Advancing Low Visibility Technologies through Industry and Government Collaboration

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Biographies:

Sally Frodge is a Systems Engineer with the FAA Navigation Services, FAA HQ. She is the Program Manager for the Enhanced Low Visibility Operations Program (ELVO), sponsored by FAA Flight Standards. Prior experience includes work with DOT OST, with duties such as spectrum protection, CoChair with her DoD counterpart on the group charged with developing issues leading to the selection of the GPS L5 frequency, and spectrum policy coordination.

Brendan English is Computer Systems Engineer at the DOT Volpe National Transportation Systems Center (Volpe Center) supporting various low visibility initiatives within the FAA. Brendan manages the Volpe Center's Otis Weather Test Facility, an outdoor weather laboratory located in Cape Cod Massachusetts. Brendan's passion for low visibility research derived from his operational experience as a U.S. Air Force officer and pilot flying helicopters on multiple deployments in a variety of low visibility conditions.

Brian O'Donnell is a subject matter expert in image and signal processing and visible and infrared imaging and works for Stinger Ghaffarian Technologies conducting work at the DOT Volpe National Transportation Systems Center (Volpe Center). Brian formerly worked for BAE Systems where he led algorithm research and development for the Army's Thermal Weapon Sight program, the Enhanced Night Vision Goggle program, and several other programs.

Alison Bisch is an Engineering Psychologist for the Aviation Human Factors Division at the DOT Volpe National Transportation Systems Center (Volpe Center). Prior low visibility research includes the assessment of airport signs, markings, and lighting to ensure interoperability with NextGen flight deck technologies for low visibility operations and to support pilot tasks in high-density, low visibility ground operations.

Abstract

Aircraft landing and taking off in low visibility is a critical area for aviation and the aviation industry. Flights can be cancelled, diverted, or delayed if aircraft cannot land or take off in low visibility. This impacts all users and stakeholders of the National Airspace System (NAS), including passengers and freight operators. Low visibility can develop from a variety of weather conditions to include fog, causing air traffic to move from Visual Meteorological Conditions (VMC) under Visual Flight Rules (VFR) to Instrument Meteorological Conditions (IMC). During IMC, aircraft are under Instrument Flight Rules (IFR) and only those aircraft that are appropriately equipped with appropriately trained crews can continue operations. If aircraft could be equipped such that flight operations could continue for a longer period of time while weather conditions degrade, more operations could continue to land and/or depart. The alternative is diversions to other airports or delayed take offs. There are great benefits to improving low visibility capabilities and this is exactly what the FAA is implementing.

In a combined effort, and as part of the Next Generation Air Transportation System (NextGen), the FAA is in the initial stages of implementing increased low visibility capabilities in an effort initiated and led by FAA Flight Standards and supported by Navigation Services. Prior to this work, Standard Category (CAT) I, CAT II, and CAT III were available. Minima are defined by the Runway Visual Range (RVR) system. New levels of service include take offs with a minimum as low as 500', as well as landing operations that include RVR 1800 (vice RVR 2400), Special Authorization (SA) CAT I, and SA CAT II. These Special Authorizations allow for advantages such as lower RVR-defined minima, lower Decision Altitude (DA), and for SA CAT II, lower life cycle costs for the infrastructure over the Standard CAT II services. In an oversimplification, Flight Standards grants operational credit for equipage such as the Head Up Display (HUD), Flight Director (FD) and Autoland so that such aircraft suitably equipped can continue with operations in conditions where other aircraft may have to be diverted. More detailed information related to this effort can be found in [Frodge 2013][1]

In addition to the improved SA levels of service, the FAA has approved straight-in landing operations below Decision Altitude (DA), Decision Height (DH) or Minimum Descent Altitude (MDA) via 14 CFR 91.175 (l) for aircraft equipped with Enhanced Flight Vision Systems (EFVS). In the simplest of terms, an aircraft operator can potentially benefit from this technology by using EFVS in lieu of natural vision to descend below DA/DH or MDA down to 100' above the touchdown zone elevation on any straight-in instrument approach. Under 14 CFR 91.175(l), EFVS technology provides aircraft operators with the ability to conduct low visibility approach operations at thousands of additional airports across the NAS rather than being restricted to a limited quantity of airports with CAT II or CAT III systems or only airports with SA approaches. Recently, in June of 2013, the FAA released a Notice of Proposed Rule Making (NPRM) that would permit operators to use an EFVS in lieu of natural vision to continue to descend from 100 feet above the touchdown zone elevation to the runway and land. Additionally, this NPRM would

[1] Enhanced Low Visibility Operations -- Increasing Flight Operations Services in the National Airspace System in Low Visibility Conditions, ION Conference MMM-2013, Frodge, Hope, Houghton

permit operators with EFVS to dispatch, release, and take-off when the destination weather is below authorized minimums[2].

With the advancement of technology and rulemaking, there are great opportunities to improving low visibility capabilities. However, as technology evolves, the Industry and Government are presented with additional challenges. More specifically, this paper looks at the challenges associated with understanding the performance of EFVS systems in a diverse set of low-visibility conditions. Weather impacts the performance of EFVS sensors and performance across manufacturers varies. Additionally, approach lighting systems may vary in layout and lighting technology, which also impact EFVS operations. These variables all contribute to the complexity of certifying EFVS equipment and of issuing authorizations to conduct EFVS operations. A quantifiable and repeatable method of assessing performance of EFVS technologies could significantly reduce the time and cost to certify an EFVS, permit new technologies to be introduced more rapidly compared to current processes, and help the FAA develop appropriate operating conditions and limitations used in authorizations to conduct EFVS operations. In a collaborative effort between the Government and Industry, this is exactly what is being pursued.

Introduction

Many factors have contributed to the complexity of assessing the performance of EFVS technology. Since 2003, when the first EFVS NPRM was published, significant advances in EFVS technologies have been made. In 2007, Congress issued the Energy Independence and Security Act that has contributed to the development of LED technology to replace traditional incandescent lighting systems. The transition to LED lights directly impacts the performance of the IR-based EFVS systems. In addition, the 2013 EFVS NPRM is drafted with an emphasis on performance based certification of EFVS systems. Considering all of these factors, the industry and government have identified a critical need to effectively assess the performance of EFVS technology and related impacts on low visibility operations. As a result, several committees were formed to include RTCA SC-213 and SAE G-20.

The Volpe Center operates and maintains the Otis Weather Test Facility, a 255 acre outdoor weather test facility. The facility provides a range of over 2500' feet and is instrumented with towers and weather sensing equipment. The facility receives a variety of low visibility weather conditions to include fog, rain, and snow. More details about the facility are described in later sections of this paper. Additional background information can be found in [Seliga 2004][3]. Leveraging the adverse weather conditions at the Otis Weather Test Facility and the variety of weather sensing equipment, the facility can be used to assess the performance of EFVS technology. In the simplest of terms, the facility would be configured like a static CAT I approach

[2] Proposed Rule, 14 CFR Parts 1, 23,25, 27, 29, 61, 91, 121, 125, and 135; Federal Register Vol 78, No. 112, June 11, 2013.

[3] Seliga, T. A., and D. A. Hazen 2004: "The Otis Weather Test Facility at Otis ANGB, Falmouth, MA: An aviation weather resource", 11th Conference on Aviation, Range, and Aerospace Meteorology, 3-8 Oct, Hyannis, MA American Meteorological Society

where (1) the EFVS technology is mounted on a tower emulating the decision height and (2) lights would be mounted down range from the EFVS replicating the approach lighting system. As the facility is exposed to weather, data is captured from the EFVS and related weather measuring systems (e.g. RVR, particle size, etc.) where a correlation between reported visibility and visibility as perceived by the EFVS can be made.

The Volpe Center, in the form of Collaborative Research and Development Agreements (CRADAs), has solicited support and interest from EFVS manufacturers and lighting manufacturers to address related performance challenges. As part of the CRADA, the government provides the manufacturer with access to the Volpe Center's Otis Weather Test Facility and related data that is collected continuously at the facility. This data includes information from the EFVS as well as RVR, transmissometers, fog spectrometer, ambient light, wind speed/direction, barometric pressure and temperature. As part of the agreement, the EFVS manufacturer and/or lighting manufacturer provide equipment to the government at no cost. This collaborative effort offers benefit to both parties and is in the interest of both parties ultimately leading to:

1. defining repeatable metrics that can be used to assess the performance of EFVS technology,
2. minimize cost of performance assessment (when compared to flying),
3. access to extensive data collection sensors that would be cost prohibitive for a single company to maintain and operate and,
4. a facility to support development of future vision technologies.

Leveraging Previous Work

Aside from the known developments and implementations of EFVS, it is important to understand the physical basis for such applications. Of particular interest in this regard is a paper by the German National Research Center for Aeronautics and Space's (DLR) Remote Sensing Technology Institute.[4] As part of its project ADVISE (ADvanced VIsual Systems for Situational Awareness Enhancement), DLR investigated the theoretical basis for employing IR cameras as part of EVS to improve visibility under ICAO standard RVR CAT I, II, IIa and IIIc landing approach conditions. Computations were performed with the aid of the MODTRAN Version 4.0 atmospheric transfer model developed by the USAF over many decades of related research and measurements dealing with IR atmospheric transmissivity and visibility. The DLR study focused on transmission in the atmospheric windows of 3-5 μm and 8-12 μm compared to that in the visible band from 0.4-0.8 μm. IR sensor properties were based on the specifications of a specific IR camera that operates in the 8-12 μm band and whose threshold Noise Equivalent Temperature Difference (NETD) is 0.15^{o}K. The influence of the sensor's transfer functions on the contrast radiance was simulated with the TACOM Thermal Vision Model (TTIM) Version 3.1 that is part of the Physically Reasonable IR-Signature Model (PRISM). PRISM is a computational methodology for simulating thermal signatures of targets and backgrounds. The

[4] K. Beier and H. Gemperlein, Simulation of infrared detection range at fog conditions for Enhanced Vision Systems in civil aviation, Aerospace Science and Technology, 8, 63-71, 2004.

model computations included consideration of climatic and seasonal aerosol types and target parameters such as their size, temperature and emissivity factors. Additional insights into the subject matter can be found in the references cited in the paper as well as throughout the extensive IR imaging literature that has evolved over the last 50-years. The DLR study investigated whether use of IR cameras with autonomous target recognition can improve the range to detect objects compared to human visual ranges under defined meteorological conditions. More specifically, and of interest for this research, the DLR study leveraged a repeatable method to determine if a target was visible through a method of contrast and intensity ratio calculations.

A list of the relevant features of the study follows:

- Consideration of ICAO visual range categories CAT I, II, IIa and IIIc as the basis for comparing visual responses in the selected IR and visual spectral ranges
- Simulation of an IR-sensor with an automated software algorithm to detect and identify an airport runway and relevant obstacles
- Calculations that compare the achievable IR detection range for a typical state-of-the-art IR sensor, yielding results for
    - The spectral contrast transmission of the atmosphere at different distances for all wavelengths ranging from the visible spectrum to the LWIR at 8-12 μm.
    - CAT I conditions arising from mid-latitude summer, rural atmospheric aerosols
    - CAT II conditions arising from mid-latitude winter, radiation fog
    - CAT IIIa conditions arising from mid-latitude winter, advection fog

The authors consolidated their results in the following table (Table 1; DLR Table 5) that indicated calculated detection ranges in kilometers (km) in the Middle IR (MIR) and Thermal IR (TIR) bands for different CAT conditions, a temperature difference of a target to background of $\Delta T = 10^{o}$ K and a detection distance or range of distances defined by a sensor Noise Equivalent Temperature Difference (NEDT) threshold of 0.15^{o} K. Except for the latter sensor parameter, these results represent the effects of the atmosphere on visibility in the MIR and TIR spectral bands.

CAT	Visibility VIS (km)	Detection Range (km) MIR 3-5 μm	TIR 8-12 μm
I	1.22	3.0-9.8	5.9-10.1
II	0.61	0.54	2.4
IIIa	0.305	0.294	0.293
IIIc	0.092	0.089	0.087

Table 1 - Calculated Runway Visual Range (RVR) or detection range performance in the IR under varying meteorological conditions compared to normal RVR in the visible spectral region of light (Beier and Gemperlein, 2004). Note that these results do not account for the sensor transfer characteristics that limit the spatial and radiometric resolution of the IR camera.

The range of IR RVR values under CAT I conditions reflects differences due to different climate and aerosol models. Notably, both IR spectral regions exhibited significantly enhanced visibilities of more than a factor of two and as much as more than a factor of eight in both the MIR and TIR bands. Aside from the results presented in the table, the study found that the TIR lowest visibility was associated with tropical climate at high absolute humidity in combination with maritime aerosols while the best TIR performance occurred in wintertime conditions with low absolute humidity and rural aerosols. The best MIR performance was associated with climatic conditions with high temperatures such as occur during summer and in tropical regions.

Under CAT II conditions, the TIR spectral region gave a factor of four improvement in visibility, while the MIR region showed no improvement (slight degradation) in visibility. For CAT IIIa and CATIIIc conditions, neither the MIR nor TIR bands showed any improvement in visibility over the visible spectrum.

The DLR study identified the capabilities of early generation IR cameras. Today's generation of IR cameras and EVS systems have demonstrated vast improvements in visibility performance under low visibility conditions. There are a wide variety of EVS products that include night vision goggles (NVG), un-cooled/cooled IR systems, and multi-spectral systems. All of these products utilize varying technologies to provide a pilot with an IR image that is useful during night and day conditions that include various types and degrees of low-visibility conditions. These systems operate across different frequencies and provide varying images based on environmental conditions. However, ***performance across EVS products can vary greatly***. The DLR report is an important study that attempts to quantify IR visibility performance relative to normal RVR visibility values. As part of the collaborative process, the government and industry are working together to promote the quantification of visibility in order to baseline EFVS technology and provide repeatable metrics that can be used to assess the performance of EVS imaging technologies.

Test Environment

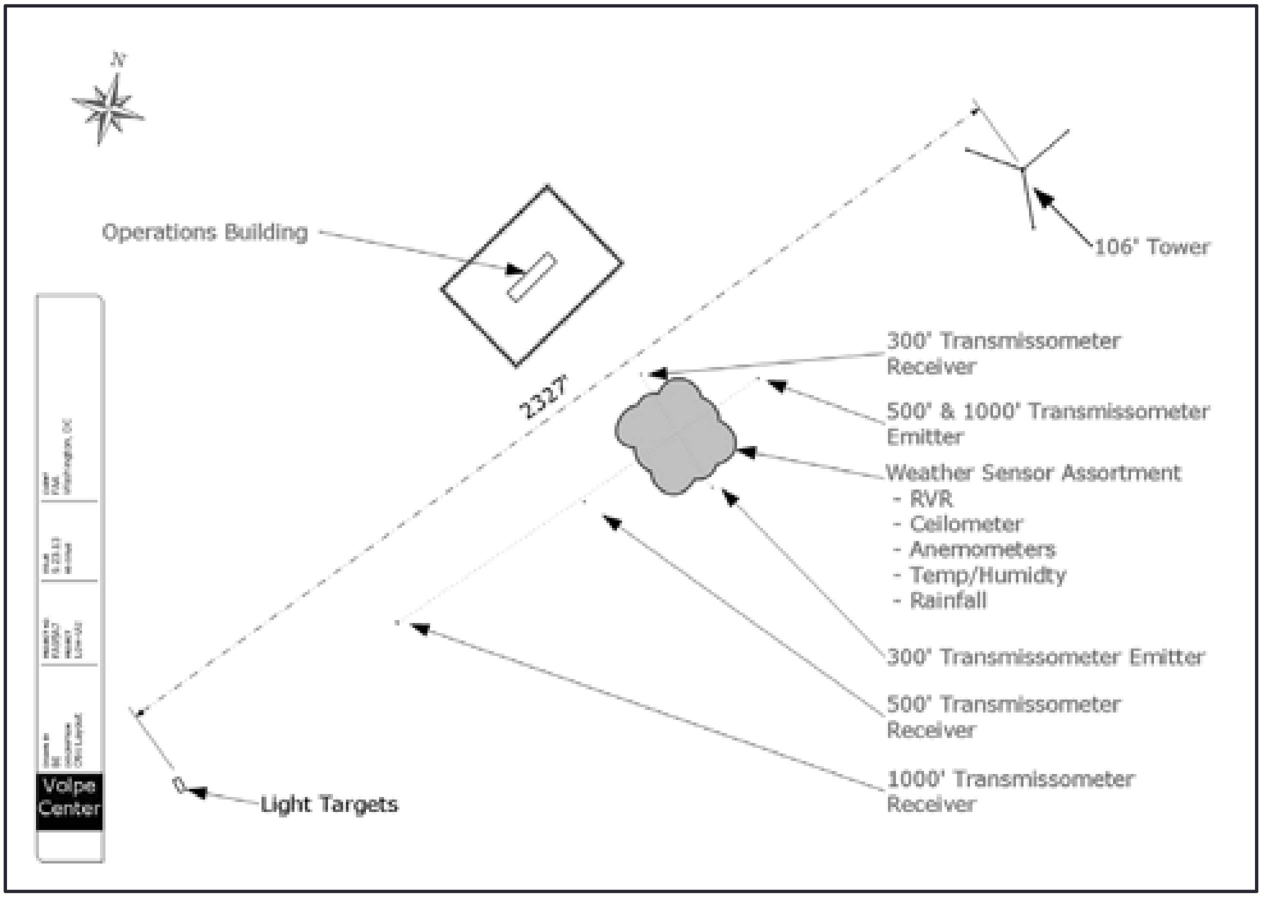
The Volpe Center's Weather Test Facility in Cape Cod, MA is ideally situated with a climate favorable for evaluating the performance of visibility and other weather related sensors. The facility is operated by the USDOT Volpe Center and has a wide variety of weather instrumentation including visibility sensors, present weather sensors, anemometers, and ceilometers. The facility is exposed to:

- 500 ft. ceilings or less and/or less than 1 SM visibility 11% of the time
- 37 inches of annual snow fall on average
- 48 inches of annual precipitation on average
- 18 thunderstorms per year on average[5]

The Otis Weather Test Facility consists of an approximate 255 acre secure tract of land on the Otis Air National Guard Base. It has served as the FAA's primary test site for evaluating the performance of NG RVR and PC RVR visibility and ambient light sensors. It also played a critical role in the development and testing of the Federal Aviation Administration (FAA) Automated Weather Observing System (AWOS) that were models for the later development of the Automated Surface Observing Systems (ASOS) that, in addition to contributing to basic needs of aviation, serves as a primary climatological observing network in the United States. Previously, the Weather Test Facility was operated by the USAF Geophysics Laboratory which used it in visibility-related research that resulted in the successful development of single point visibility sensors that form the basis of runway visual range (RVR) systems deployed throughout the world.

The following figure depicts the general layout of equipment, lights, and cameras at the Otis Weather Test Facility. The facility is equipped with telescoping towers, EVS/EFVS cameras, visible cameras, luminance cameras, RVR forward scatter meters, transmissometers, ambient light sensors, a fog spectrometer, ceilometer, barometric pressure sensors, as well as temperature and humidity sensors. In addition to the diverse sensor suite at the facility, these sensors are polled continuously and data is stored in a database that is accessible via a web interface in near real-time. Although the figure depicts one specific layout, the position of sensors, lights, and towers can be modified to address specific needs.

[5] "The Otis Weather Test Facility at Otis ANGB, Falmouth, MA: An aviation weather resource", 11th Conference on Aviation, Range, and Aerospace Meteorology, 3-8 Oct 2004, Hyannis, MA American Meteorological Society



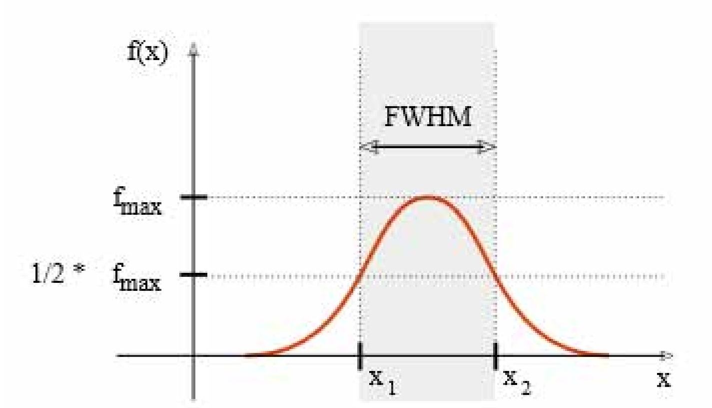
Summary of Upcoming Work

The Otis Weather Test Facility, in coordination with the FAA and Industry, is an ideal location to address a variety of research issues. The facility is being used to assist in addressing several research questions that include:

- What quantifiable metrics can be used to correlate the pilot's ability to detect approach lights and the runway environment and safely land in a given weather condition?
- How do we elicit a sight-based landing decision using EFVS technology?
- At what distance from the runway threshold does a target's visibility affect the pilot's decision to land in a given weather condition?

To help address these questions, the Volpe Center is leveraging the work that was conducted by K. Beier and H. Gemperlein. The metrics, defined in the DLR study and further expanded by the Volpe Center (identified below), will be used to correlate performance of EVS technologies using trained pilots with actual (not simulated) weather conditions recorded at the Otis Weather Test Facility. Metrics that are being investigated for this correlation study include:

- **Contrast Metrics** – the following contrast metrics make an assumption that the light or heat source is a point source with a normal distribution. Light or heat sources of different distributions will require modified equations.
    - **Full Width at Half Maximum (FWHM)**: this is an adaption of a metric used in optics. It measures the width of the target at the point that is half of the maximum amplitude.



        - For a point source of normal distribution the FHWM will have the following equality:

$$FWHM = 2\sqrt{2\ln(2)}\,\sigma \approx 2.355\sigma$$

where σ is the standard devation of the distribution.

    - **Signal-to-Noise Ratio**: the ratio of the signal the noise

$$\frac{\bar{I}}{\sigma}$$

where $\bar{I}$ is the average pixel intensity and σ is the standard devation of the pixel values of a region of interest.

    - **Contrast-noise ratio (CNR)**: the equation is $\frac{(\bar{I}_B - \bar{I}_T)}{\sigma_B}$
        - where $\bar{I}_B$ is the average intensity of the background, $\bar{I}_T$ is the average intensity of the target (i.e. light or thermal source), and σ_B is the standard deviation of the background.
    - **Contrast**: this equation is borrowed from radiography and has the form $\frac{2*\sigma}{bitdepth}$
        - where σ is the standard deviation of an area which may be the entire region of interest, the target, or the background.
    - **Area Weighted Average (AWA) Delta-T**: this equation assumes values of temperature from a thermal sensor. For our measurements we will substitute pixel intensities whether from a thermal source or not. The equation is:
        - $\Delta T = \bar{T}_T - \bar{T}_B$
            - $where$ $\bar{T}_T$ is the average intensity of the target and $\bar{T}_B$ is the average intensity of the background.
    - **Root Sum Square Delta-T (RSS)**: like the AWA delta-T, this assumes values from temperature but pixel intensities will be used. The equation is:

        - $\Delta T = \sqrt{(\bar{T}_T - \bar{T}_B)^2 + S^2}$
            - Where $\bar{T}_T$ is the average intensity of the target, $\bar{T}_B$ is the average intensity of the background, and S^2 is the variance of the target.
    - **Contrast (application of Weber's Law)**: Weber's Law states that the change in the magnitude of a stimulus is proportional to the magnitude of the stimulus, rather than being an absolute value. This law can be applied to the human visual system's ability to discern intensities. Higher intensity changes for the target and background are required to perceive the same target as the background gets brighter. The equation is

$$\frac{(\bar{I}_T - \bar{I}_B)}{\bar{I}_B}$$

where $\bar{I}_B$ is the average intensity of the background and $\bar{I}_T$ is the average intensity of the target (i.e. light or thermal source).

    -
- Other Metrics
    - **Pixel Size** – the pixel size, width and height, will be computed manually once. This will require a feature that has a width and length in physical units easily seen in the acquired image/field of view.
    - **Frame Size** – this will be in pixels acquired from the images.
    - **Pixel count** of the target and background.
    - **Noise** – the temporal standard deviation of a region of the image. For thermal cameras this region must be uniform thermally and also passive (no active or dynamic thermal bodies such as plant life or water). For visible cameras, the region will consist of the darkest region in the field of view. This measurement will be done once and periodically or as needed afterwards.
    - **Maximum intensity of a 3x3 pixel sized region of the target and of the background** – the target and background regions will be scanned (i.e. a rolling window search) for the brightest 3x3 pixel square region.
    - **Minimum intensity of a 3x3 pixel sized region of the target and of the background** – the target and background regions will be scanned for the darkest 3x3 pixel square region.
    - **Difference of maximum and minimum intensities** – The difference of the brightest and darkest 3x3 pixel regions for both the target and the background.
    - **Number of resolvable light sources** - The number of resolvable light sources when multiple light sources are in a sequence. For example, can five MALSR light sources be resolved or do they appear as one merged light source? To make this decision the Rayleigh Criterion will be applied.

Human Factors will be a significant consideration in this work and will factor into the analysis. The field data collected at OTIS will be analyzed to determine if pilots should be able to perceive targets based on an assumed visual acuity.[6] [7]

Additionally, an experiment is being designed to assess how EFVS and/or Runway Visual Range(RVR) and Prevailing Visibility (PV) sensor information affect a pilot's decision to land. This blind experiment will take place in a lab setting intended to emulate a cockpit window. Pilot participants will be outfitted with an eye tracker and taken through a randomized series of images.

The first task of the experiment will be to elicit a landing decision based on sight and RVR/PV sensor information. Independent variables include:

1. Weather Condition (ASOS weather phenomenon category)
2. Image type (EFVS vs. Non-EFVS)
3. Visual Range data (RVR vs. PV)

For each condition, pilots will be shown an image and given RVR or PV information. They will then be asked to provide the following information based on the visual cues in the image and the visual range information provided to them:

- Rate their level of comfort landing (on an operationally defined Likert Scale)
- Identify the cue(s) they noticed first
- Identify the most salient cue(s)

The second task of the experiment is to elicit a decision to land purely based on sight. Independent variables include:

1. Weather Condition (defined by an ASOS weather category)
2. Image type (EFVS vs. Non-EFVS)

Pilots will be told they have the weather and clearance to land, and like the first task, pilots will be asked to rate their level of comfort landing and indentify cues.

The analysis of the data collected in these experiments may include but are not limited to the following:

- Plot pilots' comfort level ratings based on visibility
- Determine if the presentation of RVR data, PV data, or the absence of either has a significant effect on a pilot's comfort level rating.
- Compare the subjective decision to land in a given condition with corresponding objective data of whether or not a person with a given visual acuity should be able to see targets based on contrast/metrics value(s)

[6] Commercial and airline pilots are required by the FAA to have a visual acuity for distance sight of no less than 20/20 with or without visual correction.

[7] Previous research of contrast perception as a function of visual acuity will be leveraged.

- Compare targets that participants indicated were most salient in a given condition to the contrast/metrics value(s) for the targets
- Determine what target was noticed first, and what target was most fixated on for a given weather condition using the eye tracker data
    - Compare to target(s) pilots reported noticing first, and reported as most salient

The correlation of visibility metrics and the pilots' capability to conduct a low visibility operation is an important step in the process to assess performance of EVS technologies. A quantifiable process, correlated with human perception, to assess EVS performance will allow the government and industry to (1) reduce traditional performance assessment costs, (2) reduce overall duration of the performance assessment, (3) offer an opportunity to introduce new technologies at a more rapid rate when compared to current performance assessment processes, and (4) establish specific conditions and limitations for authorizations to conduct EFVS operations.