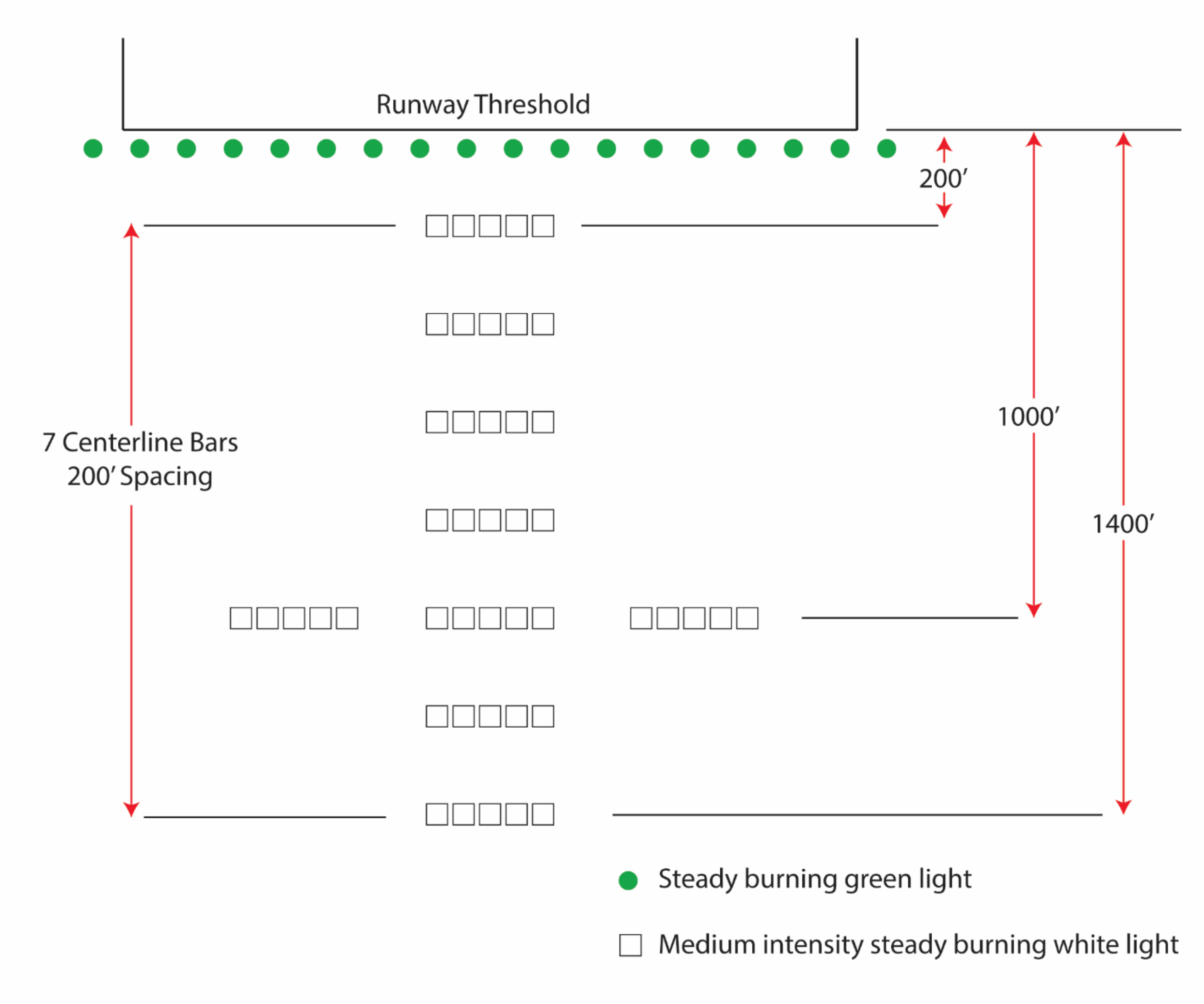
Note. MALSR are used by the FAA for CAT I precision approaches. Symbols denoting runway and lighting components are not drawn to scale.

The MALS (Figure 3.2) and Medium Intensity Approach Lighting System with Sequenced Flashers (MALSF) layouts (Figure 3.3) require less real estate for installation than the MALSR

ALS, as they either do not have sequenced flashing lights (MALS) or they have a reduced amount of sequenced flashing lights that overlap with the steady burning light barrettes (MALSF). The rectangular area of land required to install a MALS or MALSF is 1600 feet in length and 400 feet in width (FAA Order 6850.2B).

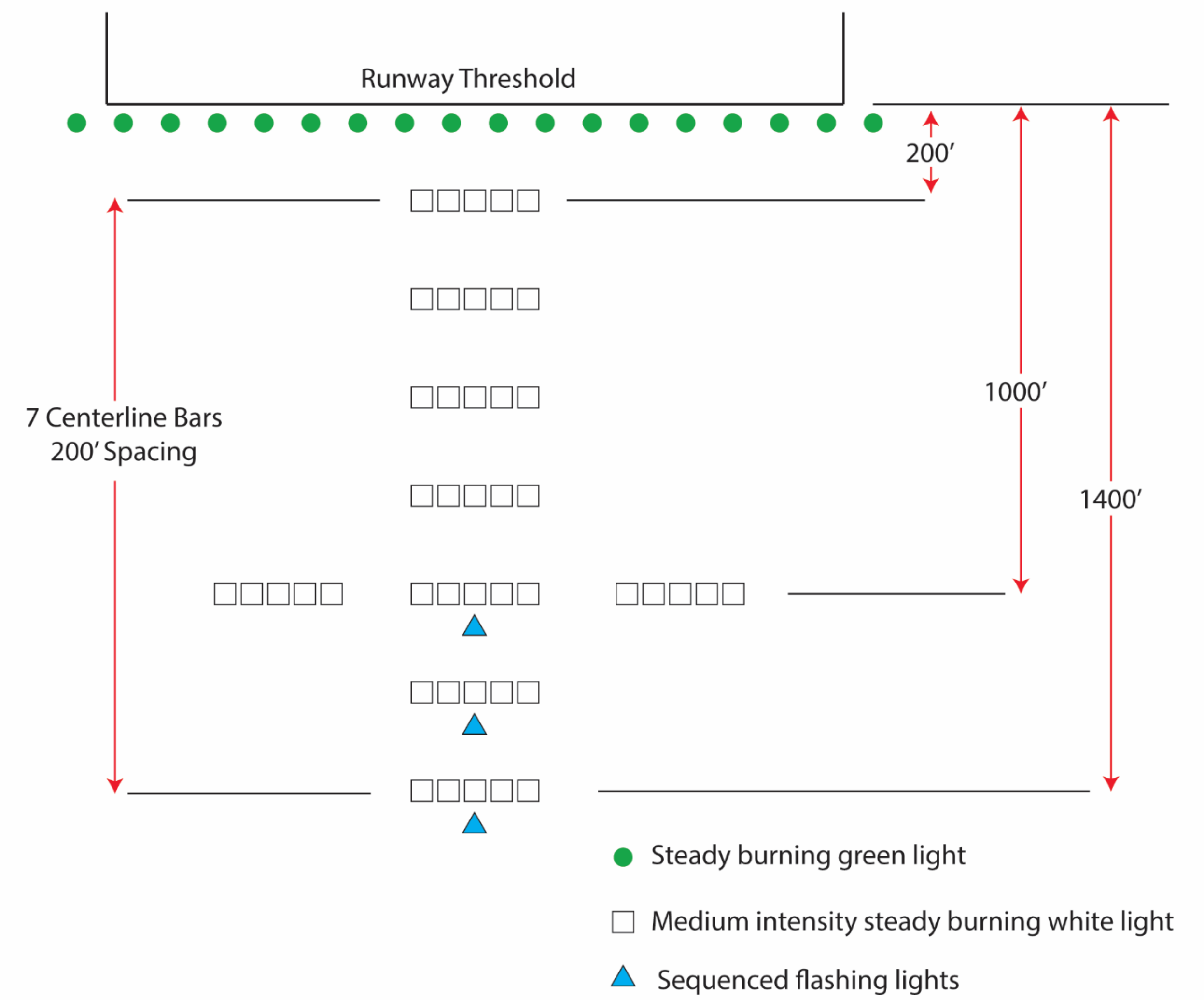
Figure 3.2

MALS layout.



Note. MALS is identical to a MALSR in the inner 1400 foot segment, but does not include any sequenced flashing lights. Symbols denoting runway and lighting components are not drawn to scale.

Figure 3.3
MALSF layout.

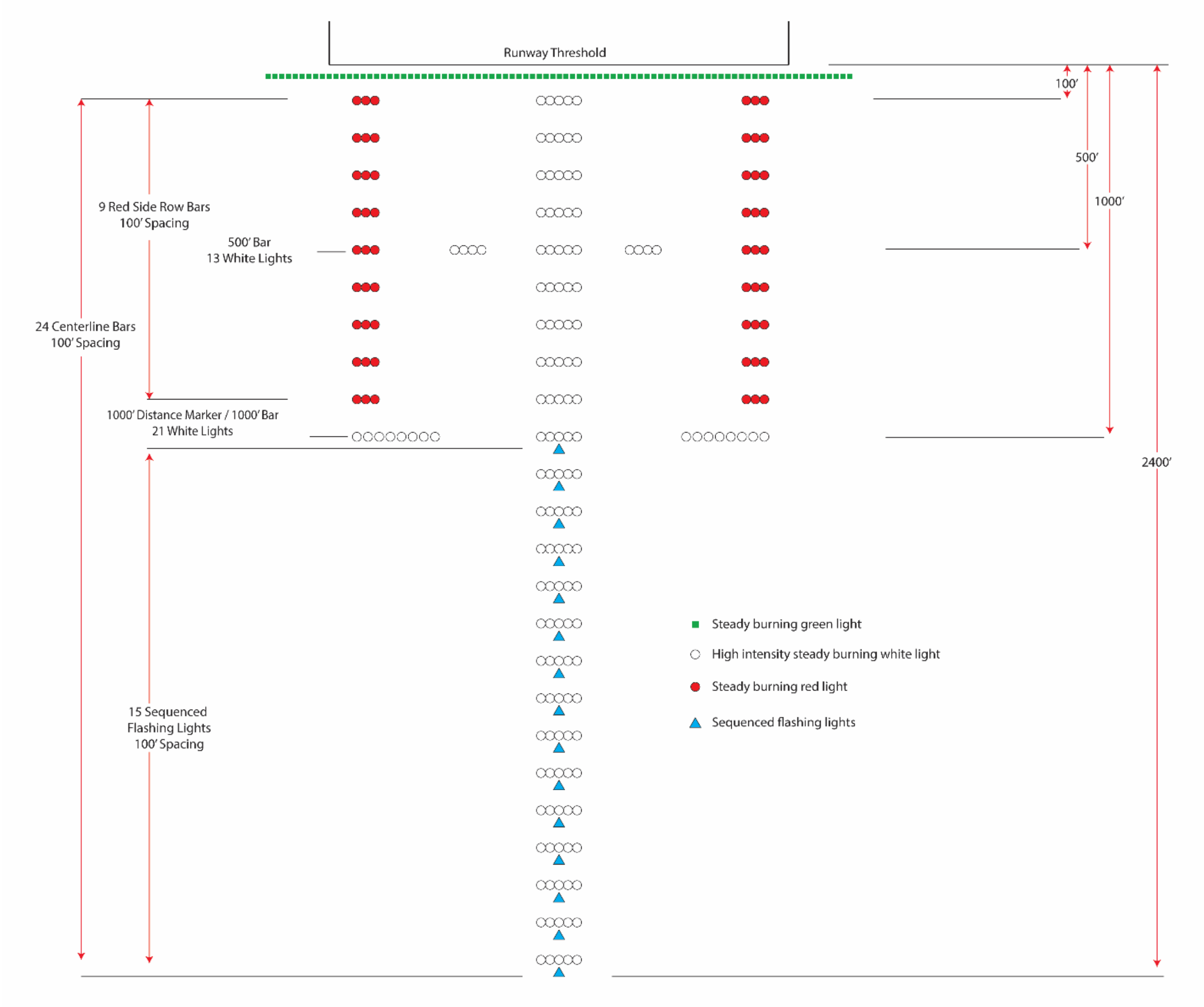


Note. Medium Intensity Approach Lighting System with Sequenced Flashers (MALSF) is similar to MALS, but are equipped with three sequences flashing for locations where approach area identification problems exist. Symbols denoting runway and lighting components are not drawn to scale.

3.2 ALSF-type

For CAT II and III approaches, ALSF-1, ALSF-2, SSALR, or Simplified Short Approach Lighting System (SSALS) provide visual guidance on runway alignment, height perception, roll guidance, and horizontal references. ALSF-2 lights have more lighting components than MALSR-type lighting, and include 49 green threshold lights, red side row bar lamps (9 rows, 54 lamps), and high intensity steady burning white lights (144 lamps), with 15 sequenced flashing lights spaced at 100 foot intervals for a total ALSF-2 length of at least 2400 feet (Figure 3.4). There are approximately 153 ALSF-2 facilities in the U.S. NAS (Federal Aviation Administration, 2019b).

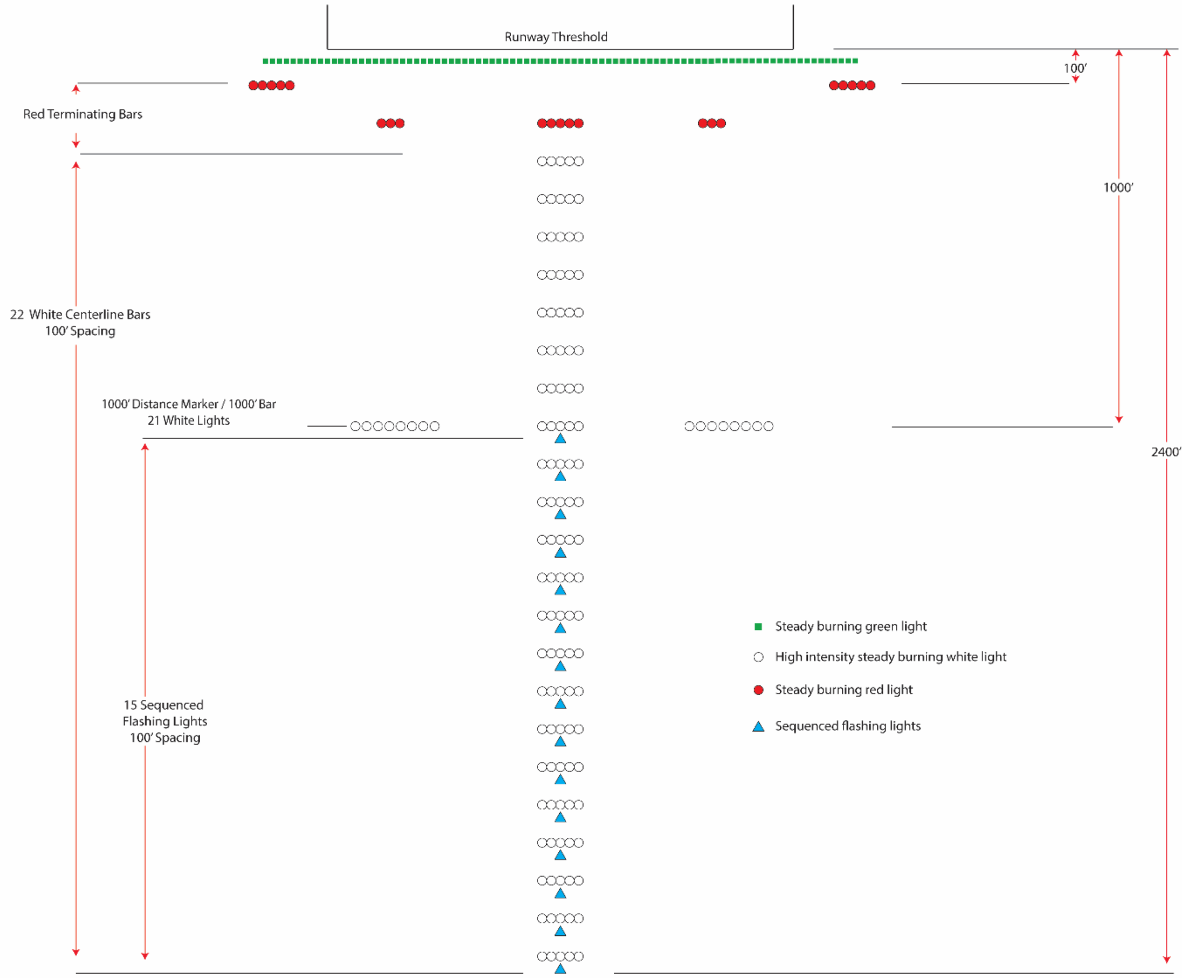
Figure 3.4
ALSF-2 layout.



Note. ALSF-2 lights represent the most complex and expensive ALS in the U.S. NAS, and support CAT II and III operations. Symbols denoting runway and lighting components are not drawn to scale.

ALSF-1 approach lights are similar to ALSF-2, but are far less common in the U.S. NAS. Differences are found in the inner 1000 feet nearest the runway. ALSF-1 lights have one distance marker crossbar (decision bar) at 1000 feet, and also have a red terminating bar consisting of 11 lights installed 200 feet from the threshold. Red wing bars or pre-threshold bars, each contain five red lights, and are located 100 feet from the threshold on either side of the runway (Figure 2.5). ALSF-1 and ALSF-2 approach lights are identical in the outer 1400-2000 feet, and have the same minimum land requirements—2600 feet in length and 400 feet in width (FAA Order 6850.2B). Modification of the ALSF-1 system includes the Short Approach Lighting System (SALS; Appendix A) and Short Approach Lighting System with Sequenced Flashers (SALSF; Appendix B). These two modified systems are 1500 feet in length.

Figure 3.5
ALSF-1 layout.



Note. ALSF-1 are similar to ALSF-2, but have fewer red wing bar lights and only one decision bar. Symbols denoting runway and lighting components are not drawn to scale.

Major differences between ALSF-2 (CAT II/III) and MALSR (CAT I) approach lights are found in the spacing between the centerline steady burning light barrettes, the intensity of the steady burning light barrettes, the presence or absence of red wing bars, and the amount of decision bars and green threshold lights (Table 3.2). The length of MALSR and ALSF-2 lights are both either 2400 or 3000 feet, depending on the slope of the land for installation.

Table 3.2
Summary of differences between MALSR and ALSF-2.

ALS	Green Threshold Lights	Light Bar Intensity	Red Wing Bars	Decision Bars	Light Spacing	Runway Equipped
MALSR	18 lamps	Medium	No	1	200 ft	900
ALSF-2	49 lamps	High	Yes	2	100 ft	153

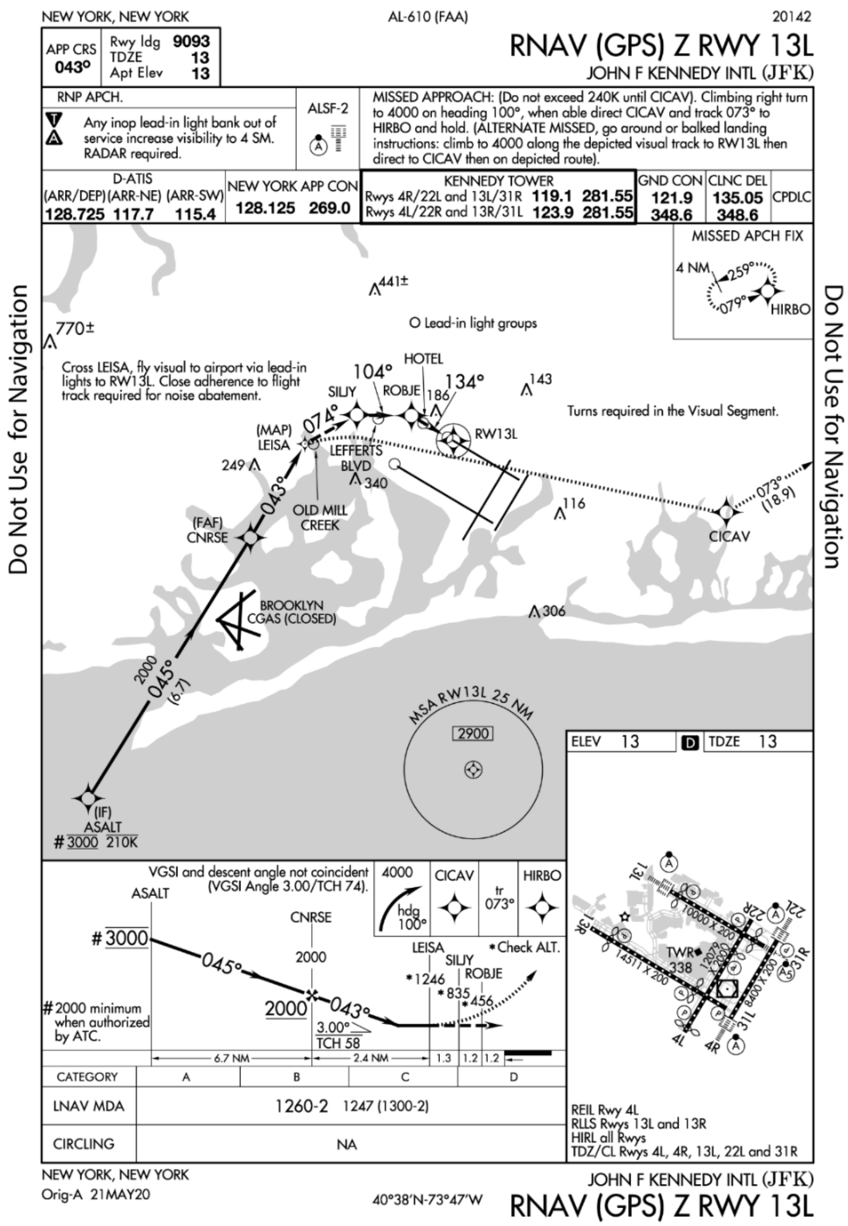
Note. No. = count of ALS currently in the U.S. NAS (Federal Aviation Administration, 2019b).

4. Runway Lead-In Light System

A runway Lead-in Light system (LDIN) consists of one or more series of flashing lights installed at or near ground level to provide positive visual guidance along an approach path, either curving or straight, where special problems exist with hazardous terrain, obstructions, or noise abatement procedures (see FAA Order 6850.2B). LDINs are positioned to be seen and followed by approaching aircraft, with lights generally flashing in a sequence toward the runway. Each light group contains at least three flashing lights in a linear or cluster configuration and may be augmented by steady-burning lights if required. Unlike ALSs, the layout of LDINs are nonstandard; LDINs may be terminated at any approved ALS, or may be terminated at a distance from the threshold compatible with authorized visibility minimums permitting visual reference to the runway environment. The layout of an LDIN is dependent on guidance required for local conditions (for example, see Figures 4.1 and 4.2).

Figure 4.1

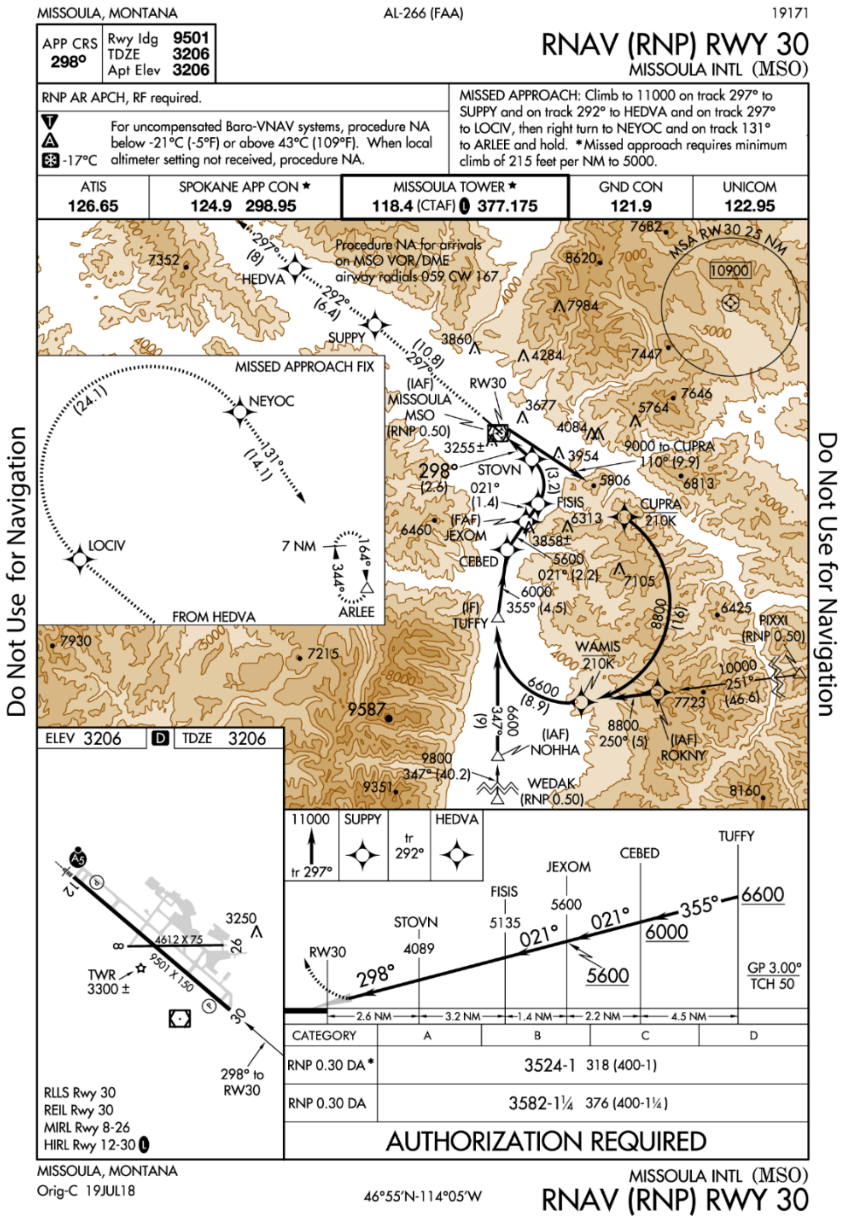
Instrument approach procedure chart for New York John F. Kennedy International Airport (JFK) Runway 13L.



Note. Here the LDIN guides the pilot around a final turn to the runway that is equipped with ALSF-2 lighting.

Figure 4.2

Instrument approach procedure chart for Missoula International Airport (MSO) Runway 30.



Note. Here the LDIN guides the pilot through mountainous terrain for a non-precision instrument approach to a runway that does not have an ALS.

As previously stated, LDINs do not have a standard layout but rather, are tailored to provide guidance as dictated by local conditions. In Figure 4.1, the LDIN provides visual guidance for a flight path in an urban area (New York City), whereas in Figure 4.2, the LDIN provides visual guidance for a path through mountainous terrain. LDINs are considered to be a visual cue, and are not classified as an ALS for precision or non-precision instrument approaches (cf. Airman Information Manual, Chapter 2, Section 1). Modern ALSs that support precision approaches incorporate many of the components originally outlined by Calvert (1948, 1950, 1957), and provide visual cues for both alignment (extended runway centerline), and distance, lateral drift, and bank cues (transverse bars); LDINs lack many of the visual cues that are fundamental to modern ALSs.

5. U.S. NAS Instrument Flight Procedures Inventory

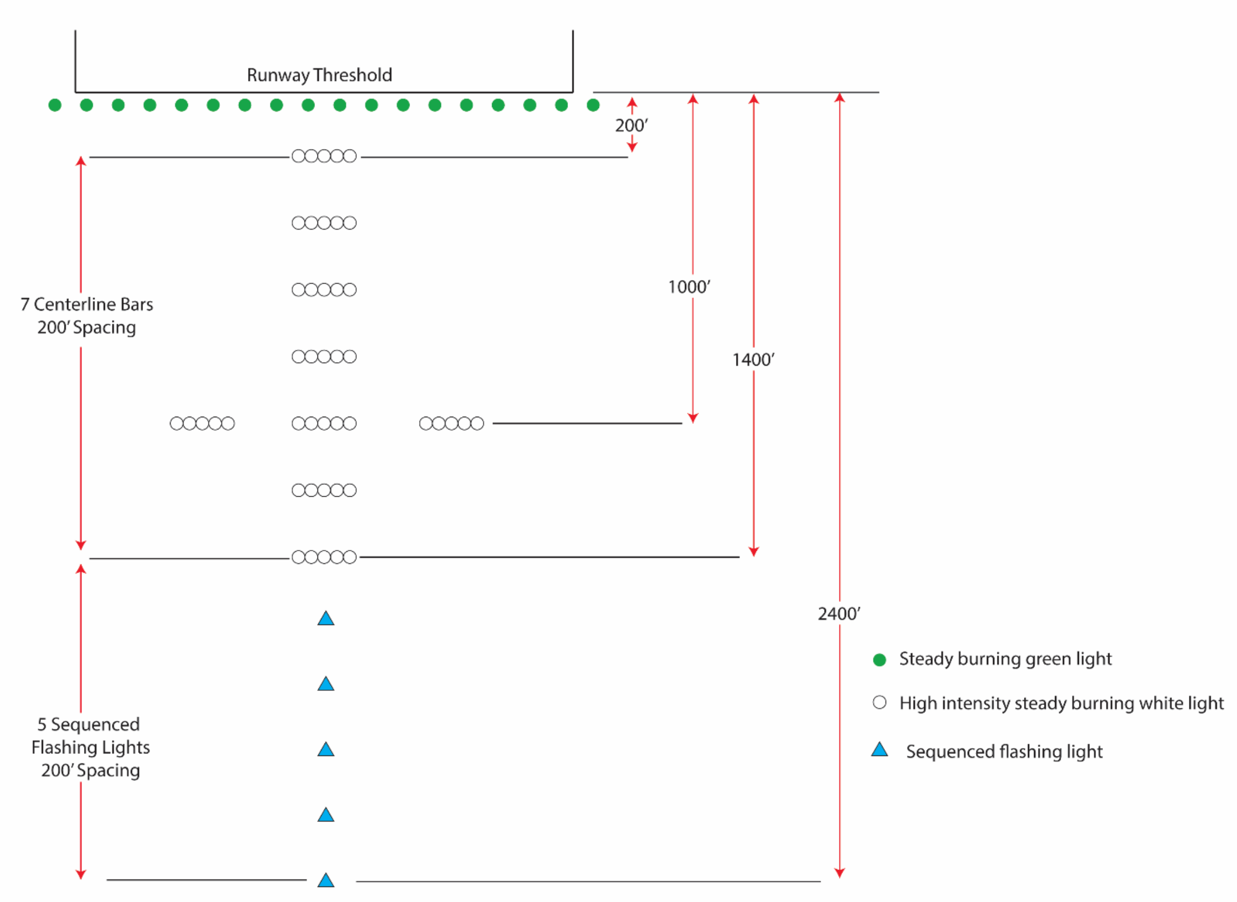
Ground facilities in the U.S. NAS must meet certain minimum requirements to support CAT I, II, and III approaches (Table 1.1; FAA Order 8400.13F). As of August 2019, there were 1,546 ILS facilities in the United States that meet U.S. Standard Type I facility minima; a Type I facility is defined as all Localizer (LOC) and Glideslope (GS) facilities that do not meet the definition of Type II or Type III (Federal Aviation Administration, 2019a). For approaches to runways that do not meet all performance or equipment requirements of a U.S. Standard, Special Authorization (SA) for CAT I, II, and III operations may be granted in certain circumstances (see FAA Order 8400.13F). For example SA CAT I procedures require Flight Operations Group and Flight Standards office agreement, and specialized equipment, including the use of a Heads Up Display (HUD) to DH and MALSR or better ALS. With respect to required lighting, the runway must also have high intensity runway lights, and required approach lights may include a SSALR, MALSR, or ALSF-1 / ALSF-2. There were 159 ILS facilities that meet U.S. Standard Type II facility minima, and only 122 facilities that meet standard CAT III minima. In addition, there were 158 ILS U.S. SA CAT I type facilities, and 66 SA CAT II type facilities that do not meet all performance or equipment requirements of a U.S. Standard (see FAA Order 8400.13F).

6. ALS Components

ALSs project light in a directional pattern starting at the runway threshold and extending into the approach area, generally at a distance of 1400 feet for non-precision instrument runways and 2400 – 3000 feet for precision instrument runways. In general, most ALSs used for precision approaches are 2400 feet in length when the GS is 2.75° or greater and 3000 feet in length when the glideslope is less than 2.75° (FAA Order 6850.2B). ALSs are designed to aid the pilot in identifying the direction to the runway and aligning the aircraft with the runway. Additionally, ALSs provide a horizon reference, roll guidance, and some cues as to in-flight visibility. To a lesser extent, ALSs may also provide some cues for height perception.

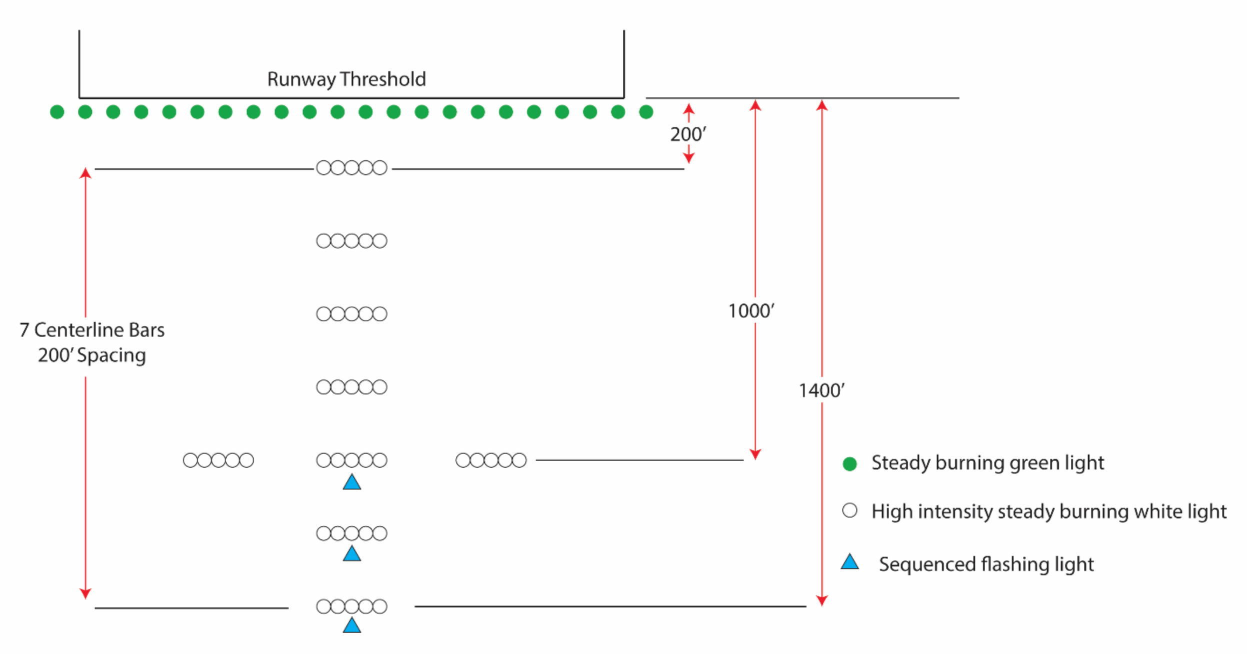
Approach lights vary in complexity and cost, and, in general, lower approach minima are associated with more expensive and dense lighting systems. Additionally, ALSs are classified as high intensity or medium intensity, based on the type of lamps and equipment used. For example, the difference between medium intensity (e.g., MALSR, MALSF) and simplified short (e.g., SSALR, Simplified Short Approach Lighting System with Sequenced Flashers [SSALF]) ALSs is the light intensity of the light barrettes (see Figure 3.1 and Figure 3.3 for MALSR and MALSF, respectively, and Figure 5.1 and Figure 5.2 for SSALR and SSALF, respectively). Medium intensity ALSs typically have two settings—low and medium white approach lights. Simplified short ALSs have three lighting intensities—low, medium, and high. Although there are differences in lighting features across the categories of ALSs, they have a key feature in common—all ALSs have a centerline that aligns with the runway centerline.

Figure 6.1
SSALR layout.



Note. SSALR are used in the same way as MALSR ALSs. SSALR ALSs are not installed as new systems in the U.S. NAS, but instead are used when CAT I conditions exist on CAT II designated runways that have a dual mode ALS (e.g., ALSF-2 / SSALR). Symbols denoting runway and lighting components are not drawn to scale.

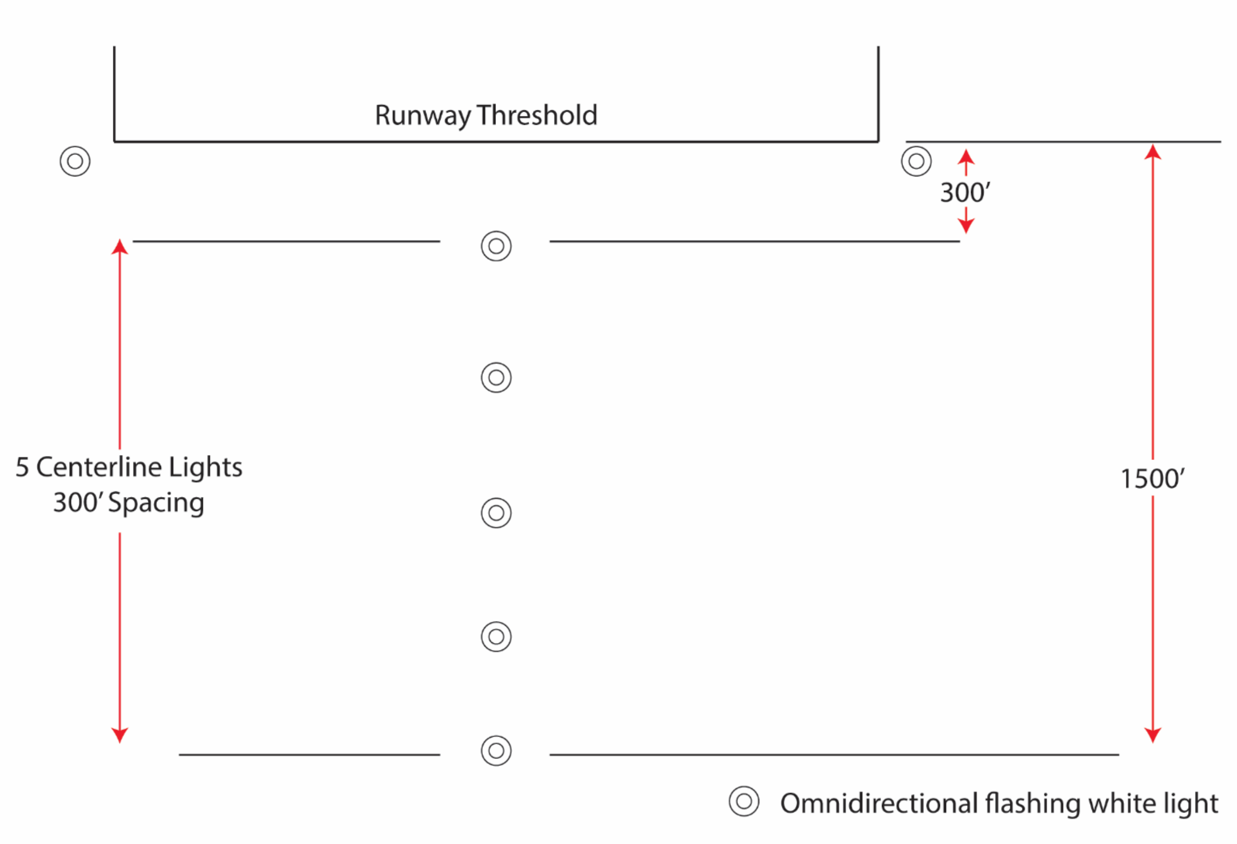
Figure 6.2
SSALF layout.



Note. Symbols denoting runway and lighting components are not drawn to scale.

Non-precision ALSs may be as simple as a series of strobe lights aligned to the centerline of the runway—as is the case of the Omni-Directional Approach Lighting System (ODALS; Figure 6.3). However, for precision approaches, the ground infrastructure requirements and complexity of the ALS drastically increase.

Figure 6.3
ODALS layout.



Note. ODALS are considered a basic type of ALS. Symbols denoting runway and lighting components are not drawn to scale.

Most precision ALSs include a combination of light barrettes and sequenced flashing lights. Light barrettes are aligned to the centerline of the runway, and typically consist of five steady-burning white lamps on each individual structure. These light barrettes are separated by 100 feet for ALSF-type ALSs, and 200 feet for MALSR-type and similar lighting systems. Light barrettes may also be arranged to form a crossbar consisting of three individual light barrette units, located perpendicular to the approach light system, and placed at specific distances from the runway threshold. This arrangement forms what is commonly referred to as a distance marker, roll bar, or a decision bar, and may serve several functions to the pilot on final approach to land. First, they provide distance to the runway information. For example, when the aircraft is on glideslope and a 500-foot decision bar passes underneath, the position of the aircraft should be approximately 100 feet above the TDZ. A decision bar located at 1000 feet from the threshold should appear to slip below the aircraft's nose at the DH. The decision bar may also serve as an artificial horizon, aiding in the transition from instrument to visual approach at the DH, or it may even serve as a pseudo attitude indicator providing a bank reference that may be used to keep the airplane's wings level during a low visibility landing. The light barrettes themselves may also provide additional out-the-window visibility cues to the pilot. For example, with a priori knowledge of the type of ALS installed at the runway, theoretically, the pilot would be able to count the number of light bars visible beyond the decision bar to obtain a more accurate estimate of the in-flight visibility; if the aircraft is located at the middle marker on an approach with the ALSF-type system, and the pilot is able to see three light bars past the decision bar, he or she would know that there is an additional 300 feet of visibility.

There are two types of sequenced flashing lights installed on some ALSs. Essentially, they are the same type of strobe light, but differ in the location at which they terminate. For MALSF, SSALF, ALSF-1, ALSF-2 ALSs, the sequenced flashing lights terminate at the decision bar. For MALSR and SSALR ALSs, for example, the sequenced flashing lights terminate where the white steady burning light barrettes begin. Sequenced flashing lights appear to be balls of light, flashing at the rate of twice per second. Prior to the DA, the sequenced flashing lights help orient the pilot in the direction of the runway, while the decision bar helps transition from instrument to visual flight.

6.1 Attributes of Effective Approach Light Systems

Attributes of effective approach light systems have been a point of interest dating back to at least the 1930s (see Pearson & Gilbert, 1947, and Lybrand et al., 1959, for reviews). Regardless of the length or type of ALS, there are certain key elements that have been identified as critical to safe and effective approach and landing guidance during restricted visibility conditions. However, it is important to consider that the information derived from these key elements largely depend on the actual visibility conditions. For example, at lower visibilities, it is likely that much of the ALS will be behind the aircraft by the time the pilot visually acquires any approach lights so that those lights in the outer segment may not be of assistance during the approach-to-land operation. In this section, minimum requirements and desired components of the approach lighting system are discussed (see Table 6.1 for a summary).

Table 6.1
Minimum requirements and desired components of the ALS.

Desired Visual Guidance	ALS Configuration Element
ALS identification	Distinct pattern of lights
Direction to the runway	Sequenced flashing lights and / or adequately spaced CL barrettes
Definition of extended runway centerline	Extended runway CLs
Roll guidance	Red terminating bar (ALSF-1), red wing bars (ALSF-2), steady burning CL barrettes, and / or transverse decision bars
Cross-track guidance	Red wing bars (ALSF-2), steady burning CL barrettes, and / or transverse decision bars
Distance from runway threshold	Transverse decision bars
Identification of runway threshold	Green runway threshold lights, red terminating bar (ALSF-1), and / or REIL (ODALS)
Height indication	Perspective angles in the ALS pattern, but mostly additional runway infrastructure (e.g., ILS)
Speed indication	Rate of passing over extended runway CLs

6.1.1 Length

At a minimum, the most crucial area of the approach during weather operations is the pre-threshold distance of 1000 feet, and because of this, ALSs should be of a length to at least cover this area (Finch et al., 1966).

6.1.2 Pattern

An effective ALS must be distinctive and easy to recognize at the DA/DH, with a pattern that it is not easily confused with other lights on the ground, such as runway lights (Katz, 1995). To avoid confusion, the ALS should not have elements of too many different dimensions or colors. Early ALSs were all red in color, but this was determined to be an inefficient color that required more energy to produce the same candlepower as white, and could be confused with other runway lighting of the same color (Pearson & Gilbert, 1947). ALSF-2 type configurations include red side row lights between the decision bar and the runway threshold (Figure 3.4). The primary purpose of these red side rows is to improve roll and cross-track guidance by providing cues on drift tracking errors. The mechanism underlying this visual guidance is thought to be the added contrast in the pattern between the extended runway centerline white steady burning light barrettes and the red side rows (McKelvey & Brown, 1964). In addition, the red color of the wing bar lights may assist the flight crew in distinguishing the approach lights from the white touchdown zone lights (TDZL), which are of the same pattern. Finally, there should be adequate separation between the green runway threshold lights and other lighting elements so that elements, such as steady burning light barrettes, do not interfere with perception of the green threshold lights.

6.1.3 Spacing

Spacing of individual segments (e.g., steady burning light barrettes) must be such that the array appears as a continuous line of lights providing runway alignment information to the pilot. Spacing of 200 feet between light segments has been found to be the maximum that will ensure that the sequential pattern of lights appear linear and indicate the direction of the runway (Katz, 1995). The number and spacing of lights must be such that guidance information is still adequate even with a malfunction or loss of an individual light.

6.1.4 Intensity

The density—that is, spacing between individual light components—must be such that there is an additive effect of individual lights to provide sufficient intensity to penetrate through obscuring medium such as fog, without individual lights being so intense as to pose a concern with glare. It has been recommended that the intensity of lights be controllable to accommodate operations during variable visibility operations (Pearson & Gilbert, 1947; Katz, 1995).

6.1.5 Guidance

The pattern should also provide directional, alignment, and orientation guidance, and should have features so that it can be quickly interpreted with little effort. This is especially important, as high speed aircraft may traverse the 1000 feet pre-threshold area in a matter of seconds. For directional guidance and alignment, the pattern should have a defined centerline that extends to the runway threshold. To determine position on the approach glide path, distances should be marked with distinctive features, and to assess attitude, the pattern should have lateral elements on either side of the centerline (e.g., a decision bar).

7. ALSs and Flight Performance

Research conducted by the FAA has evaluated the effects of reduced overall size and component density of current ALS systems with respect to minimum information needed by pilots during an approach in CAT I, II, and III minima during restricted visibility conditions (e.g., Paprocki, 1963; McKelvey & Brown, 1964; Paprocki & Gates, 1966; Weinstein, 1969; Katz, 1996; Gallagher, 2002). Reductions to the number of individual lights, light barrettes, sequenced flashers, and related equipment would reduce the cost of installation, operation, and maintenance for individual ALSs. In addition, smaller ALSs would reduce land area requirements for new installations, potentially increasing the number of runways that could support instrument approaches. Thus, it may be possible that ALSs could be installed for runways previously deemed unsuitable where terrain considerations preclude the installation of a full-length ALS (e.g., wetlands or mountainous terrain) or the availability of undeveloped land.

7.1. Evaluations of ALSs with Reduced Components for Precision Approaches

Over the past several decades, the FAA has evaluated the effects of both reducing the density of lights and overall length of ALSs to support instrument approach and landing operations. In each evaluation, the motivation was similar—is it feasible to reduce the length and/or density of the standard ALS, presumably resulting in reduced costs and real estate requirements, while at the same time maintaining safe and efficient approach and landing operations during reduced visibility conditions? In general, results from these evaluations indicated that some modifications to the standard ALS might be acceptable. In the following sections, both acceptable and unacceptable modifications for precision and non-precision instrument approaches, based on FAA research, will be discussed.

7.1.1 ALS Physical Size

When examining the effects of reducing the overall length of the ALS—a modification that would reduce the size of required undeveloped land—there appears to be little consensus. For example, results from Paprocki and Gates (1966) suggested that the height at which the ALS was first visually contacted was higher (i.e., better performance) with a longer ALS, when compared to a shorter modified ALS. In this case, the shorter ALS was 1400 feet, and was compared to what was at the time referred to as the U.S. Standard—an extensive 3000 foot long system[1]. Despite the apparent performance benefit of the longer approach light pattern, the shorter ALS still provided adequate visual guidance in CAT I visibility conditions based on the high approach success rate using a DH of 150 feet and ceiling of 200 feet or higher.

A separate FAA-sponsored study conducted to evaluate the effects of reducing the length of a MALSR from 2400 to 1400 feet while retaining three sequenced flashing lights (resulting in a MALSF; Figure 3.3) found that the MALSF was not well-received by pilot participants at a simulated RVR of 2400 feet (Katz, 1996). In fact, only 81.2% of participants indicated that a

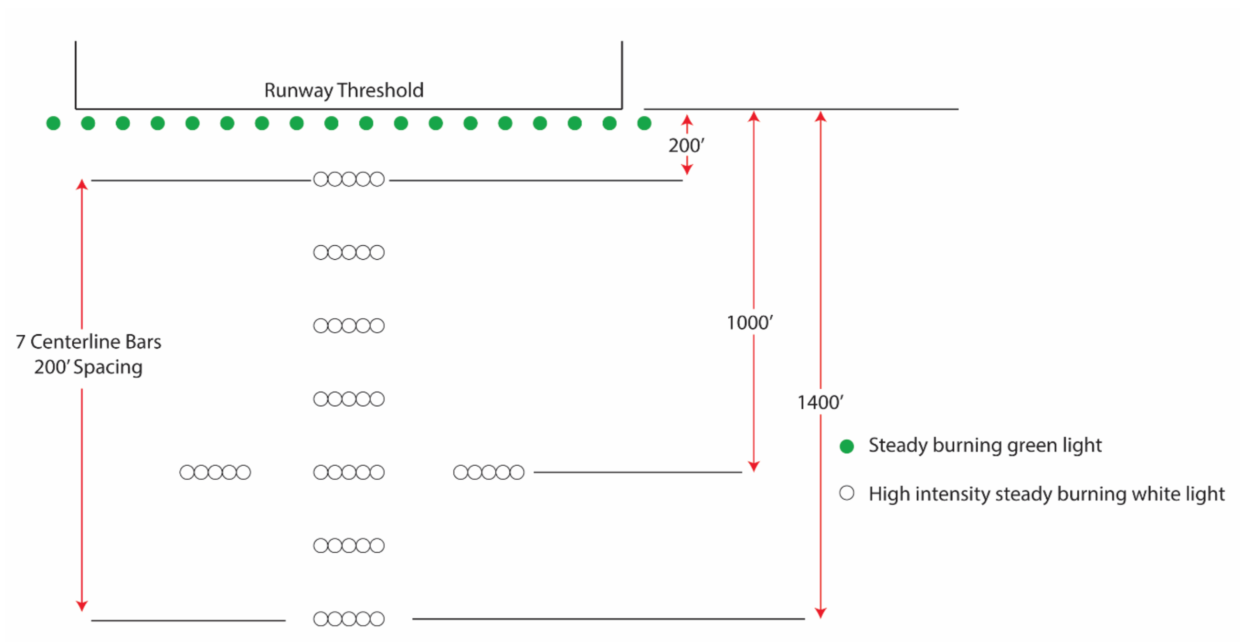
[1] The U.S. Standard ALS was an extensive 3000 feet in length ALS consisting of 28 five-light centerline barrettes spaced at 100 foot intervals, 28 rotating incandescent beacon lights located with each centerline barrette, red pre-threshold lights located 200 feet from runway, and green threshold lights spaced five feet apart across the end of the runway extending 35 feet outside the runway edge.

MALSF was acceptable for low visibility operations, compared to a 98.8% acceptance rating for the standard MALSR. Feedback included that the shorter system delayed judgment of alignment to the runway; however, the missed approach rate was the same for MALSF and MALSR approaches—3 out of 45 approaches (6%).

Results from these two studies suggest that a shorter, medium intensity, ALS that is 1400 feet in length was not widely accepted by pilots (Katz, 1996), and was also associated with an increased visual contact height (Paprocki & Gates, 1966); however, objective performance in terms of missed approach rate may be acceptable (Katz, 1996).

In what could be considered a follow-on study to Katz (1996), Gallagher (2002) evaluated the effect of a shorter 1400 foot ALS, but this time using high intensity steady burning lights to support CAT I operations. Specifically, the SSALS ALS, which includes five high-intensity lights per centerline barrette but no strobe or flashing lights with a total length of 1400 feet, was evaluated (Figure 7.1).

Figure 7.1
SSALS layout.



It is noteworthy that for this evaluation, a less restrictive simulated RVR of 3200 feet was utilized; at the time, the SSALS configuration was under consideration by FAA Flight Standards for use in adjusted minima of 3200 feet visibility (Gallagher, 2002). Out of 33 simulated approaches, only one resulted in a missed approach for a rate of 3%. Further, the SSALS was rated favorably for guidance toward the runway, altitude awareness, tracking guidance, and roll guidance. However, it was noted that without sequenced flashing lights, early alignment to the runway was inadequate. It should also be noted that in lower visibility conditions such as CAT II or III operations, the perceived benefits of a longer ALS with more sequenced flashing lights in the outer segment might largely be inconsequential. At these reduced visibility conditions, the majority of the ALS may be behind the aircraft at the point of visual contact, and the lighting aids that may be more helpful for transitioning from instrument to visual approach may include runway edge lights, threshold lights, and touchdown and centerline lighting (McFarland, 1998). In summary, the results of these studies suggest that perhaps an intermediate length ALS between the two extremes of 1400 feet and 2400-3000 feet, or a shorter 1400 foot length ALS with high intensity steady burning lights may provide sufficient visual support for low visibility approach and landing operations.

To evaluate the feasibility of an intermediate length ALS, Gallagher (2002) constructed 10 modifications of a standard MALSR that varied from 1600 to 2400 feet. All 10 configurations included the standard 1400 foot inner segment length of standard steady burning lights, but lighting barrettes were a reduced density of three lights per barrette as opposed to five with standard MALSR. To vary the overall length, the amount of sequenced flasher lights varied from three to five. Standard to all configurations were green runway threshold lighting and a 1000 foot decision bar (3 x 3 light barrettes). Testing was conducted in a Boeing 727 flight simulator during simulated CAT I conditions (RVR 2400 feet). Based on objective performance (% missed approaches), shortening the MALSR-type ALS to a length of 1600 feet was unacceptable. The two shortest ALSs—both 1600 feet in length—were associated with a high percentage of missed approaches (10% and 14%), and lower subjective ratings for the following criteria: supporting the pilot in finding the runway, awareness of altitude above the ground, lateral alignment with the runway, roll guidance, and safety.

While an ALS should not be used as a primary source of height above the ground information, it should provide support in localizing and aligning to the runway, as well as supplemental roll guidance, suggesting that these two configurations would be inadequate for CAT I operations. These two 1600 foot configurations included four and five sequenced flashing lights which overlapped with the steady burning light barrettes in the outer segment of the ALS; standard MALSR include five sequenced flashing lights that do not overlap with light barrettes. Combining these results with earlier research (Paprocki & Gates, 1966; Katz, 1996), it would appear that ALSs that utilized medium intensity steady burning lights with lengths of 1400 and 1600 feet were not well accepted by the evaluation pilots, and may be too short to support visual guidance during approach and landing operations, even with up to five sequenced flashing lights. Since the SSALS, which utilized high intensity lighting, was evaluated at a higher RVR (3200 feet), it is unclear what effect higher intensity light sources would have on missed approach rate at lower visibilities (Gallagher, 2002).

The remaining eight relatively longer MALSR-type configurations varied in length from 1800 to 2400 feet (Gallagher, 2002). Of these, the two ALS configurations associated with poor objective performance were 1800 and 2200 feet in length, each with five sequenced flashing lights. The relatively higher missed approach rate (5% each), suggested that total length and amount of sequenced flashing lights alone could not account for the relatively poor performance. The two MALSR-type configurations associated with the best objective performance (no missed approaches) were 2000 and 2400 feet in length, each with five sequenced flashing lights. The 2400 foot ALS was essentially a MALSR, but with three lights instead of five per light barrette. The 2000 foot ALS also included three lights per barrette, but reduced the overall length by overlapping two of the sequenced flashing lights with the last two light barrettes.

In general, for the eight relatively longer MALSR-type ALSs, subjective feedback indicated that pilot participants had an easier time finding the runway and had better awareness of altitude with longer ALSs. Direction toward the runway was influenced by the brightly illuminated, sequenced flashing light portion of configuration; configurations with fewer sequenced flashing lights received poorer ratings on effectiveness of pointing toward the runway. Similarly, altitude awareness was influenced by ALS length, suggesting that longer ALSs provide more time to interpret altitude guidance. The longer ALSs also were associated with higher ratings on roll guidance. In general, reducing the number of steady burning lights in each light barrette from five to three may be feasible, but a reduction in sequenced flashing lights may limit early acquisition of the ALS and result in worse objective performance when using medium intensity steady burning lights at the visibility conditions utilized in this evaluation (Gallagher, 2002).

7.1.2 ALS Lighting Component Density

In addition to the length of an ALS, the FAA has also evaluated the effects of a reduced density ALS on safety and performance during low visibility approach and landing operations. Reduced density configurations have been accomplished by reducing the spacing between lighting components, and by reducing the number of lights contained within each CL barrette. In this section, examples of research to support CAT I, II, and III operations are provided. In general, it was found that some reductions were more acceptable than others.

In an early evaluation of a reduced lighting density to support CAT I operations, Paprocki and Gates (1966) found that when comparing patterns of the same length—both 3000 feet—differences in approach light contact height were due to differences in boldness of signal due to closer spacing of CL barrettes (100 versus 200 feet). These differences were most apparent in daylight conditions with high background brightness levels, suggesting that closer spacing between barrettes may be more important in daytime compared to night when contrast may be greater. While the ALS evaluated by Paprocki and Gates is no longer in use in the U.S. NAS, it is noteworthy that differences in lighting component density on performance may largely be dependent on time of day, or lighting conditions, and future evaluations should take that into consideration.

Currently, MALSR type lighting are required to support CAT I operations in the U.S. NAS. In a direct comparison of a standard MALSR to reduced density MALSR that included three lights per CL barrette instead of five, subjective and objective results indicated that this modification might be acceptable at the evaluation visibility of a simulated 2400 feet RVR (Katz, 1996). The standard MALSR was associated with an acceptability rating of 98.8%, compared to 96.7% for the reduced density MALSR. Further, the missed approach rate was the same for both configurations—3 out of 45 approaches (6%). Comments from the reduced density MALSR approaches included that the pilot participant would not have noticed the difference if not told, three versus five lights does not matter, and the reduced density MALSR is the same as a standard MALSR.

Next, the standard MALSF (Figure 3.3) was compared to a reduced density MALSF; the reduced density MALSF included three lights per CL barrette as opposed to five. In this comparison, the standard MALSF was more widely accepted than the reduced density MALSF—81.2% versus 75.3%, respectively. Further, the missed approach rate was also higher for the reduced density MALSF—5 versus 3 out of 45 approaches. With the reduced length of the MALSF compared to a standard MALSR, and further reduced CL density, participant pilots reported that lateral guidance may have appeared too late to see drift across the extended centerline. Even with the standard MALSF, 33% of pilot participants felt that this configuration was not a viable replacement for a standard MALSR. Feedback for the reduced density MALSF was even worse—40% of pilot participants reported that this configuration did not warrant further consideration as a replacement for the MALSR. In summary, it would appear that for CAT I operations, a reduced CL density may be acceptable in terms of performance and pilot acceptance; however, reducing both the length and density of a medium intensity ALS may not be feasible—at least when utilizing medium intensity lighting such as found with MALSR-type ALSs.

Thus far, modified ALSs discussed have focused on support of CAT I operations. Katz (1996) further explored the effects of a reduced-density ALS to support CAT II and III conditions. Three reduced-density ALSF-2 configurations were evaluated at a simulated visibility of RVR 1200 feet. In this evaluation, overall length was not modified, so that all configurations were 2400 feet in length. It is also noteworthy that the ALSF-2 system is constructed with high intensity steady burning lights within each centerline barrette, as opposed to MALSR-type lights that use medium intensity lighting.

The first reduced-density ALSF-2 was constructed by reducing the sequenced flashing light density from 100 to 200 feet in the outer 1400 feet of the ALS, and eliminating the CL barrettes in the outer 1000 feet. This modification resulted in an ALS that was virtually identical to the MALSR in the outer 1000 foot segment. Feedback from the pilot participants were mixed—some pilots reported that this version was as good as a standard ALSF-2, while others said there was a big difference. Negative comments included that directional, lateral, and height guidance were affected, and the transition to approach lighting was delayed. Overall acceptability dropped to 89.8%, compared to 99% for the standard ALSF-2. Objective performance was comparable between the two configurations—the missed approach rate was 2 out of 45 for the modification, compared to 1 out of 45 for the standard ALSF-2.

The second modified ALSF-2 included three lights, in lieu of five, per CL barrette, with no changes to the outer 1000 foot segment. The majority of pilot participants reported that there was little difference between three and five lights, and that a typical pilot may not notice the difference. This configuration had an average acceptability rating of 97.7%, and all pilot participants agreed that this configuration warrants further consideration as a replacement to the standard five light ALSF-2. Further, the missed approach rate of 1 out of 45 was equivalent to that of the standard ALSF-2. The third modified ALSF-2 option was essentially a combination of the first two configurations—that is, 200 foot spacing between sequenced flashing lights in the outer 1000 foot segment, and reduced density CL barrettes to include three lights in the inner 1400 feet of the ALS. Again, feedback was largely inconsistent across pilot participants—some pilots thought that roll guidance was lacking, and that the ALS could more easily be confused with just some lights. Acceptability for this reduced-density configuration was 90%, and was associated with a missed approach rate of 2 out of 45 approaches. It would appear that there was little difference between the two modified ALSF-2 configurations, though 27% of pilot participants thought these modified ALSs were an unacceptable replacement for a standard ALSF-2 for low visibility operations. The results do give strength to the contention that a reduced density centerline barrette may be as effective as a five light centerline barrette.

In a more recent comparison of a standard ALS with an All-Strobe Approach Lighting System (ASALS), Seliga et al. (2008) evaluated an all-strobe approach lighting system as a replacement to MALSR for CAT I precision approaches. In contrast to other FAA-led evaluations of approach lighting, this evaluation was not motivated by economic considerations, but rather was a response to a Congressional inquiry. In particular, the primary claims of the developers for the novel ASALS included that the standard MALSR lighting contributed to accidents and incidents due to increased glare, and that the ASALS had a visual advantage in that they would allow pilots to maintain a state of dark adaptation upon landing. However, there was little support for this contention in the vision science literature or based on aviation accident reports. Nevertheless, flight evaluations using an FAA King Air N35 were conducted with the novel ASALS system, using the standard MALSR as a reference.

ASALS consisted of 28 omnidirectional sequenced flashing lights and two modified Runway End Identifier Lights (REIL; Seliga et al., 2008). As an aside, the basic ALS, ODALS, is the only ALS currently in the U.S. NAS that also uses omnidirectional lighting. Overall, ASALS shares a similar light pattern to MALSR, with major differences including that the ASALS centerline barrettes are composed of three omnidirectional strobe lights instead of the five steady burning lights found with MALSR, and that the ASALS does not include green runway threshold lighting—instead it includes 2 REIL lights. Both ASALS and MALSR are 2400 feet in length, with sequenced flashing lights located in the outer 1000 foot segment, and a 1000 foot decision bar to provide position information.

Results from the evaluation suggested that both objective flight performance the subjective pilot feedback supported the MALSR as the superior ALS. Specifically, using the MALSR, pilots were more likely to stay within 41 feet of the extended runway centerline compared to the ASALS, 93% versus 88%. Pilot feedback included that the ASALS did not convey proper visual guidance if the approach was flown with a greater deflection from the centerline. Additional comments included: “something missing”, “lacks contrast”, or “a black hole”. Further, the pilot participants reported that the ASALS system did not provide any advantage in visual acuity upon touchdown, compared to the standard MALSR. It was concluded that the strobe lights were useful for detection at higher altitudes, but at DH, there is a benefit to steady burning lights.

Results from these evaluations on precision approach performance demonstrated that the pilot participants found it acceptable and performance (% missed approaches) was largely unaffected when the number of lights in each CL barrette of MALSR and ALSF-2 type lights were reduced from five to three (Katz, 1996; Gallagher, 2002). While reducing the number of lights contained within each CL barrette would not reduce the real estate requirements for new ALS installations, there would be a financial benefit in terms of reduced costs for installation, maintenance, and operations over the life of the ALS. MALSR and ALSF-2 incorporating three lights into CL barrettes were well accepted by pilots, and no significant increase in missed approach rate was observed. Altering the number of steady-burning lights or increasing the spacing of strobe lights from 100 feet to 200 feet for ALSF-2 was not recommended (Gallagher, 2002).

7.2 Evaluations of ALSs with Reduced Components for Non-Precision Approaches

In the previous section, research on runway approach lighting infrastructure to support precision approaches was discussed. However, many smaller airports do not have precision approaches available on all runways. In the 1960s, the FAA sponsored research focused on approach lighting for non-precision instrument approach and landing operations, with an emphasis on identifying cost effective visual aids at smaller airports to expand low visibility operations. These studies evaluated alternatives, including simplified versions of what was considered the standard ALS at the time, as well as the feasibility of replacing a standard ALS with a strobe light alternative (Paprocki, 1963; Weinstein, 1969).

In the first such example, Paprocki (1963) evaluated simplified lighting aids for potential use for non-precision approaches at smaller airports. At the time, the U.S. policy was to install the Shortened Precision Approach Lighting System (SPALS)[2] for use at non-precision runways. The SPALS was a shortened and simplified version of the full ALS that was used for precision approaches (see Paprocki & Gates, 1966). However, even though the SPALS was already considered a simplified type of ALS, it was still cost prohibitive for widespread installation and was thought to be more complex than required for non-precision instrument approaches at low traffic airports. In response, alternatives including two simplified ALSs and approach beacon system lights were evaluated as a potential cost-effective alternative for non-precision instrument approaches at low traffic airports. The approach beacon light system was a simple design that consisted of two lights placed at 2000 and 3000 feet away from the runway threshold in the approach zone.

[2] The Shortened Precision Approach Lighting System (SPALS) was the standard U.S. Approach Lighting System shortened to 1500 feet (from 3000 feet), without sequenced flashing lights. CL barrettes were spaced every 100 feet, with a 1000 foot decision bar.

The two simplified ALSs included the SPALS, and also the Simplified Approach Lighting System[3]. The Simplified Approach Lighting System was 1400 feet in length, with 200 feet spacing between CL barrettes, and a 1000 foot decision bar. Briefly, the Simplified Approach Lighting System was 100 feet shorter than the SPALS, with 200—instead of 100—feet spacing between CL barrettes. Pilots flew approaches in nighttime conditions, and provided subjective feedback on the effectiveness of the ALS. Not surprisingly, the pilot participants reported that the approach light beacons were not effective for use alone when compared to the SPALS or Simplified Approach Lighting System. When comparing the SPALS and Simplified Approach Lighting System to each other, pilots did not have a strong preference between the two systems. This suggested that a spacing of 200 feet between lighting components might be as effective as 100 feet in certain visibility conditions. Results from actual aircraft test flights were able to support a simplified and less ALS replacement for what was at the time, the U.S. Standard (i.e., SPALS).

In a similarly motivated study, the feasibility of using RAIL for runway identification and guidance for non-precision instrument approaches at smaller airports was evaluated (Weinstein, 1969). In this study, MALS served as the standard ALS for a point of reference (Figure 3.2). The individual light components for RAIL would be less expensive to install and maintain, so there would be a financial advantage if it provided adequate visual guidance, though the required real estate for installation would not be significantly reduced. The RAIL system consisted of six sequenced flashing lights, aligned along the runway extended centerline, spaced 250 feet apart for a distance of 1500 feet away from the runway threshold in the approach zone (Figure 7.2).

[3] The acronym for the Simplified Approach Lighting System is the same as that used for a current ALS in the U.S. NAS that has a different configuration. Therefore, the full name instead of the acronym will be used to avoid any confusion.

Figure 7.2
RAIL layout.

Note. The configuration used by Weinstein (1969) included four green threshold lights on either side of the runway, rather than a row extending the entire width of the runway threshold.

The MALS system was constructed with seven CL barrettes, each with five steady burning lights. The barrettes were spaced 200 feet apart for a total length of 1400 feet, with two additional barrettes installed at 1000 feet to form a decision bar, and three sequenced flashing lights in the outer 400 feet. The MALS lighting system described by Weinstein is roughly equivalent to a MALSF approach light system (Figure 3.3). Pilot participants flew non-precision approaches during both day and night IFR and Visual Flight Rules (VFR) conditions. Based on pilot feedback, it was concluded that RAIL would not be a viable replacement for the MALS (i.e., MALSF) system for non-precision instrument approaches.

Although RAIL provided earlier identification and displacement information in all weather conditions with the exception of VFR night operations, there was a significant concern with glare during VFR night operations for the lights nearest the runway threshold. This was true even after attempting to adjust the light intensity and utilizing glare shields. In fact, the pilots reported that within 1000 feet of the runway threshold, the lights were distracting and hazardous. Overall, the MALS system was considered the better approach light aid. MALS provided adequate approach guidance for VFR/IFR day and night operations, and provided better height and roll guidance. Further, there was a concern that the RAIL system did not provide adequate roll and height guidance. It was concluded that it is uncertain if pilots were able to derive these elements of guidance from other visual cues during actual flight; however, in simulation tests in which no other visual cues are available, pilots have had extreme difficulty obtaining roll or height guidance from strobe lighting alone (McKelvey & Brown, 1964).

Results from investigations into non-precision approach and landing operations have demonstrated that CL barrettes provide roll guidance that is absent with strobe or sequenced flashing lights alone, and that a spacing of 200 feet between CL barrettes may be as effective as 100 feet spacing, depending on visibility conditions.

8. "Black Hole Effect" and ALSs

Flying over featureless terrain at night, as when landing over water, snow, or darkened areas, may lead a pilot to overestimate his or her altitude, resulting in a sometimes dangerously low glide path during approach and landing operations. This phenomenon has been termed the "black hole effect" or "black hole illusion", and has been associated with dangerously low or concave-shaped approaches, as well as aviation accidents. The black hole effect is especially a concern when flying into unfamiliar airports, making approaches to a narrow runway, or when runway edge or end lights are the only lights visible in the runway environment (Mertens & Lewis, 1981; 1982).

The FAA and others found ALSs do not have an operationally significant effect on approach angle, regardless of ALS brightness, length, or type (i.e., 1400 foot SSALS versus 3000 foot ALSF-2; Figure 7.1 and Figure 3.4, respectively; Mertens & Lewis, 1981; 1982). Further, reconfiguring an ALSF-2 type ALS to include lights on the side of the runway to decrease the perceived runway aspect ratio was also found to be ineffective in protecting against the black hole effect (Gibb et al., 2008). In fact, simulated approaches flown with no ALS, and a reconfigured ALS were associated with better performance in terms of altitude deviation compared to the standard ALSF-2 (Gibb et al., 2008).

These results suggest that even the most complex ALS in the U.S. NAS—the ALSF-2—does not protect against the black hole effect (Mertens & Lewis, 1981; 1982; Gibb et al., 2008), and that increasing the number of objects around the runway also did not improve vertical glide path performance (Gibb et al., 2008). It is likely that an ALS may perceptually increase the apparent runway ratio, causing the runway to appear narrower than it is in reality. This reinforces that the purpose of an ALS is to extend the runway environment toward the incoming pilot, but not necessary to provide cues on altitude or height above the ground. The same ALS that may increase safety in low visibility conditions may also induce pilots into dangerously low approaches at night when terrain features are absent.

There is some evidence that glide path indicator systems, such as the Visual Approach Slope Indicator (VASI) or the Precision Approach Path Indicator (PAPI), reduce deviation from a standard 3° glide path, leading to safer, more stabilized approaches (Lewis & Mertens, 1979). This was true even without ILS information, and when runway lighting was the only other cue providing vertical guidance. However, accidents attributed to the black hole effect have still occurred when PAPIs were available, such as with a Boeing 727 cargo plane crash in 2002 (National Transportation Safety Board, 2002). There is some evidence that reduced scene content results in shallower glide path (Lintern & Walker, 1991), suggesting that perhaps new enabling technologies that increase visual cues, such as synthetic, enhanced, or combined vision systems, may help address Controlled Flight Into Terrain (CFIT) concerns in certain conditions, though many questions remain. The gold standard countermeasure against the black hole effect remains pilot training to help pilots become more knowledgeable about their ecological perception.

9. Runway Lighting Systems

9.1 Runway Threshold Lighting

Although green runway threshold lighting is currently standard to all ALSs in the U.S. NAS—with the exception of ODALS—this was not always the case. In the late 1970s, MALSR-type ALS that did not include green threshold lights, were installed on airports that previously did not have approach lights. Instead, these MALSR-type ALSs relied on the airport system of green threshold lights, which usually included only four lights on each side of the runway threshold (for example, see Figure 7.2). These reduced density runway threshold lights were largely viewed as inadequate by air carrier, general aviation, and military for non-precision and CAT I approach operations (Brown, 1978). In response, the FAA evaluated the visual guidance provided by green runway threshold lighting and red wing bar lighting as potential additions to MALSR-type lighting systems. Configurations that included red wing bar lights with three or five red lights were paired with green threshold light configurations (Brown, 1978). Additionally, the green threshold lights were evaluated without red wing bar lights.

Flight tests were conducted in VFR dusk, VFR nighttime, VFR daytime, and when visibility was restricted to 1.5 miles due to fog and rain. In general, pilots reported that the same type of lights should be used across the threshold, rather than using individual lights of different brightness to “fill-in” any gaps in the existing runway threshold lighting. When evaluating the visual guidance contribution of the red wing bar lights, used in combination with the green threshold lights, it appeared that the red wing bars did not provide any visual advantage under the test conditions. Pilots judged these red wing lights as “not needed” if there was a bold threshold lighting available. Specific comments included that red wing bar lights with only three red lights outboard of the runway edge lights could be confused with red obstruction lights, or confused with VASI lights. However, two pilots reported that the five light red wing bar lights provided cues useful for roll guidance.

Overall, strengthening the threshold guidance signal was the most important improvement to the MALSR-type ALS, as well as maintaining a reasonable balance of brightness between individual green threshold lights and other runway and approach lights. It is noteworthy that the only type of ALS in the U.S. NAS that currently uses red wing bars are

ALSF-type lighting. Results from Brown (1978) suggest that red wing bars may not be necessary when a bold green runway threshold lighting is available. However, future investigations should evaluate the visual guidance provided by red wing bar lighting in visibility conditions consistent with CAT II and III approach conditions.

9.2 Touchdown Zone Lighting

TDZL systems are installed on some precision approach runways to indicate the touchdown zone when landing under adverse visibility conditions. TDZL consist of steady burning white lights that start 100 feet beyond the landing threshold and extend to 3000 feet beyond the landing threshold or to the midpoint of the runway, whichever is less. Under extremely restricted visibility conditions, such as with CAT III operations, it is possible that the visual cues provided by standard TDZL may not be sufficient to maintain runway centerline positioning during the landing rollout. This is particularly true in the rare case of extremely low visibilities and a fail-passive type of auto-land system failure.

In response to this concern, the FAA evaluated both standard and three modified TDZL systems under extremely low visibility conditions (300 and 500 feet RVR), to determine if pilot crews could identify the centerline of the runway in CAT III conditions if they had an auto-land system failure (Jones, 1990). The modified patterns had a directional pattern aspect created by de-energizing certain lights in the TDZ system, or by moving lights either longitudinally from the threshold or laterally from the centerline. All simulated approaches were auto-land with the pilot instructed to manually correct to centerline after touchdown; the aircraft was set to land 40 feet left or right of centerline, so that the pilot was required to use visual cues from lighting during rollout.

Overall, guidance to the runway centerline provided by the standard TDZL was found to be inadequate. Ten out of 14 pilots were able to determine their location relative to centerline at 300 feet RVR or lower. Further, only 9 out of 14 pilots reported the standard TDZL system as adequate at 300 feet RVR. Of the modified TDZL systems, the only one that showed promise was the lateral displacement TDZL system. Comparing the standard TDZL to the lateral displacement modified TDZL, more pilots were able to successfully accomplish the rollout completion with the modified system compared to the standard system, and all pilots were able to achieve adequate centerline orientation at or below 300 feet RVR with the modified system. Further, 13 out of 14 pilots reported that the modified lateral displacement TDZL system provided the additional guidance needed to determine the direction of the runway centerline.

These results suggest some operational benefit to providing directional information with lighting systems. The remaining two modified TDZL systems did not provide adequate visual guidance at the visibilities used in this study. The de-energized TDZL was interpreted by the pilot participants as having outages, and the longitudinal displacement TDZL was impossible to interpret when landing at high speeds and a low viewing angle.

In conclusion, during reduced visibility of 300 to 500 feet RVR with an auto-land system malfunction delivered to a touchdown point immediately over the TDZ lighting system, a pilot does not have sufficient lateral guidance to recapture the runway centerline during rollout using a "fail-passive" system using standard touchdown zone lighting. At 500 feet RVR or greater visibility, standard TDZL, centerline, and edge lighting systems do provide adequate visual cues to allow the pilot to complete the landing and rollout manually. Insufficient visual guidance from standard TDZL is only a problem if two conditions occur at the same time: 1) malfunction of the auto-land / rollout system that would cause the aircraft to touch down more than 40 feet to the right or left of runway centerline; and 2) visibility within the 300 to 500 foot RVR range or lower. The likelihood of the above situation existing would be extremely rare. Additionally, with new advanced in-cockpit vision systems, there may be less reliance on runway infrastructure to support safe landing operations, even at extremely low visibility conditions and with the rarest of autoland malfunctions.

9.3 Runway Edge Light Systems

Runway edge light systems are used to outline the edges of a runway during periods of restricted visibility. These systems are classified according to the intensity or brightness level of their light sources, as High Intensity Runway Lights (HIRL), Medium Intensity Runway Lights (MIRL), and Low Intensity Runway Lights (LIRL). During approach and landing operations in restricted visibility conditions, runway edge lighting may provide the additional visual guidance necessary for safe and efficient landing performance. In fact, the FAA has demonstrated the contribution of runway edge lighting systems to safe and efficient instrument approach and landing performance during simulated approach and landing operations (e.g., Billmann et al., 1994).

The results from this evaluation suggested that flight crews were able to operate to lower approach minima than standard CAT I without full CAT II approach and runway lighting, and that performance and participant pilot feedback was largely dependent on the runway edge lighting system configuration. It would also appear that the runway edge lighting system had a greater influence on pilot feedback and successful flight performance than other types of runway lighting, including runway CL and TDZL. Further, the influence of the ALS (MALSR versus ALSF-2) on successful performance was largely dependent on the type of runway edge lighting system included in the test configuration. For example, there was no appreciable difference in flight performance and pilot feedback between MALSR/HIRL and ALSF-2/HIRL configurations using a DH as low as 100 feet and an RVR as low as 1200 feet. However, the MALSR/MIRL configuration was viewed as inadequate for operations below standard CAT I levels.

The results from this evaluation further indicated that on reduced minima approaches, once the pilot emerges into visual conditions, approach completion probabilities were equivalent for ALSF-2/HIRL and MALSR/HIRL. It would appear that the benefits of a CAT II ALS (ALSF-2) were mitigated by the fact that when the aircraft breaks out of the weather at a lower DH, most of the ALS is behind the aircraft. Results from this evaluation also suggest that runway edge lighting systems provide critical visual cues to support instrument approach and landing procedures at the lower visibilities.

10. In-Cockpit Enabling Technologies and ALSs

10.1. Head-up Displays

Conformal HUDs replicate information on a pilot's conventional flight instruments, and provide a flight-path symbol capable of showing the pilot where the aircraft is going relative to real-world positioning (Goteman et al., 2007). The advantage of a conformal HUD to low visibility approach and landing flight performance was demonstrated using European ALSs of both intermediate length and full length[4] (Goteman et al., 2007). In this evaluation, the width of the touchdown footprint was reduced when a HUD was provided for the low visibility approach and landing, though the length of the touchdown footprint and overall landing success rate were not affected. This lateral deviation from centerline performance improvement was observed when approaches were flown at both the standard RVR and an RVR that was lower than the current standard. Specifically, when using an ALS of an intermediate length (1400 feet) the performance benefit of a HUD was observed with a standard RVR of 2230 feet and also with a less than standard RVR as low as 1800 feet. When the ALS was a full length of 2950 feet, the lateral deviation performance benefit of a HUD was observed at both a standard RVR of 1800 feet, and a less than standard RVR of 1476 feet. It is important to note that these two evaluations were not designed to directly compare a longer ALS to a relatively shorter ALS, but rather, to examine the effect of conformal HUD use on landing success and performance in two different types of flight environments.

In general, it was found that the performance benefit of using a HUD was similar when using a longer ALS and a shorter ALS system. Based on the performance data, it would appear that the minimum RVR for approach and landing operations conducted when using a HUD with flight-path symbology could be set to a lower RVR value, while maintaining a similar or even smaller lateral centerline deviation touchdown footprint.

10.2 Synthetic Vision

In-cockpit enabling technologies, such as synthetic or enhanced vision systems, may provide a visual advantage to support low visibility approach and landing operations that are independent of the actual weather or visibility conditions. In particular, synthetic vision systems provide a computer-generated image of the external scene topography that is generated from aircraft attitude, high-precision navigation, and data of the terrain, obstacles, cultural features, and other required flight information (Kramer et al., 2008). Synthetic vision may provide

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[4] The approach lighting systems were defined in the European regulations as Full Approach Light facilities (≥ 720 m) and Intermediate Approach Light facilities (420 to 719 m; Joint Aviation Authorities, 2004).

enhanced situation awareness, and support terrain and location awareness, potentially reducing CFIT accidents. It is feasible that, when a Synthetic Vision System (SVS) is available in the cockpit, the visual cues provided by approach and runway lighting could be reduced and not affect safety and performance of the low visibility flight operations. This may be especially true when compared to in-cockpit technologies, which do not provide a visual scene of the flight environment, such as a traditional HUD.

However, it has been demonstrated that runway and approach lighting may still have influence on some aspects of low visibility approach and landing flight operations, even when synthetic vision is available (Kramer et al., 2008; Ellis et al., 2011). In a simulated approach and landing flight test evaluation, pilots flew approaches with visibility levels of 3 miles, 2400 feet, 1800 feet, or 1200 feet RVR. Here, the ALS types were MALSR (CAT I), ALSF-2 (CAT II/III), and a VFR configuration (Kramer et al., 2008). The CAT I approach configuration included MALSR, REIL, PAPI, full threshold lights, and MIRL. The CAT II/III ALS configuration represented a standard CAT II approach configuration, and included ALSF-2, TDZL and CL, REIL, PAPI, full threshold lights, and HIRL. The VFR configuration consisted of REIL, PAPI, partial threshold lights, and MIRL—an ALS was not included as part of the VFR configuration. In general, when SVS was available, the type of ALS had no effect on ratings of situation awareness or subjective workload (Kramer et al., 2008).

Further, objective performance such as touchdown performance seemed to be less impacted by ALS configuration. For example, the majority of approaches were within performance based approach and landing criteria in all visibility conditions regardless of ALS configuration or DA. However, ALS type did have an effect on the ability to continue an approach below the DA, based on visual reference to the lighting infrastructure. To be specific, when flying to a DA of 100 feet with an RVR of 1200 feet—the lowest RVR utilized in this evaluation—the likelihood of completing an approach significantly increased when using a MALSR or ALSF-2 ALS, when compared to a VFR lighting configuration. In fact, at 1200 feet RVR, the VFR ALS configuration was associated with only a 51% chance of concluding to a touchdown, compared to at least 85% when using MALSR or ALSF-2 configurations.

However, it is important to note that the VFR configuration did not include CL or TDZL. Ellis et al. (2011) demonstrated that visual glances out-the-window during the landing segment increase when TDZL and CL are provided—even with SVS inside the cockpit. In this example, simulated approaches were flown at an RVR of 1400 feet, DH of 150 feet, and MALSR lighting (Ellis et al., 2011). This suggests that, regardless of SVS, lighting infrastructure may support early visual acquisition of the runway environment, or at least draw attention outside of the cockpit environment to the runway environment.

10.3 Enhanced Flight Vision System

Enhanced Flight Vision Systems (EFVS) provide a real-time external scene of the flight environment generated by sensors, normally placed in the nose cone of the aircraft, just beneath the windshield or bottom of the nose. A number of studies have evaluated low visibility approach and landing operations while using EFVS, and have found that lower than standard visibility minima approaches may be feasible (Etherington et al., 2015; Prinzel et al., 2015), and that there may be some advantage in terms of performance with EFVS compared to SVS (Kramer et al., 2011; Kramer et al., 2015). Here, the relationship between approach and runway lights, and in-cockpit advanced vision concepts will be reviewed.

As previously stated, EFVS concepts may have an advantage in terms of supporting low visibility approach and landing operations, when compared to traditional HUD, Heads Down Display (HDD), or SVS technologies. For example, it been demonstrated that flying simulated approaches using EFVS HUD concepts in visibilities as low as 300 feet RVR with MALSR or ALSF-2 (Etherington et al., 2015), and 1000 feet RVR with MALSR and HIRL (Kramer et al., 2011; Prinzel et al., 2015) may be operationally feasible. This is true for both straight-in approaches, and with an off-set that is up to 15° on runways with ASLF-2 approach lights and an RVR of 4000 feet (Kramer et al., 2015).

Further, when using an EFVS HUD, TDZL and CL seemed to have little impact on approach and landing performance, suggesting that instrument approach operations at visibilities as low as 300 feet RVR may be feasible, even without runway lighting such as TDZL and CL (Etherington et al., 2015). However, it should be noted that TDZL and CL may be important for operations in which EFVS HUD is not available. For example, the presence of TDZL and CL had a profound effect on if the landing was even attempted on approaches in which only a traditional HDD was available (50% without TDZL/CL versus 92% with TDZL/CL; Kramer et al., 2011). Additionally longitudinal touchdown position on approaches with a HUD or SVS HDD was improved when TDZL and CL were present.

In summary, approaches with EFVS HUD seem to be feasible at lower than standard visibility minima regardless of runway lighting infrastructure, when evaluated with MALSR and ALSF-2 approach lighting (Etherington et al., 2015; Kramer et al., 2011). Runway lighting may be more important for those approaches in which SVS, HUD, or HDD are utilized (Kramer et al., 2011).

11. Conclusion

This literature review has provided a historical perspective on ALS research from the FAA and others, including the relationship between the ALS, flight performance, and subjective pilot experience during low visibility approach-to-land operations. Other topics were also reviewed, including desired visual guidance, and the impact of runway lighting and enabling technologies such as onboard vision based technologies on these low visibility operations.

Airfield lighting augments capability for conducting low visibility approach-to-land operations, with approach lighting serving as the bridge from instrument to visual flight. In fact, the vast majority of flight operations are see-to-land, thus offering the opportunity for lighting to be involved. For an ALS to be effective, visual flight in the approach zone requires certain visual cues for safe operation. These cues include the following: identification, alignment, roll guidance, flight guidance, distance, and positive threshold definition. Many of the critical key features originally identified by Calvert in the 1940s and 1950s are included in modern ALSs, including an extended runway centerline and transverse bars to provide an artificial horizon for distance, bank, and lateral deviation cues.

ALSs are expensive to both install and maintain, and are not feasible for all runways due to availability of real estate or terrain restrictions (e.g., wetlands or mountains). Based on the results of this literature review, it was determined that certain modifications to standard ALSs may be acceptable, without having a significant impact on flight performance or safety. For example, it may be feasible to reduce the density of steady burning light barrettes from five lights to three, without having a significant effect on roll guidance (Katz, 1996; Gallagher, 2002). This modification would not reduce the overall real estate required for new ALS installations, but would reduce installation and maintenance costs over time.

The results from four separate evaluations indicated that strobe-only approach lights may not be sufficient to support low-visibility precision approaches due to reduced roll guidance, particularly when the aircraft is not exactly aligned with the extended runway centerline (Paprocki, 1963; McKelvey & Brown, 1964; Weinstein, 1969; Seliga et al., 2008). However, other questions remain, such as the effect of high intensity steady burning lights as opposed to medium intensity lights, to support CAT I approaches. MALSR lighting utilizes medium intensity individual lights with a minimum length of 2400 feet, but some research suggests a shorter 1400-foot ALS with high intensity lighting (i.e., SSALS) may be feasible (Gallagher, 2002). However, this flight evaluation was conducted at a higher visibility of 3200 feet RVR, rather than CAT I visibility of 2400 feet RVR. Future evaluations interested in the relationship between lighting intensity and ALS size would need to evaluate the configuration at minimum or less-than-minimum visibility conditions for the approach category of interest.

Factors that can influence the effectiveness of an ALS include both the visibility conditions during which the lights will be used and the maneuverability of the most critical aircraft using the lighting system. For example, CAT II and III operations involve aircraft with high approach speeds at the lowest of visibilities. In these conditions, it is important to consider that the majority of the ALS may be behind the aircraft at the point when the flight crew makes visual contact with the approach or runway environment. In this circumstance, the vast majority of the expansive ALSF-2 lighting array simply may not be seen, and thus, is unusable during a very low visibility CAT II or III approach. In these conditions, the lighting aids that may be more helpful for transitioning from instrument to visual approach may include runway edge lights, threshold lights, and TDZL and CL (McFarland, 1998; Billmann et al., 1994).

New advances in enabling technologies, such as onboard vision-based technologies, may obviate or reduce the need for some of the runway and ALSs detailed in this report. These advanced vision systems, including synthetic vision, enhanced vision, and combined vision, may provide "equivalent vision" capabilities, allowing the flight crew to visually acquire the approach and runway lights or environment in lower visibility conditions than natural vision would allow.

Future investigations should consider the role of enabling technologies inside the aircraft, in addition to airport infrastructure outside the aircraft. Landing of an aircraft in all kinds of visibility conditions cannot be accomplished with certainty because of approach or runway lighting alone, but will require a combination of airport infrastructure as well as technologies located within the cockpit.

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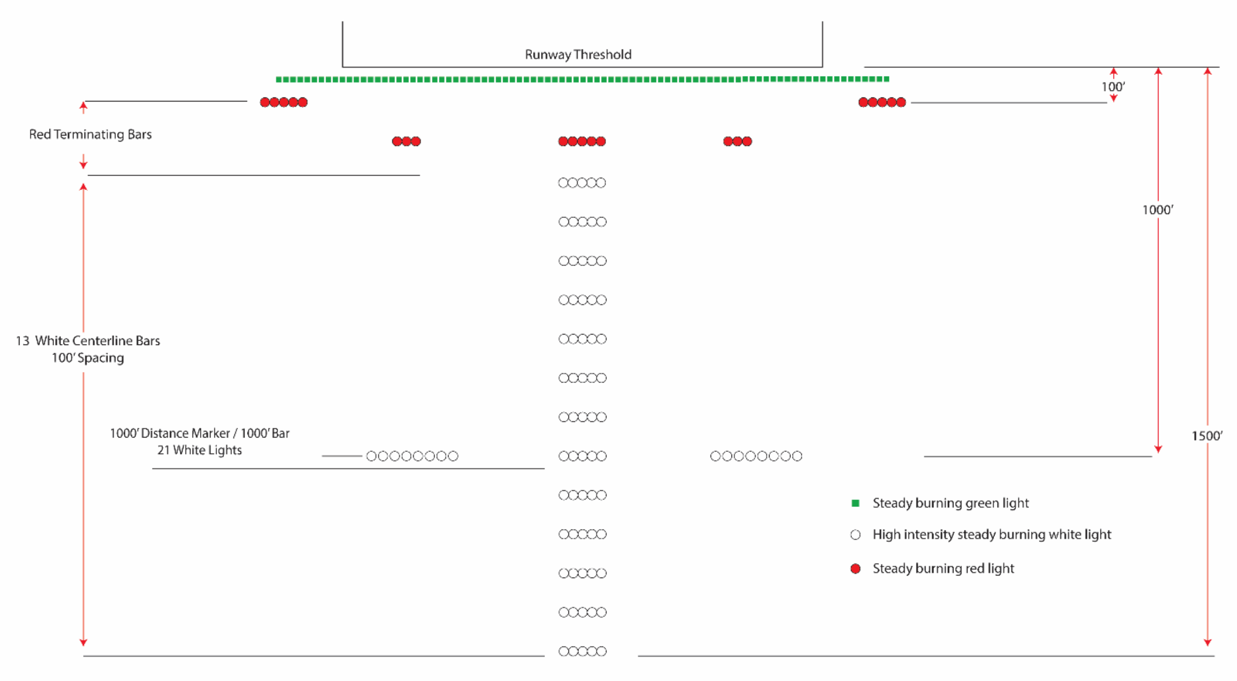
Appendix A: SALS Layout



Appendix B: SALSF Layout