Evaluation of the Vaisala LT31 Transmissometer as a "Gold Standard" Visibility Sensor

Market Research, Test Experiences, and Validation

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14. ABSTRACT

The FAA sponsored the Volpe Center to identify, acquire, and test a replacement sensor for its existing visibility standard, the Tasker 500 transmissometer. The Volpe Center identified the Vaisala LT31 as a viable candidate; purchased an LT31 and installed it side-by-side with a Tasker 500 transmissometer and other weather sensors; and collected and analyzed data from a one-year collection period to assess the feasibility of replacing the Tasker 500 standard with the Vaisala LT31. This report details the market research, data collection campaign, and results of the side-by-side comparison, with a recommendation that the FAA adopt the Vaisala LT31 for use as the new visibility standard.

15. SUBJECT TERMS

FAA, aviation, weather, visibility sensor, RVR, transmissometer, forward scatter meter, Vaisala, LT31, Tasker, Tasker 500

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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List of Abbreviations

Abbreviation	Term
ASCII	American Standard Code for Information Interchange
AWRF	Aviation Weather Research Facility (now named Volpe Test Range)
DUT	Device Under Test
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IR	Infrared
JBCC	Joint Base Cape Cod
KFMH	Coast Guard Air Station Cape Cod
METAR	METeorological Aerodrome Report
MOR	Meteorological Optical Range
NAS	National Airspace System
NG-RVR	Next Generation Runway Visual Range system
NIST	National Institute of Standards and Technology
PC-RVR	PC-based Runway Visual Range system
PC-RVR VS	PC-based Runway Visual Range system Visibility Sensor
PNT	Positioning, Navigation, and Timing
RVR	Runway Visual Range
UDP	User Datagram Protocol
VPN	Virtual Private Network
VS	Visibility Sensor
VTR	Volpe Test Range (formerly named Aviation Weather Research Facility)

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Executive Summary

In late 2019, the Federal Aviation Administration (FAA) determined that it was desirable to examine an alternative to the existing "gold standard" visibility sensor, the Tasker 500, based on the experiences of the Volpe Center ("Volpe") in operating these sensors. Tasker 500 transmissometers, which stopped being manufactured in the 1970s, were once in widespread use in the National Airspace System (NAS). However, over the past several decades, they were replaced by new forward-scatter-meter visibility sensors, which are called the Next Generation Runway Visual Range system (NG-RVR; beginning in the 1990s) and the PC-Based Runway Visual Range system (PC-RVR; beginning in the 2000s).

Because of their long history as visibility sensors, and because of certain desirable characteristics of transmissometers as a standard instrument when compared to forward-scatter meter – the other type of aviation visibility sensor in widespread use – several Tasker 500 systems have been maintained by Volpe for use in validating new visibility sensors. However, the final decommissioning of the last Tasker 500s from the NAS, the resulting difficulty in access to spare parts, combined with the ongoing expense associated with maintaining these decades-old systems, led the FAA to accept Volpe's recommendation that other transmissometers be evaluated as potential replacements.

In Phase I of this effort, which was conducted beginning in autumn 2019 and proceeded through most of 2020, Volpe performed a literature and market survey to identify possible alternative transmissometers. As a result of this market research (covered in detail in Appendix E: Possible Alternative Transmissometer Systems – Market Survey), Volpe identified the Vaisala LT31 transmissometer as the most viable alternative to the Tasker 500s available on the market. Volpe drew up a test plan for the FAA, recommending that the existing PC-RVR visibility sensor performance standard be the benchmark for performance of the LT31 when compared to the Tasker 500, with some modifications to accommodate both the differences between transmissometers and forward-scatter meters, and to recognize that in order to serve as a new standard, a sensor would ideally perform well even under more challenging conditions. The FAA accepted Volpe's recommendation and test plan, and Volpe acquired an LT31 transmissometer to be used in a test campaign. Although the COVID-19 pandemic somewhat delayed the acquisition of the LT31 and its installation, the sensor was installed in 2021.

In Phase II of the project, Volpe then performed an approximately 12 month long data collection and test campaign, between September 2021 and October 2022, at the Department of Transportation's Volpe Test Range (VTR), located on Joint Base Cape Cod (JBCC), in accordance with the test plan (note that until recently, the VTR was known as the Aviation Weather Research Facility (AWRF)). The scheduling of the campaign was planned to improve the likelihood of collecting data in the three most common visibility-impairing weather conditions – fog, rain, and snow. During the testing, Volpe identified certain anomalies in the performance of the LT31 when compared to the Tasker 500 standard and raised these as a concern to the FAA.

With the FAA's help, Volpe coordinated with Vaisala, the manufacturer of the LT31, in an attempt to identify whether these anomalies were likely to be related to the individual sensor being tested not performing as intended, or as a result of a systematic difference in measurement between the two sensors. Vaisala proposed that certain optical characteristics of the Vaisala visibility standard (the Vaisala MITRAS transmissometer) are different from the Tasker 500. Vaisala provided both proprietary and open-literature documentation to support this claim, which has a plausible physical explanation. This literature also provided Volpe with a way to “convert” or “correct” the Vaisala LT31 measurements to account for the fundamental differences between the MITRAS, used to calibrate the LT31, and the Tasker 500 standard used by the FAA. Volpe implemented this conversion on the already-collected data, and found that it caused the LT31 measurements to agree with the Tasker 500 measurements to within the defined specification.

After consultation with the FAA, Volpe and the FAA agreed that 1) it was not desirable to modify the existing visibility standard and 2) for possible ongoing use of the LT31 as a replacement standard, it was not desirable to rely on a Volpe post-collection correction process to map the LT31 measurements to the Tasker 500. Volpe and the FAA jointly requested that Vaisala implement a correction in the instrument itself which would cause the LT31 output to agree with the Tasker 500. Vaisala was able to provide such a correction, in the form of updated firmware for the LT31, in May 2023. Volpe performed a brief additional period of data collection between June and July 2023 in order to verify that the Vaisala-implemented firmware correction agreed with the Volpe-implemented post-hoc correction.

After the implementation of the Vaisala correction to the LT31 data, the LT31 data agrees closely with the Tasker 500. The data from this secondary data collection, when combined with the results of the post-hoc correction performed by Volpe on the main dataset, provide confidence that the LT31, as updated, agrees with the Tasker 500 to within the performance standard defined in the test plan. Because the performance has been demonstrated to be adequate, and because of the many operational advantages of the LT31 over the aging Tasker 500 transmissometers, Volpe recommends that the FAA accept the Vaisala LT31 as the new “gold standard” visibility reference.

1. Introduction

Runway Visual Range (RVR) is defined by the International Civil Aviation Organization (ICAO) as "[t]he range over which the pilot of an aircraft on the centre line of a runway can see the runway surface markings or the lights delineating the runway or identifying its centre line." (ICAO, 2005) RVR information, as captured by Contract Weather Observers (CWOs), or by automated sensing equipment – which is far more typical at major airports – is used to inform pilots on prevailing visibility conditions for guidance during the execution of takeoffs and landings, and thus impacts the safety and efficiency of airport operations.

The Federal Aviation Administration's (FAA) Navigation Services Office - Lighting Systems Group (AJM-3222) is responsible for the acquisition, deployment and replacement of RVR sensors and systems throughout the National Airspace System (NAS). These items are essential to the safe and efficient operation of airports, and especially Instrument Landing System (ILS)-equipped runways, through the determination and reporting of visibility conditions at touchdown, midpoint and rollout locations of such runways.

The oldest RVR measurement systems in relatively recent operation in the NAS are Tasker 500 transmissometer systems. The FAA began deploying Tasker 500 transmissometer systems as replacements for their predecessors, primarily Tasker 400 systems, in the mid-1970s. As technology advanced, the FAA became interested in deploying forward-scatter-meter-based RVR measurement systems because of advantages in upfront costs, sensor reliability, and ongoing maintenance costs. As a result, the Tasker transmissometer systems have now been entirely replaced by forward-scatter-meter-based systems referred to as the New Generation RVR (NG-RVR, entry into service in the mid-1990s) and PC-based RVR (PC-RVR, entry into service in 2009) systems, with the last Tasker 500 systems being retired from the NAS circa the late 2010s.

Because of advantages in the theory of operation of transmissometers over forward scatter meters, the validation of the performance of replacement RVR systems still uses the measurements of transmissometer systems as the "gold standard" with which new RVR systems' measurements must agree. However, the Tasker 500 transmissometers have now been entirely removed from the NAS and as a result are increasingly difficult to maintain and calibrate. For this reason, the FAA decided to pursue the validation of a new transmissometer system, which is in current production, as a reference system to alleviate the cost and difficulty of keeping the Tasker 500 transmissometers operating reliably and accurately.

This report details the results of the evaluation of a modern transmissometer-based visibility measurement system – the Vaisala LT31 – by comparing a test unit against the existing Tasker 500 systems at the Volpe Test Range (VTR) at Joint Base Cape Cod, located in Falmouth, Massachusetts. This report details the test facility used for the evaluation process; the market survey performed by Volpe to select the most appropriate transmissometer system for testing; the installation of the selected system (the Vaisala LT31); the results of the testing; and Volpe's recommendations to the FAA as to whether the LT31 is an appropriate option as a new "gold standard" visibility measurement system.

2. Project Background and Objectives

2.1 RVR – Measurement Techniques and Instrumentation Design

Transmissometers are considered by the FAA to be the gold standard of automated RVR measurement due to their straightforward concept of operation and successful long-term use in the NAS. Transmissometers measure atmospheric light attenuation using a projector and receiver pair that are typically separated by tens to hundreds of feet. The specified separation between the pair – known as the baseline distance, or simply as the baseline – determines the range of RVR conditions the instrument can accurately measure. The transmitter emits a collimated (and, depending on the sensor, modulated) beam of light, and the receiver contains a photodiode or other light sensor which converts the received light into an electrical signal whose intensity is affected by the transmissivity of the atmosphere. Thus, the received signal accounts for how much of the emitted light beam is being absorbed and/or scattered by atmospheric particles such as moisture, dust, snow, and rain (Clark & Abbott, 2012). The raw electrical signal can be converted into an extinction coefficient through the use of a calibration factor.

The relatively large distance that separates the projector and receiver, especially when compared to forward scatter meters, allows a transmissometer system to sample a large volume of atmosphere. Using a large atmospheric sample to calculate RVR produces a measurement that is inherently more representative of the visibility conditions at the airport as a whole.

While transmissometers are, in principle, excellent options to measure visibility in an airport environment, certain aspects of their design and method of operation are undesirable for wide deployment in an operational context. The physics of transmissometer measurement, when combined with the mechanics of the necessary calibration process, mean they can only accurately measure visibilities from about $\frac{1}{2}$ to $\frac{2}{3} \times$ baseline distance to about 20 × baseline distance. This relatively narrow dynamic range makes it difficult to cover the entire range of reportable RVR values (RVR of 6,000 feet or below) (FAA, 2020, pp. 2-8-1) with a single sensor. Transmissometers are also sensitive to window contamination on the projector and receiver lenses and require frequent window cleaning as a result. Calibration is only possible on a clear day, making regular calibration difficult at certain sites and/or during certain seasons. Finally, transmissometers require high-precision alignment between projector and receiver, which is potentially subject to drift and must be verified at least after every calibration.

Because of the operational disadvantages of transmissometers, once forward-scatter-meter-based RVR systems were developed and validated, the FAA ultimately chose to replace transmissometer-based RVR systems in the NAS with forward-scatter-meter-based RVR systems. Forward scatter meters have some significant benefits over transmissometers, especially for wide use. Because the forward scatter meter is a compact unit with a combined projector-receiver array that can be mounted on a single pole, forward scatter meters are much less sensitive to alignment issues and can more easily be fixed to frangible mounts. Forward scatter meters are, both by method of operation and by design, less sensitive to window contamination and require significantly less maintenance overall. They have higher dynamic range than transmissometers, meaning a single sensor can more easily cover the entire range of reportable RVR. Forward scatter meters can be calibrated under practically any weather conditions because of the use of reference plates with known scattering performance. It is important to remember, however, that those plates are ultimately manufactured by calibrating them to cause the same scattering as a known fog density, with the associated visibility being measured by a reference transmissometer. That is, the performance of a typical forward scatter system is inherently calibrated relative to the measurements performed by a transmissometer.

One disadvantage of forward scatter meters is that they sample a much smaller volume of air than their transmissometer predecessors. A single forward scatter meter cannot always accurately characterize patchy (i.e. inhomogeneous) atmospheric conditions, especially under very low wind. As a result, the siting and number of forward-scatter-meter-based RVR systems can be important when conditions are regularly inhomogeneous. Another disadvantage that is inherent in forward scatter meter technology is that they only measure how much light is scattered, not how much is absorbed. Both components contribute to reduced visibility. However, for the most common atmospheric obscuration types (fog, rain, and snow), the scattering effect is by far predominant in reducing visibility, and therefore forward scatter meters are well suited to accurately measure visibility.

While the FAA has realized significant operational benefits from the switch to forward-scatter-meter-based RVR systems, transmissometer technology is, in principle, better able to characterize reduced visibility under all conditions. Transmissometers can also be calibrated on a clear day in an absolute sense, without reference to another instrument. Many of the drawbacks of transmissometers are less relevant when considering an instrument to be used as a testing and calibration standard. The difference in total costs associated with maintenance, calibration, and window cleaning is less significant when operating a single or small number of instruments at a dedicated test site. It is also notable, as is detailed in Section 3.3.3 below, that newer transmissometer designs incorporate a wide range of user-friendly features that mitigate many of the legacy transmissometer disadvantages (e.g. automatic window contamination compensation and automatic self-calibration).

As a result, Volpe proposed to the FAA that, subject to acceptable performance, a transmissometer system be chosen as the replacement for the “gold standard” transmissometer that currently serves as the reference system, and the FAA concurred with that proposal.

2.2 Test Objectives

In order to evaluate a new RVR sensor as a potential replacement for the “gold standard" transmissometer, two primary concerns arise:

1) Addressing the reliability and maintainability concerns associated with the existing Tasker 500 standard instrument; and
2) Confirming that any potential replacement sensor meets accuracy requirements – meaning that it agrees with the existing Tasker 500 standard to within acceptable bounds.

We anticipated that concern 1 would be easily addressed, by virtue of the fact that we would be acquiring a newly manufactured sensor, while the Tasker 500 transmissometers were nearing the end of their feasible operational life. Our main focus during this evaluation, therefore, was on the measurement performance of the device under test (DUT), and the discussion of measurement performance occupies most of this report. However, we did naturally monitor the reliability and maintainability of the DUT by virtue of deploying it for testing, and we also briefly discuss our experiences with the DUT from the point of view of reliability and maintainability.

2.2.1 Primary Metric for Comparison Between the Reference Sensor and Device Under Test – Extinction Coefficient / Meteorological Optical Range

In both transmissometers and forward scatter meters, a projector and receiver pair are used to measure the atmospheric extinction coefficient. This value describes how much light is scattering and/or being absorbed by atmospheric particles. Visibility is inversely proportional to the extinction coefficient. That is, the value of the extinction coefficient is high when visibility is low and vice versa (Clark & Abbott, 2012). The meteorological optical range (MOR) is a measure of visibility, and is generally defined as the distance over which the light emitted from a known source is reduced to a particular fraction of its original intensity, with the most widely used definition in aviation requiring a reduction to 5% of the original intensity. MOR is essentially the inverse of the extinction coefficient, related through a constant.

Because RVR specifically means the range at which runway markings and/or lights are visible, RVR itself involves not only the transmissivity of the atmosphere but also other factors, such as ambient lighting, the intensity of runway lights, and the type of target being observed (e.g. whether the target is a light or a runway marking). The Volpe Test Range is an outdoor lab, not a runway, without runway edge markings or correct runway approach lighting, making it impossible to do a full RVR calculation.

However, the extinction coefficient is the most important variable when estimating RVR. It is the only variable present in each of the widely accepted formulas for RVR calculation, regardless of lighting conditions. Relative to the other RVR input variables, errors in the extinction coefficient have the largest impact on the calculated RVR value. The extinction coefficient (or MOR, which is inversely proportional to the extinction coefficient) is the metric used for the performance comparison between the Tasker 500 and the Vaisala LT31 in this report.

3. The Volpe Test Range

3.1 Facilities and Experience

The Volpe Test Range (VTR) – until recently, known as the Aviation Weather Research Facility (AWRF) – is a 150-acre site located on a relatively flat ridge at Joint Base Cape Cod (JBCC) in Falmouth, Massachusetts, as depicted in Figure 3-1 and Figure 3-2 below. The facility is known for inclement weather conditions throughout the year, making it an ideal outdoor laboratory for the evaluation of technology under challenging conditions. The VTR consists of an operations building and several measurement sites, each of which contain one or more weather sensors. Data from the various sensors is transmitted to servers in the operations building. The images below, taken from Google Earth, provide a bird's eye view of the environment near the facility, as well as the broader geographical context.

Volpe's Aviation Weather and Position Navigation and Timing (PNT) Applications division (V345) manages the VTR and coordinates collaboration across a variety of the Center's divisions to access subject matter expertise in meteorology, information technology, mechanical and electrical engineering, data management and analysis, construction engineering, airport operations management, aviation operations and flight deck technology, air traffic control and management, systems engineering, and human factors.

Figure 3-1: VTR Overview[1]

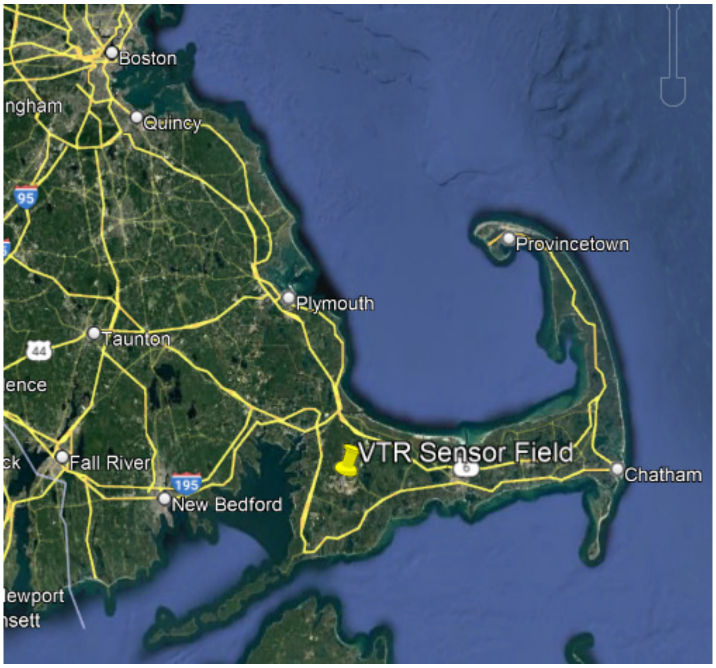

Figure 3-2: VTR Broader Context[2]

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[1] Figure 3-1 contains imagery from Landsat/Copernicus and the U.S. Geological Survey.

[2] Figure 3-2 contains imagery that is © Airbus 2024.

3.2 Climatology

Regional climatic influences in Massachusetts are determined by the distance from the relatively mild ocean waters, elevation, and type of terrain. These factors divide the state into three climatological divisions: Western, Central, and Coastal (CoCoRaHS, 2014).

Total precipitation averages from 40 to 50 inches per year at stations having long-term records. The Coastal Division (the driest) receives only about two inches of precipitation less than the Western Division (the wettest) annually. Cape Cod falls into the Coastal Division. The increased likelihood of storms makes the Coastal Division the wettest in the winter season. Much of the winter precipitation is in the form of rain or wet snow. Occasionally, freezing rain falls. Cape Cod's annual snowfall averages from approximately 27 to 37 inches. 29% of the days had visibility less than or equal to one mile for at least part of the day (during the period Jan 1, 2010 to Dec 31, 2017). There are an average of 16 thunderstorms per year, the average wind speed is 9 knots with a maximum of 40 knots, and the temperature range is from -10°F (-23°C) to 99°F (37°C), with the average winter temperature near 30°F. The VTR experiences reduced visibility weather conditions throughout the year, including fog, rain and snow. Extreme weather is uncommon.

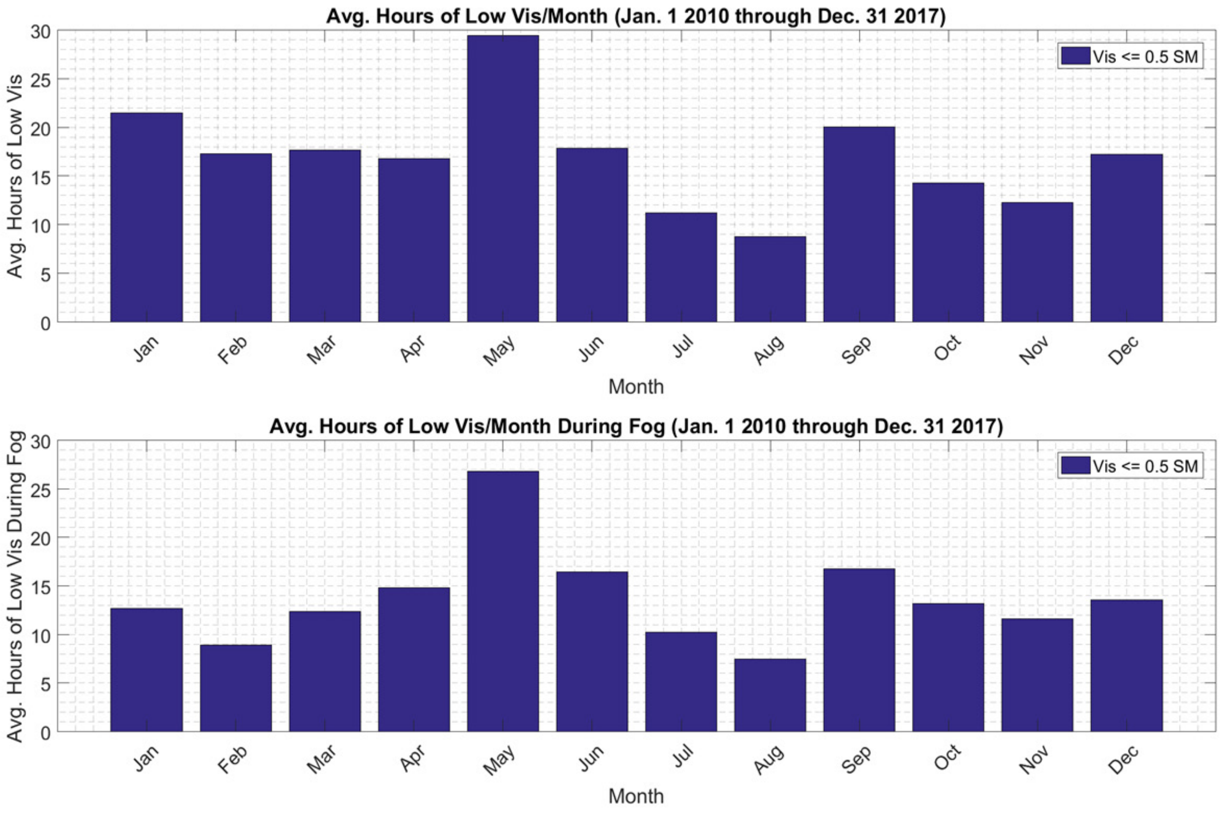

Figure 3-3 Low Visibility Statistics at the VTR

3.3 Sensor Descriptions

3.3.1 Reference Transmissometer – Tasker 500

The Tasker 500 is the FAA's legacy "gold standard" transmissometer that currently serves as the reference system for the determination of the atmospheric extinction coefficient. Photos of the projector-receiver pair of a Tasker 500 are shown in Figure 3-4 and Figure 3-5 below.

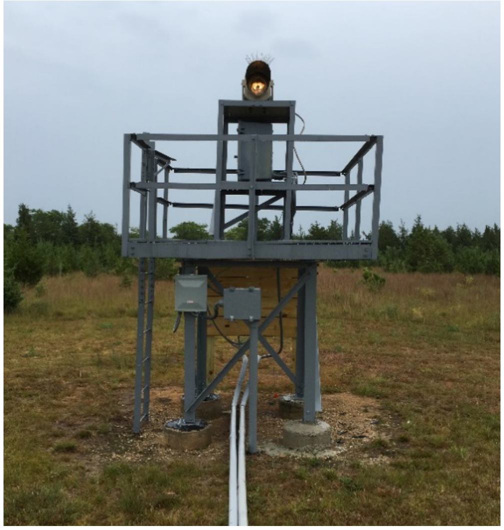

Figure 3-4: Tasker 500 Projector

Figure 3-5: Tasker 500 Receiver

There are two Tasker 500 transmissometer units installed at the VTR with a 250- and 300-foot baseline. For the purposes of our evaluation, Volpe used these two Tasker 500 transmissometers already installed at the VTR as the reference sensors, with the 250-foot baseline Tasker as the primary reference sensor. The 250-foot-baseline unit was previously installed with a 500-foot baseline distance, but was relocated to a 250-foot baseline for the purposes of this test. The move to a 250 foot baseline allowed for a direct side-by-side comparison between the Tasker 500 and the Vaisala LT31 being tested, as well as improved ability to measure very low MOR.

Reliable MOR measurements using a Tasker 500 transmissometer typically range from two-thirds of the baseline distance to twenty times the baseline distance (Burnham, 1997, p. 4). For the tested Tasker setup, this meant the 250 foot baseline Tasker could reliably measure MOR from roughly 167 feet to 5,000 feet and the 300 foot baseline Tasker could measure MOR from roughly 200 feet to 6,000 feet. The two Tasker transmissometers are configured in a cross pattern so that they have a common area within their respective sample volumes. This arrangement is useful in determining the homogeneity of various adverse weather conditions. The effect of baseline length on measurable extinction coefficient/MOR is listed in Table 3-1 below.

The Tasker transmissometers were maintained in good working order throughout the test, with a particular emphasis on the 250-foot-baseline unit, which was the primary reference sensor. Ongoing maintenance and calibration adjustments[3] were required in order to maintain the systems in optimal working order.

Table 3-1: Effect of Transmissometer Baseline Distance on Ability to Measure RVR Relevant to FAA Instrument Approach Categories

FAA Instrument Approach Category	Lowest Authorized RVR Minimum (ft)	Can Be Measured With 250' Baseline?	Can Be Measured With 300' Baseline?	Can Be Measured With 500' Baseline?
I	2600 (1800 with TDZ and centerline lighting) (FAA, 2018)	Yes	Yes	Yes
II	1000 (FAA, 2018)	Yes	Yes	Yes
Current Category III	0 (FAA, 2018)	No	No	No
Former Category IIIa	700 (FAA, 2020)	Yes	Yes	Yes
Former Category IIIb	150 (FAA, 2020)	Yes[4]	No	No
Former Category IIIc	0 (FAA, 2020)	No	No	No

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[3] In summary: the projector and receiver pairs are aligned precisely by using an optical tool designed for the instrument. A linearity test is performed to ensure a proportional relationship between the scaling of the input signal to the receiver and the transmissivity metering. The projector beam is calibrated to the receiver such that 100% transmissivity (i.e., no measurable obstructions to visibility) equates to a nominal pulse output rate of 4000 per minute. The alignment and calibration procedures are fully prescribed in the Tasker 500 manuals.

[4] A Tasker 500 transmissometer with a baseline of 250 feet can measure MOR down to approximately 166 feet. The Vaisala LT31 is advertised as being able to measure MOR down to half its baseline distance, or 125 feet.

3.3.2 Device Under Test – Vaisala LT31 Transmissometer

The LT31 is a transmissometer currently manufactured, sold, and supported by Vaisala. The LT31 was selected as the DUT after a literature search and review of manufacturers, which allowed Volpe to suggest what it believed to be the most plausible alternative to the Tasker 500. For a summary of Volpe's research into the transmissometer market as of late 2019, see Appendix E: Possible Alternative Transmissometer Systems – Market Survey. A picture of each end of an LT31 unit *in situ* is provided in Figure 3-6 and Figure 3-7 below.

Figure 3-6: LT31 Receiver

Figure 3-7: LT31 Projector

Vaisala is a Finnish company, founded in 1936, well-known for developing, manufacturing, and marketing products and services for environmental measurement. It has approximately 1,800 employees and annual revenue of approximately $400 million (as of 2018). Based on Vaisala's history of success and established leadership in the weather instrumentation field, we believe the risk that this transmissometer system will stop being supported in the near future is low. The forward-scatter-meter-based RVR systems currently used across the NAS are also Vaisala sensors (as detailed in Section 3.3.4.1 below), and they have a proven track record of performance and reliability.

The LT31 has a number of features that make it attractive as a potential replacement gold standard, which are listed below.

1. Vaisala claims its performance meets ICAO Annex 3 (Meteorological Service for International Air Navigation), Attachment A (Operationally Desirable Accuracy of Measurement or Observation) standards (Vaisala, 2020), which are displayed in Table 3-2: ICAO Annex 3 RVR Standards below.

Table 3-2: ICAO Annex 3 RVR Standards (ICAO, 2007)

Element to be Observed	Lower Range of RVR	Upper Range of RVR	Operationally Desirable Accuracy
Runway Visual Range	0 m (0 ft)	400 m (1312 ft)	± 10 m (33 ft)
	400 m (1312 ft)	800 m (2625 ft)	± 25 m (82 ft)
	800 m (2625 ft)	Unlimited	± 10%

   For the 75 m (approx. 250 foot) baseline, Vaisala claims the LT31 will accurately report MOR in the range of 37.5 m – 10,000 m (123 ft – 32,808 ft).

2. The LT31 has an integrated forward scatter sensor which, through a Vaisala-patented methodology, automatically detects measurement drift and adjusts sensor settings accordingly. The LT31 automatically recognizes suitable conditions for this self-calibration.
3. The LT31 performs an automatic fine alignment to help resolve alignment drift, a natural consequence of small relative movements in the position of the projector and receiver over time which gradually degrades accuracy if not compensated.
4. The LT31 is equipped with long, narrow weather-protection hoods to reduce window contamination from precipitation, and includes a blower that creates an air curtain in front of the receiver window to exclude contamination by wind-driven precipitation or dust.

The overall physical dimensions of the LT31 are similar to those of the Taskers. The projector and receiver each weigh about 180 lb and are typically mounted at a total height of 2,685 mm (105.7 in / 8.8 ft). The LT31 will accept typical US 120 V / 60 Hz alternating current (AC) power, and has a total power consumption of at most 800W, meaning it is easily supplied by a typical 15A circuit. Its data output is through a standard RS-232 serial data port.

3.3.3 Comparison of Relevant Features of Reference Transmissometer (Tasker 500) and Device Under Test (Vaisala LT31)

Tranmissometers used for measurement of RVR were developed in 1942 and accepted for airport use in 1952. The Tasker 500s themselves were acquired from the Tasker division of Whittaker Corporation and deployed beginning in the mid-1970s as replacements and upgrades to earlier transmissometer systems (primarily Tasker 400 systems) (Ingrao, 1976). While Tasker finalized the Tasker 500 design in the mid-1970s, Vaisala has had the benefit of decades in advances in electronics and manufacturing over the period between the Tasker 500 design and the present. Vaisala also has the benefit of operational experience with their previous instruments (e.g. the MITRAS) as well as user reports from competing and predecessor products, including the Tasker 500 itself, about which aspects of the design and operation of those sensors are desirable and which are not. As a result, the instrument is designed to address the most common shortfalls of legacy transmissometer systems. A comparison between important features of the Tasker 500 and the Vaisala LT31 transmissometers is shown in Table 3 below.

Table 3-3: Differences Between Tasker 500 and Vaisala LT31

Feature	Tasker 500	Vaisala LT31	Comments
Automatic Alignment Adjustment	Not available; manual alignment checks performed monthly.	Fine adjustment performed automatically.	The LT31 will report if alignment drift is too large to be compensated.
Blowers/Heaters to Reduce Window Contamination	Present.	Present.	None.
Calibration	Manual process that requires an observer to estimate prevailing visibility and calibrate accordingly, checked weekly.	Automatic self-calibration using a forward scatter meter to accurately measure extremely high visibility and calibrate accordingly.	The forward scatter meter on the LT31 is used for calibration and present weather, not visibility measurement, when in operational mode.
Light Source	GE #120-PAR/64 (120 watt sealed-beam halogen bulb) – rated life no more than 10,000 hours (approx. 1 year).	White high-power LED, no rated life specified (but LEDs are generally longer-lived than halogen bulbs).	Lamp replacement in the Tasker requires a burn-in period of several days as well as triggering a calibration.
Manufacturer Support	None – production ended around 1980.	Available – still in production.	None.
Present Weather Detection	None.	Forward scatter meter provides type and intensity of precipitation (optional feature).	LT31 data could provide supplemental present weather information to determine precipitation/obscuration type. Present weather capability is an inexpensive option we plan to purchase.
Self-Diagnostic Reporting	None. Manual observation and maintenance is critical to maintain reliable operation.	Extensive automated self-diagnostics that report sensor parameters and report malfunctions or performance degradation.	None.

Feature	Tasker 500	Vaisala LT31	Comments
Window Contamination Compensation	None. Cleaning required biweekly and after snow or rain.	Automatic.	The LT31 will also report if contamination is too great for reliable measurements.

Maintenance requirements and reliability are key concerns when operating any instrumentation, especially at an automated data collection site like the VTR. Although Volpe has an existing stockpile of spare Tasker parts, they span a wide range of manufacturing generations and ages, and are generally of unknown usability. Tasker 500 units have not been manufactured in many years, and there is no available manufacturer or other commercial support. As a result, the Tasker 500s will become more difficult to maintain over time, especially when considering consumable items like the incandescent bulbs used for the projector.

Volpe expects the availability of spare parts and tools to be much better for the DUT for the foreseeable future. Volpe does not currently have a stockpile of parts for the DUT, unlike for the Tasker 500s. However, given the history of the manufacturer and its ongoing support for previous transmissometer models, Volpe believes that Volpe and the FAA would have significant warning – measured in years – before support for the DUT was ended. At that time, the FAA could make preparations (i.e. buying a stock of spare parts) to keep the DUT operating as long as deemed necessary.

3.3.4 Supporting Sensors and Supplementary Data

In addition to the primary test instruments – the Tasker 500 systems and the DUT – Volpe has additional sensors collecting data, including a Vaisala WXT-520 weather station, an OTT Parsivel[2] Present Weather Sensor (a disdrometer), and a Vaisala FA-19200 forward scatter meter (also referred to in this report as the visibility sensor for the PC-RVR system, or PC-RVR VS). These sensors provide information about ambient conditions at the test site, including a secondary measurement of extinction coefficient/RVR, general information about wind speed, direction, and precipitation conditions, and more detailed information about precipitation conditions. The disdrometer is capable of measuring the size distribution and rate of rain droplets, snow, and hail. In general, the data collected by the supporting sensors has been used for diagnostic information in the case of significant disagreement between the DUT and the reference Tasker 500, rather than being a routine component of data analysis.

The Vaisala FA-19200 forward scatter meter sited in the sensor field was used during this evaluation as a secondary measure of extinction coefficient. For the reasons given in Section 2.1, the forward scatter meter is less desirable than a transmissometer as a measurement of extinction coefficient for the validation of a new reference sensor, especially given that the DUT itself is a transmissometer rather than a forward scatter meter. As a result, the FA-19200 has not been used as a primary source of extinction coefficient data during the test period. However, it has been used as a tool to perform a post-hoc calibration of the Tasker 500 for reasons given in detail in Section 4.2.1 below. More information about the FA-19200 can be found in Section 3.3.4.1.

To help determine the prevailing weather conditions during low visibility periods, previous test campaigns have used a combination of the weather station, the disdrometer, and local METARs (METeorological Aerodrome Reports) from the nearby KFMH station (Cape Cod Coast Guard Air Station). The weather station is configured to measure and report most parameters once per second; the disdrometer is configured to report measurements over 60-second intervals; and METARs are generated every hour and contain, among many other parameters, a report on any existing “obscurations” or “precipitation” in the area.

However, a comparison between the present weather reporting functionality of the LT31 and the METAR reports from KFMH (the results of which are not detailed in this report) revealed that the agreement between the two sources was adequate to justify using the present weather output from the LT31. The LT31 present weather output provides substantially better temporal resolution than the METARs, and is characterizing the weather at the data collection site rather than a site over a mile away. For similar reasons, although the weather station and disdrometer have provided valuable confirmation and validation of prevailing weather conditions in the past, and data from these sensors was collected and archived, their data has not been used for the analysis detailed in this report. Instead, the output from the present weather detection feature on the LT31 was used to classify low-visibility weather as either fog, rain, or snow.

3.3.4.1 Forward Scatter Meter – Vaisala FA-19200 Visibility Sensor (VS)

The VS component of a PC-RVR consists of a transmitter, receiver and control processor. Unlike a transmissometer, the transmitter and receiver of the forward scatter meter (FSM) are mounted on a single stand, only eight inches apart. They are both angled forward and slightly downward. The mechanical alignment is critical and set at an angle of 42 degrees, which is a peak angle at which light scatters from water droplets in the air. The transmitter sends continuous infrared pulses in a narrow beam via a 5 mm lens. The receiver lens collects the light scattered forward and focuses it to the positive-intrinsic-negative (PIN) photodiode. The signal is then amplified and precision-filtered. The remaining signal is sent to the processing unit for the calculation of the atmospheric extinction coefficient and corresponding MOR. A photo of a PC-RVR VS installed at the VTR is shown below.

Figure 3-8: PC-RVR VS (FA-19200)

3.4 Test Configuration

The LT31 transmissometer has three recommended baseline lengths – 30 m (98 ft), 50 m (164 ft), and 75 m (246 ft). To create optimal conditions for direct comparison of the legacy Tasker 500 and the LT31, the reference Tasker 500 and the installed LT31 were both installed using a 250 foot baseline. The DUT is located side-by-side, approximately 15 feet (4.6 m) apart, and as height-aligned as practicable to the reference Tasker unit so that the two units are sampling as close to the same volume of atmosphere as possible. The capability of the LT31 to accommodate a 250 foot baseline, which is also the most commonly used baseline for the Tasker, allows for a truly apples-to-apples comparison between the performance of the LT31 and the Tasker. The projector and receiver of the DUT are installed in a reversed orientation from the 250 foot baseline Tasker in order to ensure that the receiver of both the Tasker and the LT31 can only see their respective projectors, to avoid any potential cross-contamination of the projector signal.

Figure 3-9: VTR Test Site Layout, below, depicts the locations of the two Tasker transmissometer projector-receiver pairs and the legacy PC-RVR VS and other ancillary weather sensors. The diagram includes the reversed projector-receiver orientation for the DUT.

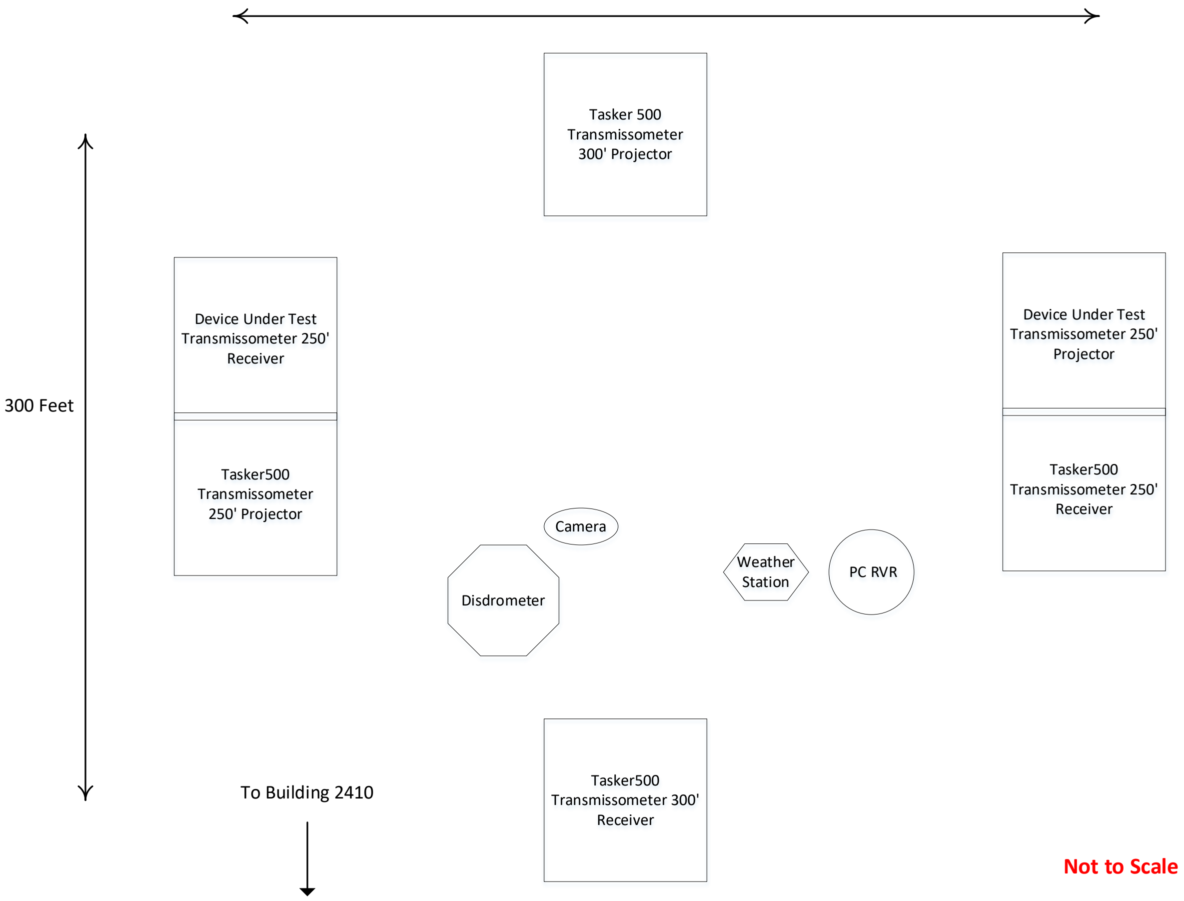

Figure 3-9: VTR Test Site Layout

3.5 Data Communications

3.5.1 Sensors and Servers

Sensor data is transmitted to the main building via wireless transceivers and fiber optics. Where viable, sensors leverage existing fiber optics infrastructure. Most sensors, however, transmit their data back to the VTR building via wireless transceivers.

Each sensor transmits data at a fixed interval. The Tasker transmissometers and legacy PC-RVR VS provide data every 15 seconds and other sensors produce data at varying sample rates. All sensor data routes into a MOXA serial device server. The MOXA server packages the serial data into Ethernet based User Datagram Protocol (UDP) packets, which are sent to the VTR data collection server.

The data is time stamped by the data capture utility software running on the server. Local time (EDT/EST) is used as the common time base for sensor data and it is derived from the Windows clock, which in turn is synchronized to a web-based National Institute of Standards and Technology (NIST) time server. The data is then saved into separate dedicated directories for each sensor and the data capture utility software subsequently writes a file to the appropriate sensor-designated directory every hour.

3.5.2 Internet and Networking

Access to the Internet is provided through a regional service provider at a bandwidth of approximately 20 megabits per second (Mbps). Due to JBCC IT security protocol, the physical fiber connection to the internet service ends at the JBCC communications building. The signal carrying the internet connection is then transmitted via microwave link to the VTR building. The microwave link serves as an Ethernet extender.

All the raw ASCII data that is produced by the sensors collected is saved to a local server at the VTR. A backup is kept at the Volpe Center via remote data transfer. While all of the data is collected at the VTR server (in ASCII format), the data processing and analyses are done at the Volpe Center.

Remote administration is provided through secure Virtual Private Network (VPN) connectivity to a hardware firewall. Once connected via VPN, remote administration of the VTR network and remote desktop connection to the VTR server is available for monitoring and troubleshooting.

4. Data Collection

4.1 Scope of Data Collection

Two periods of data collection were ultimately undertaken: a main period of data collection from October 20, 2021 through October 5, 2022, and a secondary period of data collection from late June 2023 through August 2023. The main data collection was designed to cover the entire range of prevailing weather conditions – fog, rain, and snow – by running for one calendar year, although the data ultimately collected was somewhat less than one full year, as there were occasional sensor outages. The secondary data collection was designed to validate a Vaisala firmware correction to the LT31 measurements, and a significantly smaller amount of fog and rain data was sufficient to accomplish the validation.

4.2 Visibility Sensor Operation and Calibration

The data collected from the LT31 and the Tasker 500s are used for time-synchronized comparison to validate the LT31 performance relative to the 250-foot baseline Tasker 500. This section of the report briefly describes the calibration and operation of the visibility sensors used during the evaluation, including both the reference transmissometers (Tasker 500), the DUT (LT31) and the supplemental visibility sensor (FA-19200).

4.2.1 Tasker 500

The Tasker 500 transmissometer system measures light attenuation using a project and receiver pair separated by several hundred feet (the distance between the projector and receiver is the baseline). The transmitter emits a collimated beam of light, and the receiver contains a photo-diode to convert the received light into electrical pulses that are directly proportional to the transmissivity of the atmosphere. The system accounts for how much of the light beam is being absorbed and scattered by atmospheric particles such as moisture, dust, snow, and rain (Clark & Abbott, 2012).

The Tasker 500 transmissometer system has a pulse counter to count the number of pulses accepted by the receiver over time, and reports pulse count at set intervals. The transmissometer systems are calibrated to report roughly 4,000 pulses each minute on a clear day with no obstructions[5]. The number

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[5] The output of the pulse amplifier is a pulse rate proportional to the light intensity received from the projector. The number of pulses is based on a linear correlation to atmospheric transmissivity; when transmissivity is at its highest (e.g. perfectly clear day), the output pulse rate per minutes is 4000 pulses, while total obstruction would theoretically generate 0 pulses.

of pulses received per minute are used to calculate an extinction coefficient (σ) that represents atmospheric transmissivity over that time period. Calibration of the system is performed by performing a linearity check of the electronics; cleaning and aligning the optical components of the system; and adjusting the size of the receiver iris so that the output pulse counts match the ideal pulse counts for the observer estimate of visibility.

It is noteworthy that the pulse count reported by the transmissometer is obtained based on all of the light reaching its receiver. Other light sources besides the transmissometer's transmitter could contribute to the reported pulse count, if light from these other sources reaches the receiver. As a result, previous studies have generally shut down the Tasker 500 lamp for a few minutes on a regular basis (typically once per hour or every two hours) to characterize the background illumination. Recent experience with these aging systems has shown that this procedure now causes more harm than good. After lamp shutdown and restart, it takes a variable amount of time – ranging from a few minutes to tens of minutes – to restore steady lamp intensity. Based on operational experience, the background light contribution is small (on the order of 1 – 10 pulse counts under high-visibility conditions) in comparison to other sources of error like inevitable small variations associated with calibration; as a result, early in the data collection period, the Tasker 500 lamps were changed from having shutdowns every two hours to continuous operation. This substantially improved data availability and reliability by removing the regular occurrence of the lamp warm-up fluctuations.

The formula used to calculate the extinction coefficient σ for a one-minute time period is

$$\sigma = -\left(\frac{1}{b}\right)\ln\left(\frac{n_{p,o}}{n_{c,i}} * \left(\frac{n_{c,i}}{n_{c,o}}\right)\right)$$

Where b is the distance between the light source and the observation point (baseline distance) in meters, $n_{p,o}$ is the corrected number of observed pulses (i.e. the observed count minus the background check value, if any) reported for that minute, $n_{c,i}$ is the ideal number of pulses the transmissometer is calibrated to report over one minute given high-visibility conditions, and $n_{c,o}$ is the true number of observed pulses the transmissometer reports over one minute given high-visibility conditions. This expression has not been simplified to emphasize the presence of the parameter $\left(\frac{n_{c,i}}{n_{c,o}}\right)$, which has not been used in previous analyses.

Because of the age of the Tasker 500s, during the data collection period, there was sometimes substantial drift in calibrated clear-atmosphere pulse counts over time scales ranging from minutes to days, including immediately after the completion of a calibration procedure. Because it was impossible to correct this instrument characteristic, a post-hoc correction procedure was performed to scale the recorded values to the nominal calibration. This procedure is described in detail in Tasker 500 Post-Hoc Recalibration. A brief summary of the methodology is that the FA-19200 visibility measurements were used to identify periods of high visibility, and the raw pulse counts during those periods of high visibility were used to calculate the parameter $\left(\frac{n_{c,i}}{n_{c,o}}\right)$. This parameter was needed in order to scale the observed pulse counts under high-visibility conditions to the ideal pulse counts. This parameter was recalculated regularly on a rolling time basis because of the observed drift of the instrument. This process is similar to the auto-calibration process used by the DUT, which also uses a forward-scatter meter to identify periods of high visibility and uses the measured signal from the receiver to calibrate the reported visibility.

4.2.2 Vaisala LT31

The Vaisala LT31, as a transmissometer, works in the same fundamental way as the Tasker 500 – light is emitted by a projector and the intensity of the light is measured at the receiver. Unlike the Tasker, however, the LT31 is a piece of modern measurement equipment. As a result, as described in Section 3.3.3, it requires far less manual intervention to produce reliable measurements.

Initial coarse alignment is performed manually, after which the LT31 itself performs a fine alignment procedure. The LT31 then monitors its alignment and adjusts as necessary to compensate for effects like frost heave. If the alignment drifts outside of the automatic compensation range, the LT31 alerts the user. This did not occur during testing.

Calibration proceeds similarly to alignment. After initial installation, the LT31 is calibrated for signal offset and visibility response manually. Offset is measured with the receiver signal blocked so that no light is allowed in, and the visibility response is measured through a combination of visibility from the integrated PWD and, optionally, an observer-measured MOR. Much like alignment, the LT31 has an automatic calibration feature which allows it to compensate for phenomena like window contamination (and, indirectly, alignment drift), and the LT31 will report an alarm if the calibration is invalid or if other factors like window contamination are invalidating the measurement. This also did not occur during testing.

The LT31 measures extinction coefficient/MOR at 1 Hz, with a default reporting interval of ten seconds between reports. The reported extinction coefficient/MOR is based on a one-minute moving average of the most recent measurements. In order to facilitate time-alignment with the Tasker measurements, the LT31 was configured to report visibility measurements once every 15 seconds.

4.2.2.1 LT31 Integrated Present Weather Sensor Output

The integrated Vaisala present weather sensor (PWS) – which we believe, based on communication with Vaisala, is essentially identical to the Vaisala PWD22 – has three main components to provide present weather characterization: a forward-scatter meter, which provides the ability to measure visibility and particle size (note that the visibility output is disabled when integrated into the LT31, although it is used internally for the auto-calibration process); a capacitive sensor to measure moisture accumulation on the sensor; and a thermistor-based temperature sensor. The combination of these sensors allows the PWD22 to report weather and precipitation types formatted according to WMO Table 4680, as well as formatted with NWS abbreviations. The output provides instantaneous, 15-minute, and 1-hour code determinations. The LT31's integrated PWS was our source of weather characterization for this evaluation, and the LT31 was configured to report PWS data every 15 seconds, just like the visibility measurements.

4.2.3 PC-RVR Visibility Sensor

The PC-RVR VS, which is described in Section 3.3.4.1, is also configured to report an extinction coefficient every 15 seconds. Each reported value represents a one-minute running average, just like the Taskers and the LT31. The visibility information reported by the PC-RVR VS was used only for the identification of high-visibility periods for the post-hoc corrections of the Tasker data. The measurements from forward-scatter meters are often additionally smoothed beyond the one-minute running average for applications like METARs to account for the relatively small sample volume. This was unnecessary for our application. As such, the PC-RVR VS measurements at the 15-second reporting interval were aligned with the 15-second interval data from the Taskers and the LT31.

The calibration process of the PC-RVR VS is similar to that of the transmissometers, with one key difference. Like the transmissometers, an electronic offset is measured and corrected for by entirely blocking the transmitter and receiver head. Unlike the transmissometers, the PC-RVR VS is performed by installing a calibration plate of partially-opaque glass with known scattering characteristics. In effect, the sensor is calibrated by artificially reducing visibility to a known value. The difference between the technology arises from the theory of operation – for the transmissometers, the largest received signal is at high visibility; while for a forward-scatter meter, the largest received signal is at low visibility. The high end of the scale is used to calibrate the sensor measurements as the received intensity decreases.

5. Performance Standard and Data Analysis Methodology

5.1 Accuracy Requirements Derived from the PC-RVR VS Standards and Applicability to the Device Under Test

To determine whether the LT31's performance is sufficiently accurate to be used as a new gold standard, Volpe adapted the existing standard used to validate new PC-RVR visibility sensors, while keeping in mind that some of the requirements applied to evaluate forward scatter meters are not necessarily relevant to the DUT.

The FAA performance requirements for a PC-RVR, which were used as our guide, are stated in Specification FAA-E-2772B. The relevant requirements for the VS component are described here.

The first requirement for PC-RVR VS performance is given in **FAA-E-2772B: 3.2.2.3.2 VS measurement range**:

> *To cover the full RVR range of 100 to 6,500 feet, the sensor measurement range shall cover the range of 1.0 to 300 inverse kilometers (km^{-1}) with a resolution of 0.01 km^{-1} or 1 % of the measurement, whichever is greater.*

Given that a reference transmissometer should be able to validate performance over the entire required MOR range of new visibility sensors, this is relevant to the DUT. According to the Vaisala specifications sheet, the LT31, when installed at a 250 foot baseline, can measure MOR down to 125 feet. Our opinion is that given the extreme rarity of MOR values near the 100 foot value and the small size of the "blind zone" between 100 feet and 125 feet, the advantages of being able to compare a Tasker and the DUT at equal baselines outweigh the inability for the DUT to measure MOR for the 100 – 125 foot range. The transmittance measurement resolution of the DUT is 20 bits, which is more than enough to meet the resolution requirement.

It is also important to mention that if the LT31 is determined to be a suitable replacement for the Tasker 500s, Volpe, on behalf of the FAA, will likely install a second LT31 transmissometer in a cross pattern with the existing installation, much like the Tasker 500 setup. In this case, Volpe anticipates installing a shorter-baseline LT31 to cover the lower visibility range.

The second set of requirements pertains to VS accuracy. The RVR value derived from a PC-RVR's measurements is highly sensitive to the VS measurements of the extinction coefficient, and so significant consideration is given to the VS accuracy requirements. The VS accuracy requirements are defined in **FAA-E-2772B: 3.2.2.3.5 VS accuracy**, and are based on one-minute running averages of extinction coefficients (as required in **FAA-E-2772B: 3.2.2.3.1 VS measurement processing**). The accuracy requirements for the VS are as follows:

a) *Under homogeneous atmospheric conditions, scatter meter measurements shall agree with those of a reference transmissometer to within 15 % (standard deviation) for σ (reference) > 3 km^{-1} [MOR < 1000 m]. The 15 %-standard-deviation requirement is tested at the 90 % confidence level; that is, 90 % of the one-minute-average readings of the scatter meter shall agree to within ±25 % with the simultaneous one-minute-average readings of the reference transmissometer(s). Outliers (that is, more than a factor two difference) shall not occur for more than 0.2 % of the measurements.*

b) *The fog response of the sensor shall drift by no more than 10 % in 90 days. Note that window contamination correction may be needed to meet this requirement. Window contamination correction shall account for any differences in the effect of dirt and water droplets.*

c) *In some cases, snow clogging of the sensors' windows can lead to non-conservative RVR values. Sensor design shall provide valid measurements under virtually all snow conditions. Under conditions where snow clogging adversely affects sensor performance, the sensor shall detect snow clogging and disable its output if a valid measurement cannot be made.*

d) *The fog and snow response (relative to the extinction coefficient) of the sensor shall agree to within 10 %.*

e) *The unit-to-unit fog response shall vary by no more than ± 7 % when calibrated by the same scattering device.*

f) *The fog response of a sensor shall vary by no more than ± 3 % when calibrated by different calibration devices.*

g) *The sensor offset (clear day response) caused by self-scattering and/or electronic offset shall be less than ± 0.3 km^{-1}. The zero-light sensor offset (heads blocked) shall be no greater than ± 0.2 km^{-1}.*

Requirement (a) is the primary accuracy requirement, and we have used the same specification stated here for a PC-RVR VS to test the DUT (replacing scatter meter with transmissometer where appropriate), with one modification. Because the reference transmissometer and the DUT share the same operating principles, with the same baseline, and were physically sited adjacent to each other, Volpe has not limited evaluation to homogeneous conditions. However, we collected data from two Tasker 500 instruments – one with a 250-foot baseline immediately adjacent to the DUT, and one with a 300-foot baseline crossing the sensor volumes of the main reference Tasker 500 and the DUT. This allowed us to assess performance under both homogeneous and inhomogeneous conditions.

Requirement (b) limits the degradation of performance in fog over time that is frequently experienced by forward scatter meters between recommended calibrations. This is less relevant to the DUT, which compensates for window contamination and provides diagnostic information, including warning users if performance is degraded. We tracked sensor contamination warnings (if any) from the DUT, but did not otherwise specifically evaluate this requirement; it is less relevant to a potential standard, which will be frequently maintained.

Requirement (c) is important for PC-RVR devices in particular because their sensor hoods are typically much shorter, and the apertures of the sensor heads are typically much smaller, than a transmissometer. As a result, snow clogging is much more likely to be an issue for PC-RVRs than for a transmissometer. Both the Tasker and LT31 transmissometers also have heating and blower systems designed to keep the receiver and projector clear of obstructions. We did not explicitly test this requirement, but we did regularly inspect the sensor and did not notice any snow clogging events in operation.

Requirement (d) is specifically relevant to forward scatter meter technology because of the different scattering characteristics of snow and fog. It is not relevant for transmissometer technology *in principle*. However, data collection showed that there were systematic differences between the Tasker 500 and the DUT under fog (and rain) versus snow conditions, which are explained in detail later in the report. These differences were resolved by manufacturer updates to the LT31 software.

Requirement (e) is not relevant to transmissometer technology. The DUT is making a direct measurement of transmissivity and is not relying on a secondary reference like a scatter plate for calibration. We did not test this requirement.

Requirement (f) is, again, not relevant to transmissometer technology for the same reason as requirement (e). We did not test this requirement.

Requirement (g) is not relevant to the DUT. These are essentially calibration factors unique to forward scatter meters. Where there might be relevance to other technologies (e.g. ensuring that the zero-light response of the sensor is adequately close to zero), the effect of any offset will be apparent in the data. In addition, requirement (g) is most important for a sensor technology with a large production base to ensure low sensor-to-sensor variability. Because the requirement is largely targeted at forward scatter meter technology, and because this effort was aimed at evaluating only one DUT, we did not test this requirement.

5.2 Data Analysis Procedure

As detailed in section 5.1 above, item (a) of the relevant specification (FAA-E-2772B: 3.2.2.3.5) is the primary accuracy requirement that we have used for the evaluation. A significant difference between our proposed test and the wording of item (a) is that we have evaluated the performance of the DUT under all conditions, not just during homogeneous conditions. Further data analysis restricted to homogeneous conditions was also performed, with a slightly more inclusive homogeneity criterion compared to previous practice[6].

Because a new gold standard should perform adequately under all weather conditions, we have separately characterized the measurement accuracy of the DUT under fog, rain, and snow conditions, which is consistent with the wording of FAA-E-2772B, which has specified requirements for behavior during fog, rain, and snow.

5.2.1 Synchronizing Data for Analysis

The Tasker 500 transmissometers, the LT31, and the FA-19200 PC-RVR VS were configured for 15 second reporting intervals. The Tasker 500 transmissometer reports raw pulse counts on this 15 second interval, while the LT-31 and the PC-RVR report 1 minute rolling averages. Other supporting sensors are configured at various time intervals based on desired time resolution.

Due to sensor limitations, it is not possible to establish absolute time synchronization across all sensors. Instead, the time base is established downstream, at the data collection server. Data is prepared for analysis by grouping together the closest measurements in time between the DUT and the reference transmissometer(s) for comparison. The DUT measurements have been used as a master dataset for time synchronization, and have been time-aligned with the calculated extinction coefficient / MOR from the Tasker 500 transmissometers and other sensors.

In order to establish a common temporal averaging scheme so that the Tasker measurements agree with the one-minute averaging already used by the DUT and the PC-RVR VS, for each measurement report from the Taskers, the total change in pulse counts over the preceding minute is calculated. From this change in pulse count, an extinction coefficient (and therefore an MOR), which is inherently a temporal average of the preceding minute, is calculated. For each measurement available from the DUT, the temporally closest measurement from the reference Tasker and other visibility sensors was identified. If the closest measurement from the reference Tasker (or other sensor) was collected within 20 seconds of the DUT measurement, the measurements are considered “effectively simultaneous”, and

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[6] Further details on the homogeneity criterion, and the difference from previous practice, are provided in Appendix C: Homogeneity Criterion.

are paired with each other for analysis. If they are more than 20 seconds apart, then they are not considered effectively simultaneous, and they are not matched for analysis.

Barring sensor outages, DUT measurements generally have a corresponding effectively simultaneous measurement from both of the Tasker transmissometers, as well as being effectively simultaneous with other ancillary sensors, including the PC-RVR VS. In these cases, the timestamp assigned to all of the effectively simultaneous measurements for the purposes of analysis and plotting is the timestamp associated with the DUT measurement.

Because our primary focus was validating the DUT against the adjacent 250 foot baseline Tasker, if a DUT measurement did not have a corresponding 250 foot baseline Tasker measurement, it was not included in our analysis. Situations where effectively simultaneous measurements from both the DUT and the 250 foot baseline Tasker were present were included in the analysis regardless of the presence or absence of measurements from other sensors (except where homogeneity requirements were imposed; homogeneity evaluation required measurements from both Taskers).

5.2.2 Data Processing, Filtering, and Analysis Sequence

Data selection and processing for the analysis followed a procedure that was generally similar to previous PC-RVR VS evaluation efforts, with a few exceptions (e.g. the relaxed homogeneity criterion, as mentioned above). The procedure for analysis was performed as follows:

1. Quality filtering of Tasker transmissometer data: after extinction coefficients were calculated from the raw pulse counts from the transmissometers, various quality filters were applied to ensure that, e.g., pulse counts during a lamp shutdown/background check period were not used.
2. Recalibration of Tasker transmissometer data: as described in detail in Appendix B: Tasker 500 Post-Hoc Recalibration, the Tasker transmissometer data was retrospectively recalibrated by determining the true baseline pulse count during high-visibility conditions, rather than assuming that the ideal values of approximately 4,000 pulses per minute was maintained. This approach has been followed in previous studies (Burnham, 1997, p. 33).
    a. Note: This step also involved a 3.5% reduction in the measured extinction coefficient from the Taskers under foggy conditions. This adjustment was performed because of the lack of an IR cut-off filter in the Tasker transmissometers, which was present when the Taskers were in operational use. This figure is derived from previous analysis (Burnham, 1997, p. 33).
3. Synchronization of data sources: the DUT was used as the master instrument, and other data points were be assigned as “nearly simultaneous” to each DUT measurement, as described in section 5.2.1 above.

4. Manual background check or other adjustments: for any specific events where it was evident that the reference transmissometer measurements were precise, but not accurate, because of a bad background check or other cause, the affected transmissometer measurements were corrected as needed.
5. Analysis: the procedure described in section 5.2.4 was followed to generate the analysis results.

5.2.3 Weather Characterization

A comparison (not detailed in this report) between the LT31 present weather output and other weather characterization sources, including the KFMH METAR and ancillary sensors present at the VTR, revealed that the LT31 provided an accurate characterization of the prevailing weather condition, at least for the high-level categorization of fog / rain / snow which had been planned for the analysis.[7] Consistent with the result of this comparison, we used the LT31 present weather output to characterize the prevailing weather condition as fog, rain, or snow.

5.2.3.1 Sorting of PWS Output into Fog, Rain, and Snow

The instantaneous WMO SYNOP codes from WMO Table 4680, as reported by the PWS, were used to categorize individual LT31 reports as occurring during fog, rain or snow. For categorization, numerical codes 10 (“mist”) and 30 – 34 (various types of fog) were grouped as fog measurements; codes 50 – 56 (various types of drizzle), 60 – 66 (various types of rain), and 80 – 84 (rain showers) were grouped as rain measurements; and codes 70 – 73 (various types of snow), 74 – 76 (various types of ice pellets), and 85 – 87 (snow showers) were grouped as snow measurements. Not all of these codes were reported in the data. Because of the substantial amount of available data, in order to cleanly separate performance under the three major weather conditions, these precipitation types are exclusive – i.e. weather reported as, for example, mixed rain and snow, was not used in the analysis.

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[7] Volpe did not attempt to validate the full spectrum of present weather conditions that are reported by our LT31, which is equipped with the present weather sensing option. As a result, we do not make any representation in this report as to how accurately it characterizes details which are used for fine-grained weather condition determination (e.g. rain or snow rate). However, our understanding is that the integrated present weather sensor is equivalent to, or identical to, the PWD22, which is a present weather sensor currently marketed by Vaisala. We have no reason to believe its performance is inadequate for our anticipated uses. As such, we anticipate continuing to use the present weather sensing feature in the future.

5.2.4 Data Analysis Procedure

The data analysis procedure for comparing the measurements of the DUT to those of the reference transmissometer is described below. This procedure uses the subset of data resulting from the filtering methods described above. The full range of obscuration and precipitation types are grouped generally as fog, snow, or rain, as described in Section 5.2.3.1. This methodology is similar to what has been used in previous PC-RVR VS validation efforts.

1. The reference transmissometer extinction coefficients are converted into MOR values to facilitate interpretation of the data. The conversion formula is given by $MOR = 3/\sigma$, as described in Appendix F: RVR Calculation Methodology. The DUT already reports MOR values directly, so they do not need to be converted.
2. For each effectively simultaneous set of DUT and 250 foot baseline Tasker measurements, the ratio of the DUT MOR to the reference transmissometer MOR is calculated.
3. The MOR ratios are separated into 20 logarithmically-spaced bins based on the reference transmissometer MOR values.
4. For each bin, the MOR ratio distributions are analyzed. The median of the bin of ratios is calculated, along with various percentiles.
5. All the MOR values that fall within the required accuracy limit as defined in section 5.1 above – meaning σ (reference) > 3 km^{-1} [MOR < 1000 m] – are lumped into a single bin. The distribution of MOR ratios is then calculated for this bin.
6. The results of the analysis for each logarithmic MOR bin and the overall MOR distribution are used to confirm if the accuracy requirements are met for the DUT.
7. This analysis procedure is repeated for the subsets of data corresponding to each general adverse weather category. In this way, the DUT accuracy requirements are tested for overall performance as well as a variety of obstruction types.

6. Analysis Results

6.1 Summary of Results

The initial results of the analysis procedure revealed significant differences between the extinction coefficients / MOR reported by the DUT compared to the Tasker 500 standard after performing the time-matching and analysis procedure described in Section 5.2. In particular, the MOR reported by the DUT significantly overestimated the MOR measured by the 250 foot baseline Tasker 500. In addition, this overestimation of MOR was worse at lower measured MOR values. This result was surprising; in order to validate the conclusion, the DUT measurements were also compared to the 300 foot baseline Tasker as well as the PC-RVR VS, and the overestimation of MOR was consistent relative to all other visibility sensors.

In short, the initial results of the DUT were not only not compliant with the existing standard, they were non-compliant in the worst direction – they overestimated visibility, and did so more significantly as visibility declined.[8] However, across all atmospheric conditions, the reported MOR from the reference Tasker (and the other visibility sensors) and the DUT were highly correlated. It was clear that all the sensors were measuring the same fundamental phenomena.

For obvious reasons, this gave Volpe significant concerns about recommending the adoption of the DUT as a possible visibility standard. However, after consultation with Vaisala (the manufacturer of the DUT), an apparent cause of this difference was established. The basis of the difference is more fully explained in Appendix A: Cause of LT31 Visibility Overestimation Relative to Tasker 500 During Main Data Collection, which includes a summary of the physics, as well as a short statement from Vaisala. In short, the difference in measurement results was driven by optical differences between the Tasker 500 and the reference transmissometer used by Vaisala to calibrate the DUT.

Scientific literature referenced by Vaisala allowed Volpe to perform a post-hoc correction to the data collected by the DUT, and performing the post-hoc correction changed the DUT measurements such that they agreed, within the specified tolerance, with the reference Tasker. This gave Volpe and the FAA more confidence that the DUT could be modified to serve as a new standard. However, it was clear that post-hoc corrections were not a sustainable way to generate reference MOR measurements in the long run. When Volpe and the FAA raised this concern, Vaisala agreed to provide a modified version of the firmware for the DUT which – according to Vaisala – would correct the issue.

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[8] Actually, the overestimation was present during fog and rain, but not during snow. This was an interesting result, which ultimately gave Volpe additional confidence in Vaisala's explanation for the physical mechanism behind the difference in measurements.

As detailed in Section 6.3 below, Volpe conducted further data collection, although within a more limited scope, in order to evaluate whether the DUT, after Vaisala's updates, would perform adequately under the existing standard. Based on the additional data collection, Volpe is now reasonably confident that the updated DUT is a suitable replacement for the Tasker 500, and recommends that the DUT (the Vaisala LT31 transmissometer) be adopted as the new standard instrument for visibility measurement by the FAA.

6.2 Main Data Collection

The original period of data collection began in October 2021 and ended in October 2022. The results of the analysis, separated out into fog, rain, and snow, and evaluated both with and without a homogeneity criterion applied, demonstrated unsatisfactory results from the DUT, as discussed in the summary above.

The main data collection ultimately served three purposes:

1) It identified the significant overestimation of visibility of the DUT relative to the reference Tasker using the default calibration parameters;
2) It allowed Vaisala, Volpe, and the FAA to examine the overestimation and determine a plausible root cause;
3) It provided a large dataset to which a post hoc correction could be applied, which established that Vaisala's proposed correction was likely to succeed.

Because of schedule and budget constraints, the post-update data collection from the DUT was substantially smaller in scope. Volpe believes that the combination of the results from the Volpe-imposed post hoc correction of the original data (which is essentially identical to the later corrections implemented by Vaisala[9]) and the post-update data collection is needed to fully justify the recommendation that the DUT be adopted as the new FAA visibility standard.

The results displayed in the remainder of this section are the box and whisker plots showing the statistical agreement between the reported MOR values from the DUT against the reference Tasker. For readers unfamiliar with the plots, the first plot will be accompanied by a description of the elements within the plot. The remainder of the plots will not have a similar detailed description, but will be accompanied by a summary of the findings.

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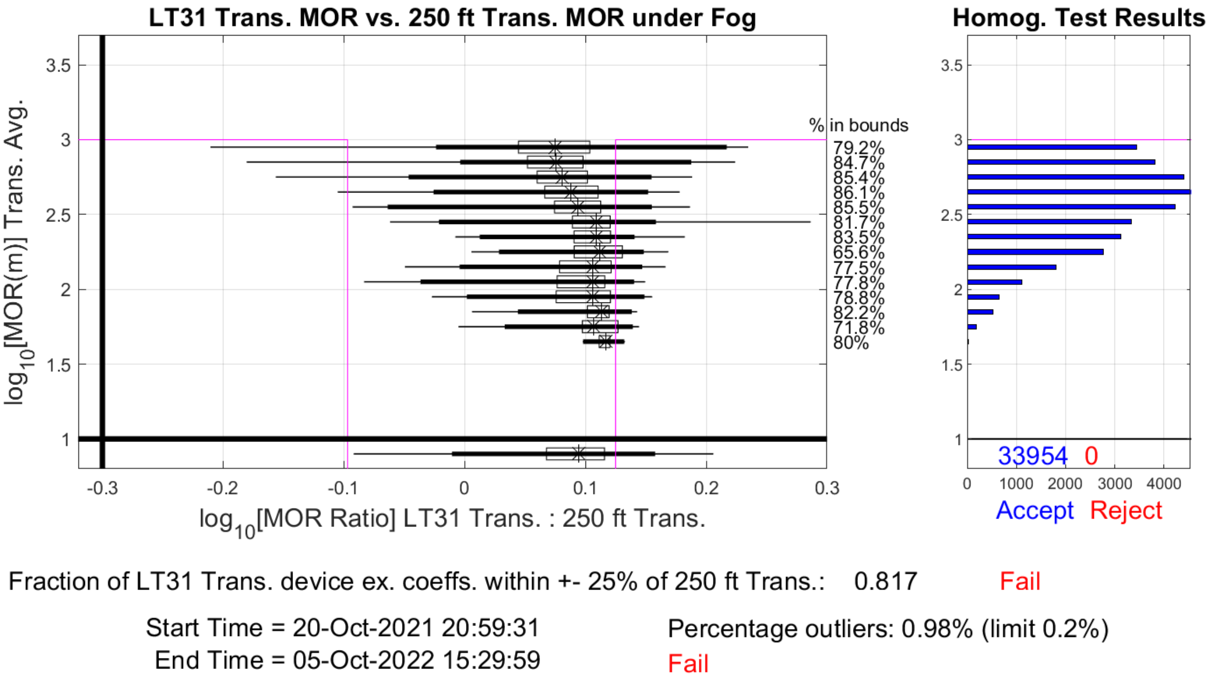
[9] Although the exact implementation of Vaisala's correction is considered proprietary and cannot be disclosed in this report, the Volpe Center has documented the post-hoc correction Volpe imposed, derived from the open literature, in Appendix A: Cause of LT31 Visibility Overestimation Relative to Tasker 500 During Main Data Collection. Volpe is confident based on both data collection and documentation provided by Vaisala that the Vaisala correction provides nearly identical results.

6.2.1 Main Data Collection – No Homogeneity Requirement

6.2.1.1 Fog

The total amount of data collected under foggy conditions, with visibility less than or equal to 1,000 meters, was approximately 5.9 days (141.6 hours) over the one-year period of data collection.

6.2.1.1.1 Original Results - No Correction Applied



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.817 Fail

Start Time = 20-Oct-2021 20:59:31
End Time = 05-Oct-2022 15:29:59

Percentage outliers: 0.98% (limit 0.2%)
Fail

Figure 6-1: Main Data Collection; Fog; No Homog. Req.; No Correction Applied

The plot above has two main elements: on the left, there is a sub-plot showing the statistical results for the individual MOR bins of the comparison between the DUT and the reference Tasker transmissometer, and on the right there is a sub-plot showing the results of the homogeneity testing. Additional data is shown below the two plots, including the fraction of measurements falling within the accuracy requirement (in this case, 0.817 or 81.7%), and whether that passes or fails the requirement; the date and time of the first and last measurements in the subset of the overall data used for this plot; and the percentage of outliers as defined in FAA-E-2772B, with a similar pass/fail evaluation for the outlier criterion shown below the percentage value.

The main sub-plot on the left has divided the MOR range from 10 meters to 1000 meters (approximately

33 feet to 3,300 feet) into twenty logarithmically evenly distributed bins, consistent with prior practice. All of the time-matched MOR values for both the reference Tasker and the DUT are assigned to one bin or another based on the MOR value for the reference Tasker. The DUT measurements are divided by the reference Tasker measurements, and the base 10 logarithm of the ratios is computed. The 2.5th, 5th, 25th, 50th, 75th, 95th, and 97.5th percentiles of the log ratios are then displayed as a box and whisker plot for each bin. The thin line stretches from the 2.5th to 97.5th percentiles; the heavy line stretches from the 5th to 95th percentiles; the box stretches from the 25th to 75th percentiles; and the asterisk indicates the 50th percentile (or median). Below the box and whiskers for the individual bins, the aggregated result for the subset of the data relevant to this plot is displayed. Only the aggregated result is critical, according to the standard, but plotting by individual bins has been useful to see if the behavior of the sensor is variable based on visibility, as it is in this case.

The magenta lines on the main plot show the outer boundaries of the acceptable ratios given in FAA-E-2772B; 90% of the data must fall within these boundaries to pass the main accuracy criterion. Each bin has the relevant fraction of the measurements which fall within the acceptable limits plotted along the right edge of the plot. Once again, only the aggregated result is the key metric based on the standard, but the values are shown on a per-bin basis as well as for the aggregated data.

On the right hand sub-plot, the results of the homogeneity testing is shown, again on both a per-bin and aggregated basis. The PC-RVR performance standard specifies that the PC-RVR only be tested against measurements where the atmosphere was known to be homogeneous. For reasons discussed earlier in this report, we begin our analysis by not imposing this criterion – which has been implemented here by forcing the homogeneous flag to “true” for all measurements. This is reflected in the bars displaying that all measurements pass the homogeneity criterion. This is not the case; true homogeneity results are shown in the sections labeled “Homogeneity Requirement”.

The results of this plot clearly show the measurement phenomenon discussed earlier in this report. The log10 values of the MOR ratio (DUT measurement divided by reference measurement) are clearly and substantially positive for all bins. The aggregate result has a median log10 ratio of approximately 0.094, corresponding to a median overestimate of the visibility of about 24%. It is also evident from the position of the bin centers that this overestimate is worse at lower visibility. The DUT fails both the test on the accuracy of the aggregate data and the test on the number of outlier measurements.

However, the DUT measurements are, overall, strongly correlated with the reference transmissometer. The heavy line – which indicates the range of the middle 90% of the data – is generally no wider than the space between the magenta lines, with a narrower spread at lower visibility. This is what would be expected for a functioning instrument; as the visibility decreases, so does the relative impact of calibration error (or calibration difference). It is clear that the issue is not that the DUT is not able to measure the atmospheric conditions adequately; rather, the issue that there is some systematic difference between the way the sensors report visibility under the same atmospheric conditions.

6.2.1.1.2 Post Hoc Correction Applied

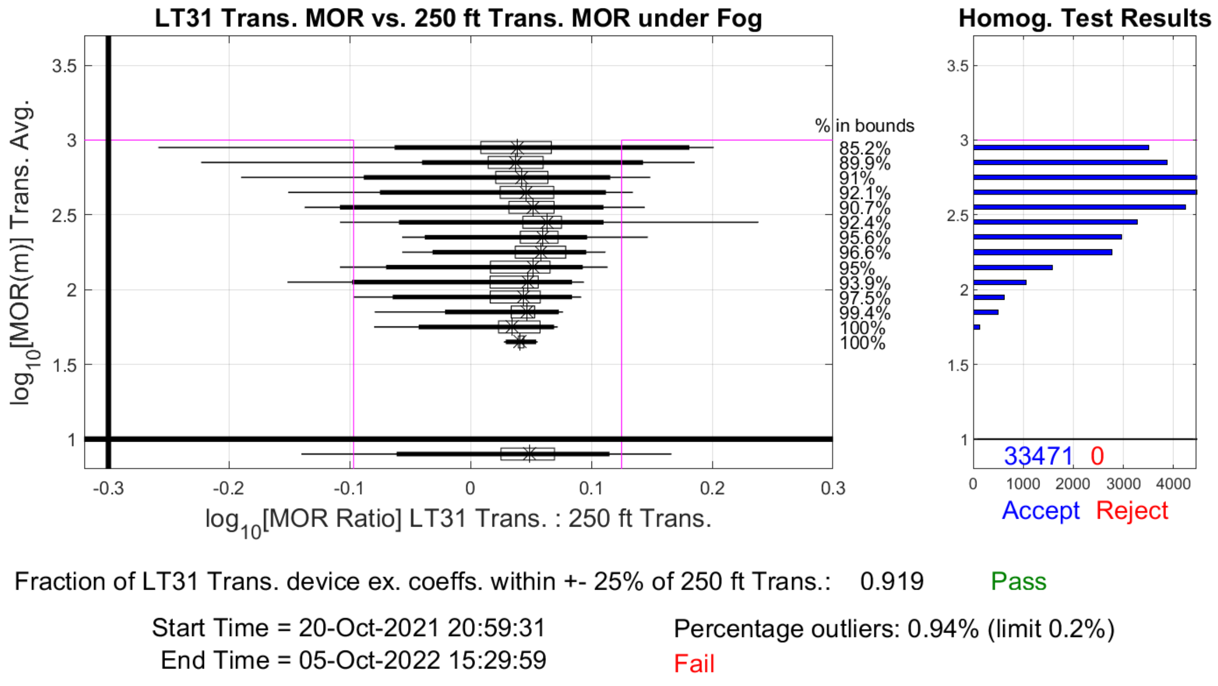


Figure 6-2: Main Data Collection; Fog; No Homog. Req.; Post Hoc Correction Applied

As discussed in the introduction to this section, after discussions with Vaisala, they provided a plausible physical explanation for the difference between the Tasker results and the DUT. The optical differences between the Tasker and the reference transmissometer used by Vaisala to calibrate the DUT will inherently lead to different measurement characteristics consistent with the observed behavior (i.e. the DUT overestimating visibility, with greater differences at lower visibility values). Based on reference material provided by Vaisala, Volpe developed a post-hoc correction to apply to the data.

The results after the post-hoc correction are considerably more consistent with the Tasker. A relatively small, but consistent, overestimation remains at the median level. However, the observed pattern of overestimation worsening at lower visibility has been removed, and the DUT now agrees with the Tasker to within the level required by the specification. Enough outliers remain in the dataset for the DUT to fail that criterion, but it is important to remember that the specific target value of 0.2% was developed for the agreement between a forward-scatter meter and a transmissometer under homogeneous atmospheric conditions, and we have not imposed that restriction here.

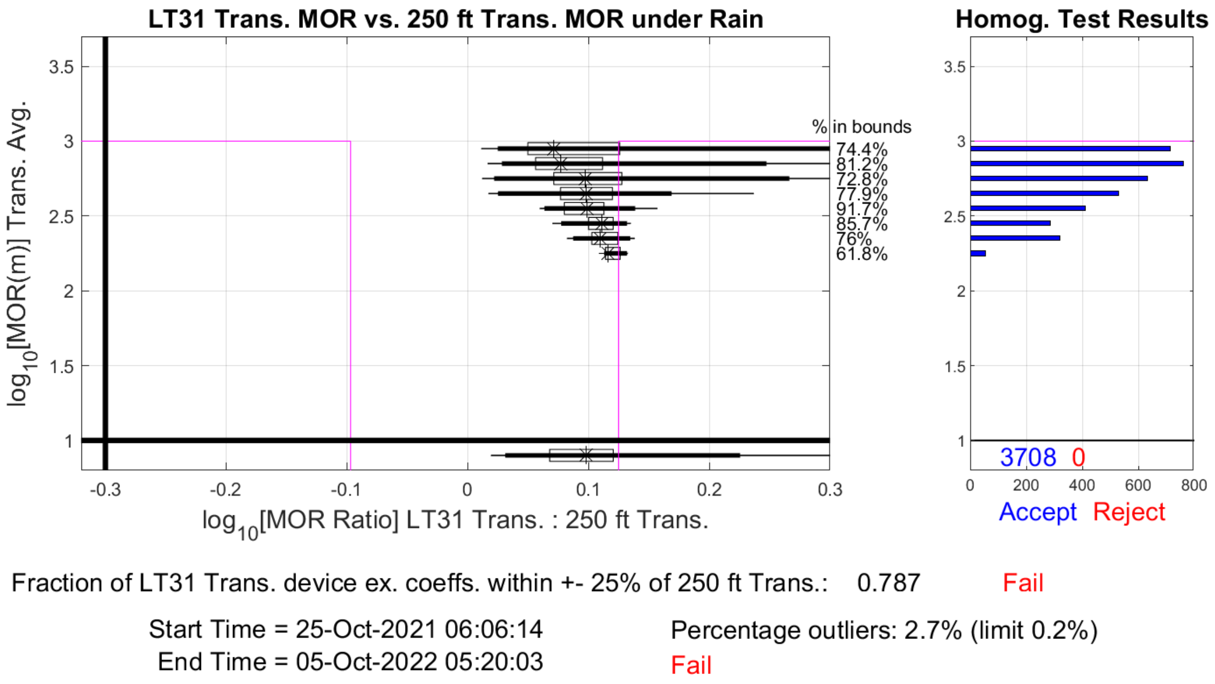
An additional analysis was performed after restricting the data to data collected under homogeneous conditions. In the interest of brevity, the plots are presented in Appendix D: Complete Set of

Comparison Box Plots. They show that the agreement between the two devices gets slightly better, and that the DUT also passes the outlier criterion. In short, with the post-hoc correction applied, the DUT passes the accuracy requirements to be acceptable as a new visibility standard under foggy conditions.

6.2.1.2 Rain

The total amount of data collected under rainy conditions, with visibility less than or equal to 1,000 meters, was approximately 0.64 days (15.4 hours) over the one-year period of data collection.

6.2.1.2.1 Original Results – No Correction Applied



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.787 Fail

Start Time = 25-Oct-2021 06:06:14
End Time = 05-Oct-2022 05:20:03

Percentage outliers: 2.7% (limit 0.2%)
Fail

Figure 6-3: Main Data Collection; Rain; No Homog. Req.; No Correction Applied

The results of the comparison between the DUT and the reference Tasker during rain are qualitatively similar to the results under fog, with the main observation being, once again, that the overestimation is worse at lower visibility.

Two interesting features of the data are that the overestimation in rain appears to be slightly more significant than the overestimation in fog, and that the distribution of ratios, especially at higher visibility values, has a much heavier tail in the positive direction than in the negative direction (i.e. the distribution is asymmetrical) when compared to the median ratio of MOR measurements. That is, not only is the DUT slightly more likely to overestimate visibility compared to the reference Tasker in rain than in fog, but also that, relative to the median behavior, overestimation is much more likely than underestimation. It is not obvious whether this phenomenon has a physical cause, or if it is an artifact associated with the lower number of measurements compared to fog.

6.2.1.2.2 Post Hoc Correction Applied

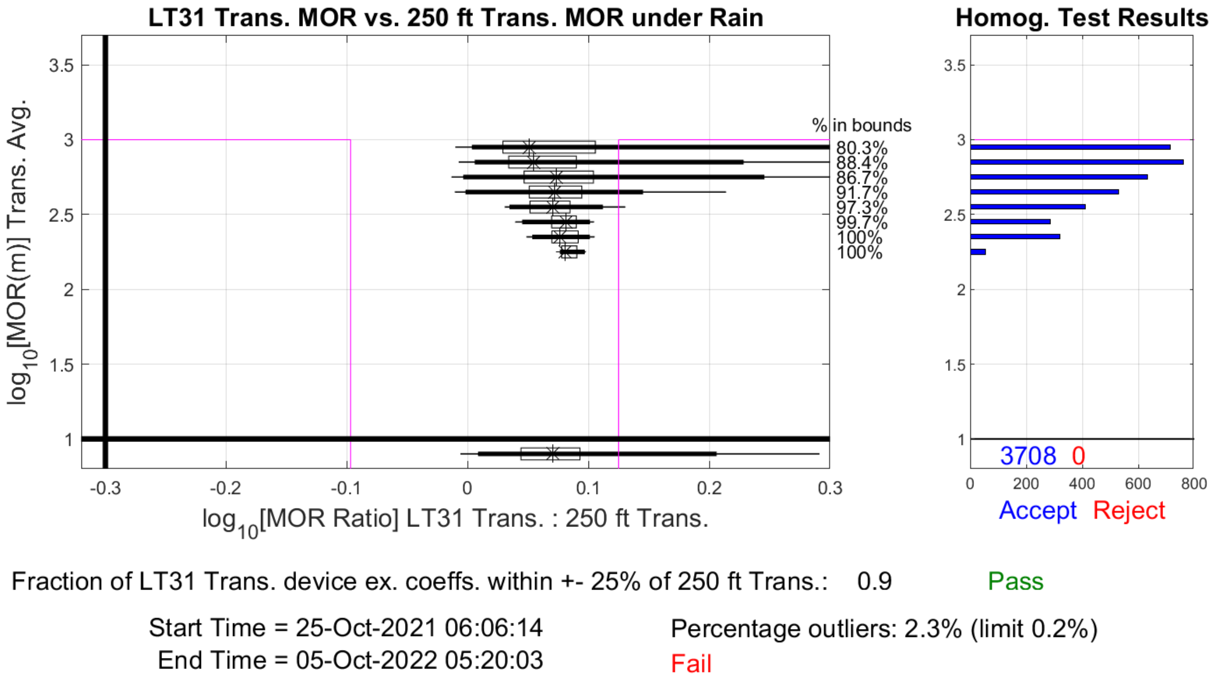


Figure 6-4: Main Data Collection; Rain; No Homog. Req.; Post Hoc Correction Applied

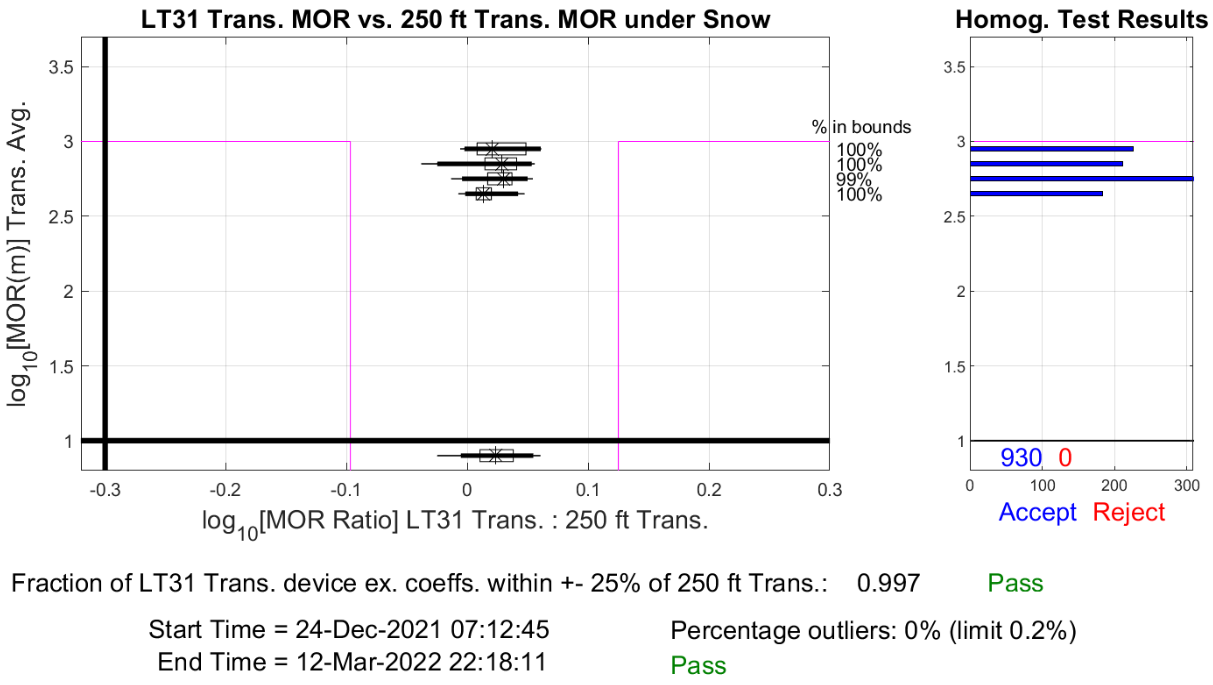
After the application of the post-hoc correction, the data is once more qualitatively similar to the results in fog, but with the same caveats previously mentioned. Even in inhomogeneous conditions, the corrected measurements from the DUT now fall within the accuracy specification. Once again, we see a greater proportion of outliers than allowed by the specification – but, just like in fog, if the analysis is restricted to homogeneous conditions, the DUT has slightly improved performance at the median level, and is compliant with the limit on outliers. Once again, see Appendix D: Complete Set of Comparison Box Plots in order to see the relevant box plot.

In fact, if homogeneity is imposed, all the outliers in the data are eliminated, suggesting that, even at the same visibility, inhomogeneity – and, therefore, significant sensor to sensor variability in reported visibility – is more likely in rain than in fog. This is borne out by looking at the relative frequency of inhomogeneous measurements under the two weather conditions. Roughly 17% of measurements below the visibility threshold of interest (1000 m / 3300 ft) were inhomogeneous in fog, while roughly 29% of measurements below the same threshold were inhomogeneous in rain.

6.2.1.3 Snow

The total amount of data collected under snowy conditions, with visibility less than or equal to 1,000 meters, was approximately 0.16 days (3.9 hours) over the one-year period of data collection.

6.2.1.3.1 Original Results – No Correction Applied



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.997 Pass

Start Time = 24-Dec-2021 07:12:45
End Time = 12-Mar-2022 22:18:11

Percentage outliers: 0% (limit 0.2%)
Pass

Figure 6-5: Main Data Collection; Snow; No Homog. Req.; No Correction Applied

The results of the comparison between the DUT and the reference Tasker during snow conditions are considerably different from the results during fog and rain. Rather than having a large systematic bias towards overestimation of MOR, the DUT appears to measure visibility in snow essentially identically to the reference Tasker. There is still a slight positive bias at the median level, but the amount of bias is easily within normal instrument-to-instrument variability. Additionally, the tails of the distribution are nearly symmetrical. The performance of the DUT during snow was acceptable without any measurement correction, so none was applied post-hoc.

6.2.2 Summary of Results from Main Data Collection

The initial analysis of the data from the main collection effort were not favorable to the DUT. As mentioned in the executive summary for this report, these results triggered discussions with Vaisala about the systematic and large differences between the DUT and the reference Tasker under low-visibility conditions due to fog and rain, but not snow. Ultimately, Vaisala provided a physical explanation for the observed behavior, which provided a rationale for the application of a specific post-hoc correction methodology. When this post-hoc correction was applied, the performance of the DUT became acceptable under the standards established in the test plan.

However, neither Volpe nor the FAA believed that it was a desirable situation to be using a Vaisala LT31 as the gold standard transmissometer subject to the application of this post-hoc correction. That would provide too many opportunities for human error in documenting and maintaining the process needed to perform these corrections. Volpe and the FAA approached Vaisala about incorporating these corrections at the sensor level, rather than post-hoc. Vaisala ultimately provided an updated firmware which they claimed incorporated the relevant corrections. Although neither Volpe nor the FAA had any reason to doubt Vaisala's claim, we decided that a secondary data collection was needed to have full confidence that the built-in correction was working as intended.

6.3 Secondary Data Collection

The secondary data collection, which was used to validate the Vaisala firmware correction, took place through the summer of 2023 (late June 2023 through mid-August 2023). Although the duration of the data collection was substantially shorter than the main data collection, Volpe and the FAA agreed that given the results from the main data collection – especially the success of the post-hoc correction – a significantly shorter time frame was acceptable to establish whether the Vaisala firmware correction produced results comparable to the post-hoc correction. Because this data collection occurred in the summer, Volpe was unable to collect any data under snowy conditions; however, no correction was necessary under snowy conditions, so this was considered an acceptable risk from a validation perspective.

6.3.1 Secondary Data Collection – No Homogeneity Requirement

As with the main data collection, the results are displayed in box plot format. The emphasis on the main body of the report is on the results without imposing the homogeneity requirement, but as with the main data collection, the results after imposing the homogeneity requirement are displayed in Appendix D: Complete Set of Comparison Box Plots.

6.3.1.1 Fog

The total amount of data collected for the secondary data collection under foggy conditions, with visibility less than or equal to 1,000 meters, was approximately 2.4 days (57.6 hours).

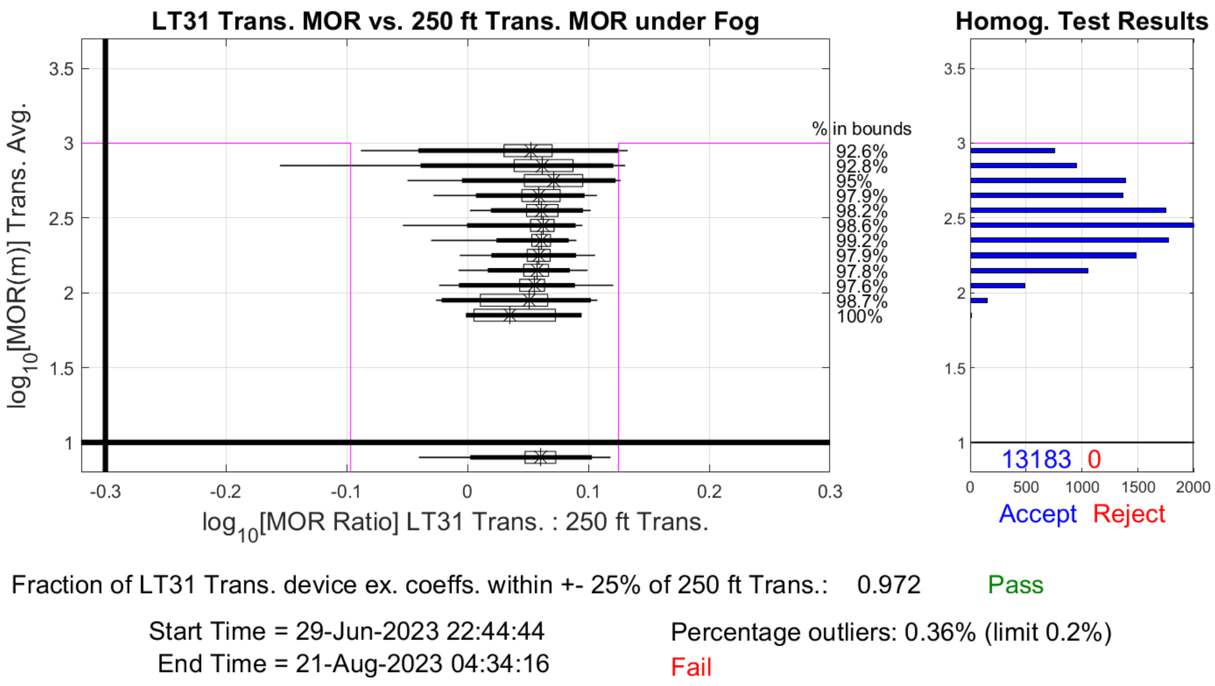


Figure 6-6: Secondary Data Collection; Fog; Vaisala Firmware Correction Applied

The results during fog from the data collected after the application of the correction at the firmware level by Vaisala are at least as favorable to the DUT as the results from the main data collection after the post hoc correction. Essentially all of the DUT measurements fell within the +- 25% error bounds, and there were only a small number of outlier measurements (although more than the outlier criterion allows) even without imposing a homogeneity requirement. It is also clear that there is still a relatively small, but systematic, bias of the DUT to produce higher estimates of visibility than the reference Tasker.

6.3.1.2 Rain

The total amount of data collected for the secondary data collection under rainy conditions, with visibility less than or equal to 1,000 meters, was approximately 0.06 days (1.4 hours).

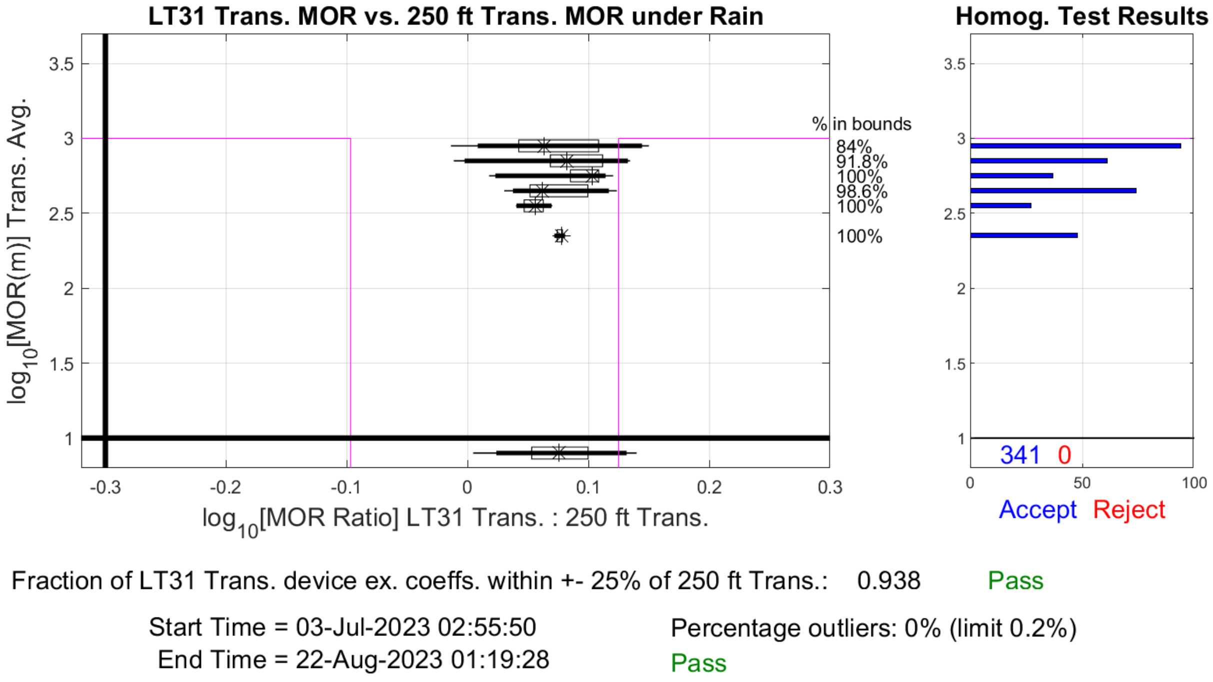


Figure 6-7: Secondary Data Collection; Rain; Vaisala Firmware Correction Applied

As with the results under fog, the results of the analysis after the implementation of the firmware correction by Vaisala are at least as favorable to the DUT as the results after the post hoc correction of the main data collection. Once again, we see that the DUT meets the accuracy bounds specified in the test plan, and that in this case there were no observed outliers, even without applying a homogeneity requirement. Again, just as in fog, we see a relatively small but consistent tendency for the DUT to produce higher visibility measurements compared to the reference Tasker.

6.3.2 Summary of Results from Secondary Data Collection

The analysis of the secondary data collection produced results that are very similar to the results of the main data collection after the post-hoc correction. In both fog and rain, the DUT passes both the accuracy and outlier requirements. During the secondary data collection, this is true even without imposing any homogeneity criteria – although, because there was considerably less data collected, this could simply be a sampling effect.

As the behavior in the secondary data collection is consistent with the corrected data from the main data collection, there is no reason to believe that the Vaisala firmware correction is materially different from the post-hoc correction, and therefore the DUT can be considered validated after the firmware update.

7. Experiences with Reliability and Maintainability

As discussed in Section 2.2: Test Objectives, the primary objective of this overall effort was to identify a suitable replacement for the Tasker 500 transmissometers that would be significantly more reliable and lower-cost to maintain, while also meeting the accuracy requirements to be acceptable as a new standard instrument. Because we purchased a brand new LT31 and installed and operated it according to manufacturer specifications / recommendations, we anticipated that the LT31 would easily be more reliable and lower-maintenance than the Tasker 500 transmissometers tested under the same conditions. As a result, most of this report has been dedicated to the side-by-side performance evaluation. In order to complete our assessment of the LT31 as a possible replacement visibility standard, we now turn to an evaluation of our experiences with reliability and maintainability.

There is no question that the LT31, overall, performed much more reliably and with far less manual intervention required than the reference Tasker 500 transmissometers. The advertised features of the LT31 generally worked as described during this test effort. The coarse/initial alignment and calibration processes were straightforward, including both the manual and automated features. The physical features of the transmissometer (weather protection hoods, hood heaters and blowers, etc.) that were designed to maintain continuous, low-intervention operation in all weather conditions, functioned correctly. The LT31 appeared to correctly monitor and compensate for phenomena like gradual alignment drift and window contamination, and the alarm features seemed mostly reliable – although we did have a measurement problem that was not appropriately flagged by internal alarms, which is described later in this section.

Despite the overall positive experience operating the LT31, we did encounter a few notable reliability concerns. This section of the report details our experiences operating the LT31 over the course of this test effort. We encountered two significant problems with the LT31 unit that we operated during the testing which led to significant downtime.

The first significant issue we encountered appeared to be related to an electrical disruption, although we never discovered the root cause. The Volpe Test Range is located on primarily sandy (and therefore high-impedance) soil, and occasional lightning strikes occur in the vicinity. During late January/early February of 2021, we experienced a winter storm associated with relatively high winds which disrupted power distribution to our sensors, which was apparently associated with a fault in the transformer feeding our facility. A number of our sensors, including the LT31, experienced disruption and/or operational anomalies.

Although we purchased the enhanced electrical protection option for our LT31 (the “TERMBOX-9000”), and we installed the sensor according to Vaisala’s manual (including appropriate grounding of the sensors themselves and proper installation of the power and data cabling), it became apparent that something had damaged the master CPU board in the LT31 (located in the receiver) or erased its operating system. We had to ship the damaged board back to Vaisala, and received a replacement board. The entire process took about three weeks, partially because of Volpe staff availability to visit the VTR, but mostly driven by the turn-around time associated with our interactions with Vaisala support, including shipping time to and from Finland.

The second significant issue we encountered during our evaluation was moisture infiltration into the projector/transmitter unit of our LT31 in late May/early June 2022. At this time, the LT31 had been physically installed at the VTR for approximately one year. We initially observed erratic measurement behavior, and in the process of attempting to diagnose the issue, we observed condensation on the interior of the transmitter windows. The misbehavior of the LT31 was troubling because it had only spent a year in the field; even more troubling was the fact that the LT31 was reporting erratic measurements without triggering any of its automated quality warnings.

After some diagnostic work with Vaisala support, we ultimately had to ship the entire transmitter unit back to the manufacturing facility in Finland, where Vaisala ultimately needed to replace both the measurement CPU (LTC112) and the transmitter unit (LTL212) before shipping it back to us. The turn-around time, from when we first engaged Vaisala support to when we received the operable transmitter unit, was approximately six weeks, which was a substantial amount of downtime during our roughly 12 months of main data collection. Fortunately, it happened during the early to mid summer, a time frame which did not impair our overall ability to collect adequate data for the evaluation. If the same failure had occurred during winter, it might have severely limited our ability to collect enough snow data.

Although this section of the report documents the LT31-related complications we experienced during the testing, we do not know how typical our experiences are. Despite the issues we experienced, the LT31 we tested was still, overall, significantly more reliable and maintainable as a sensor than the Tasker 500 units used as reference sensors. Over the course of the test campaign, and in the months following the main data collection, we were able to significantly improve our lines of communication with Vaisala, and we anticipate that the improved communications will facilitate more rapid troubleshooting and repairs in the future.

8. Conclusions

From the outset, this multi-year testing effort was planned to identify and test at least one possible reference visibility sensor to replace the existing Tasker 500 transmissometers used as the reference standard by the FAA. The Volpe Center identified the Vaisala LT31 as a potentially suitable replacement, and conducted data collection, both during an originally-planned primary data collection and a secondary data collection, over the course of more than one calendar year from 2021 – 2023. This effort was designed to validate the performance of the LT31 against the existing "gold standard" transmissometer, the Tasker 500, using an adapted version of the existing PC-RVR VS performance standard.

The results of the primary data collection indicated that the LT31 overestimated visibility relative to the existing standard, and that it would not pass the performance criteria as-is; however, the primary data collection also showed that the LT31 appeared to be consistently measuring the same atmospheric phenomena as the Tasker 500 transmissometers, but with some kind of systematic difference. Collaboration between Volpe, the FAA, and Vaisala identified a plausible physical explanation for the difference, and a correction that could be applied in order to bring the LT31 performance in line with the FAA's Tasker 500 standard. The suggested correction was initially supplied to Volpe in graphical form, and ultimately as a correction implemented in the firmware of the LT31. This correction was validated both by applying it post-hoc to the main data, collected between October 2021 and October 2022, and by doing a supplemental data collection between June 2023 and August 2023. The results of both validations provide strong evidence that the Vaisala LT31 performance meets the standards established at the beginning of the test.

Reliability and maintainability of a potential new standard were the main drivers of this test effort. Because of the increasing maintenance burden associated with keeping the Taskers in good working order, as well as the declining availability of parts, the LT31 was selected in no small part because it was currently being manufactured by a large and reputable vendor. Although Volpe experienced two non-trivial sensor outages, our conclusion is still that the LT31 is substantially more reliable than the Tasker 500 transmissometers, and we hope that improved engagement with Vaisala will enable even better performance in the future.

Because the Vaisala LT31 represents a more reliable and maintainable instrument, and because – once corrected – its performance agrees well enough with the existing standard under the pre-established accuracy criteria, Volpe recommends that the FAA accept the Vaisala LT31 – with firmware correction enabled – as the new "gold standard" visibility sensor.

9. Recommendations for Future Efforts

Some of the experiences during this test campaign revealed areas of improvement for future visibility sensor test and evaluation efforts. Below, we list recommendations to facilitate these future efforts, and provide some rationale.

- *Evaluate data early, and evaluate data often, especially when evaluating new sensor models*

In the PC-RVR evaluation efforts that immediately preceded this test campaign, Volpe's strategy for evaluation of those visibility sensors had been well-established, both by reference to the PC-RVR performance standards and to our historical practice. We used an adapted version of this strategy for this particular campaign. However, these recent PC-RVR test campaigns were of significantly shorter duration and were more routine/limited. Rather than needing to evaluate a brand-new sensor as we did here, they were focused on validating the performance of recent production batches of future design. As such, other than periodic informal spot checks to see whether the instrumentation was all tracking together, our practice was to wait until the data collection effort had ended and do the analysis all at once.

In this test campaign, although we did identify an interim data analysis as a desirable goal, and did perform some analysis before the end of data collection, we could have discovered the measurement differences between the LT31 and Tasker 500 earlier than we did. Although it ultimately turned out that Vaisala needed several months to perform the firmware update, in principle we might have been able to avoid the secondary data collection if we had identified the phenomenon earlier in the campaign.

- *Do not hesitate to engage with the manufacturer on performance issues*

As mentioned above, Volpe did identify the LT31 performance issue during the main data collection effort. We then spent considerable time performing validation checks on our collected data to ensure complete confidence in our results before engaging Vaisala on the issue. Although there certainly needs to be an appropriate distance between the manufacturer of the sensor (Vaisala) and the organization evaluating its performance in support of the FAA (Volpe), in retrospect, earlier engagement with Vaisala would have been fruitful. Once informed of the Volpe findings, Vaisala investigated the issue internally and ultimately discovered (or rather *recovered*; see below) both the physical explanation for the difference in the results between the LT31 and the Tasker 500, and an appropriate correction to be applied, within a few months. In combination with performing data analysis earlier in the campaign, better coordination with Vaisala once the issue was discovered could have shortened the evaluation process.

- *Improve documentation and dissemination of testing and experimental findings, even where issues are resolved during the campaign*

Once the LT31 overestimation phenomenon was discovered by Volpe, and confirmed to likely be a real phenomenon by Vaisala, Volpe spent some time reviewing internal documentation, including extensive paper records, of previous testing efforts. We discovered a memo dating from ca. 2004 – 2005, which was the time frame during which Volpe was testing the Vaisala FS11 for use in the PC-RVR system, that described a systematic overestimation of visibility by the FS11 with respect to the Taskers. Vaisala confirmed from their own records that this issue had been identified at that time.

Because the underlying cause of the disagreement are optical differences between the Vaisala MITRAS transmissometers used as the calibration standard for Vaisala visibility sensors and the Tasker 500, this disagreement is inherent (if not explicitly corrected) in all Vaisala visibility sensors when compared to the Tasker 500. If this knowledge had been preserved within the institutional memory of the FAA, Volpe, and/or Vaisala, the disagreement would not have been surprising – and indeed, could potentially have been corrected before installation and testing.

This issue has – ideally – been mitigated for future use of the LT31 (including any additional sensors or replacements) because Vaisala incorporated the correction into the firmware, but it can reasonably be expected to continue to arise. This recommendation is intended both as good future practice and to help maintain this phenomenon within institutional memory.

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Appendix A: Cause of LT31 Visibility Overestimation Relative to Tasker 500 During Main Data Collection

After discussion with Vaisala about the systematic differences between the measurements of the Tasker 500 and the Vaisala LT31, Vaisala provided a physical explanation of the differences based on the different characteristics of the Tasker 500 and the LT31. Of particular importance is the difference in view angle for the receiver of the calibration standard used for the LT31 – which is the Vaisala MITRAS transmissometer. The MITRAS transmissometer has a substantially wider view angle than the Tasker 500.

As mentioned in Section 2.2, under most weather conditions, the primary factor reducing visibility is scattering of light by particles in the air. The view angle of the Tasker 500 is narrow enough that essentially all light generated by the projector which ends up ultimately being scattered along the path of the beam cannot enter the receiver. The wider view angle of the MITRAS transmissometer when compared to the Tasker 500 allows more scattered light to enter the MITRAS receiver. Because transmissometer measurement of visibility is based on comparing the light intensity at the receiver to a known clear-air value, the additional reception of scattered light for the MITRAS standard causes it to report higher visibility than the Tasker 500. This phenomenon is particularly noticeable at low visibility where there are substantially more hydrometeors present.

This explanation is physically plausible, and Vaisala was able to provide scholarly references[10] demonstrating the magnitude of the effect as it varies according to prevailing visibility and the baseline distance separating the projector and receiver. Volpe implemented a correction based on these scholarly references, which provided substantially the same correction effect as the Vaisala-implemented correction. Volpe has documentation of the exact correction implemented by Vaisala, which is Vaisala-proprietary data, and is confident in its understanding of the Vaisala correction process.

Vaisala's summary explanation of the systematic visibility measurement difference between the LT31 and the Tasker 500 is below:

> Vaisala Transmissometer LT31 was developed both for use as a reference transmissometer and for operational use at airports. It was developed to mimic human observation of visibility. The LT31 response is based on its predecessor transmissometer MITRAS response. The MITRAS also mimicked human vision to provide the best operational utility. International and independent comparisons have shown that the MITRAS visibility reporting meets the human observer estimations and the applied comparison references in an excellent way.

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[10] See, e.g., (Booker, 1977, pp. 5-29)

> However, there are other kinds of transmissometers in use. Some transmissometer designs use much narrower transmitter beam and narrower receiver's view angle. Narrow beam transmissometer's response differs from LT31 and MITRAS response. Since a narrow beam transmissometer is used as visibility reference in U.S., Vaisala developed and implemented an algorithm to adjust LT31 visibility response to agree with the FAA visibility standard.

Volpe takes no position on which instrument, the Tasker 500 or the MITRAS/LT31 (under default settings), provides a better match to human estimates of visibility. From Volpe's point of view, the most important factor for the FAA is continuity of the standard. This is why Volpe and the FAA engaged Vaisala to implement a correction/adjustment factor to enable the LT31 measurement behavior to match that of the Tasker 500.

Appendix B: Tasker 500 Post-Hoc Recalibration

During the course of the data collection, the stability of the Tasker 500 reference transmissometers degraded somewhat, which was identifiable by a non-negligible drift from the calibrated pulse count during high-visibility periods.

Although some of the instability was resolved by removing the lamp shut-down procedure, it became necessary to implement a post-hoc recalibration procedure. The concept was to identify periods of known high visibility and examine the pulse counts reported by the Taskers during those periods, in order to identify the true number of pulses reported during high visibility rather than making the assumption that the clear-day pulse count held steady at the nominal value.

This concept requires a way to identify periods of known high visibility; doing so in an automated way required the use of a non-Tasker visibility sensor. The two options considered for this identification were the DUT itself and the PC-RVR VS. To avoid reliance on the DUT to inform the calibration schedule of the reference systems, which would be somewhat circular, the PC-RVR VS was used to identify periods of high visibility. This allowed the calculation of a recalibration factor to adjust the raw pulse counts to pulse counts which were all scaled to the nominal value, allowing comparison of data even with calibration drift. The algorithm used to apply the recalibration is described in pseudocode below.

```
• For each Tasker measurement:
    1) Consider the previous 1 hour of data collected by the PC-RVR VS in order to identify if it contains a period of high visibility
        a. The previous hour of data is considered to include a period of high visibility if at least 10 minutes of collected data during the hour had a reported extinction coefficient of less than 0.1 $km^{-1}$, equivalent to a visibility of at least 30 km (approximately 18.6 statute miles)
```

2) If the previous hour of data included a period of high visibility:
    a. Calculate the 92nd percentile of the pulse count for the preceding hour of Tasker measurements[11], and define this as $n_{c,o}$, which is the number of counts observed under high-visibility conditions
    b. Calculate the scaling factor $\frac{n_{c,i}}{n_{c,o}}$, where $n_{c,i}$ is the number of counts that would ideally be observed under high-visibility conditions and is defined as 3,970 for the 250-foot baseline Tasker and 3,950 for the 300-foot baseline Tasker[12]
    c. Scale the observed pulse count for this Tasker measurement by multiplying the observed pulse count by the scaling factor
3) If the previous hour of data did not include a period of high visibility:
    a. Apply the scaling factor from the most recent period of high visibility

When the Taskers were calibrated, they were calibrated to the nominal pulse counts listed above. This recalibration procedure allows us to use the best information we have available to scale the observed pulse counts relative to the most likely high-visibility pulse counts, even if that has drifted off of the nominal values. This procedure was initialized with a scaling factor of 1, and was performed with the entire database of collected data, which meant the scaling factor smoothly tracked calibration drift (if any) as it changed over time.

The low-visibility events included in the analysis of the main data collection had correction ratios for the reference Tasker 500 (which had the 250' baseline) ranging from approximately 0.918 to approximately 1.103. The median value of the correction ratio was 0.999, and the mode was 0.984. For the secondary data collection, the range was approximately 0.905 to 1.032, with a median of 1.018 and a mode of 1.017.

---

[11] This choice was not arbitrary, and was based on the choice of a requirement of ten minutes of high visibility. Because the Tasker maximum pulse count could drift even within the span of an hour, there was not necessarily a one-to-one correspondence between the measurements where the PC-RVR VS was reporting its highest values of visibility and when the Tasker pulse counts were highest. However, by guaranteeing (via the PC-RVR) that at least ten minutes (or $\frac{1}{6}$ of the hour) are high visibility, we can characterize an approximate "clear day" pulse count. We do so by selecting the Tasker pulse counts which make up the top $\frac{1}{6}$ of the distribution of pulse counts (which should correspond to high-visibility periods, even if they are not a one-to-one match to the specific PC-RVR measurements with the highest visibility), and then taking the median of that value. This characterizes the middle of the distribution of the highest observed pulse counts, which is used as a nominal high-visibility value. As a percentile of the entire hour, then, we need to take the percentile corresponding to the highest $(1-\frac{1}{12})$ of the measurements during the hour, which is $100 * 0.91\overline{6}$ and rounded to the 92nd percentile.

[12] The values of 3,970 (250' Tasker) and 3,950 (300' Tasker) approximately correspond to the pulse counts which should be observed at a visibility value of 30 km / 18.6 mi with a nominal calibration where 4,000 pulses per minute corresponds to zero loss. These values were chosen because they were the pulse counts used to calibrate the Taskers at those baseline distances, both in the current assessment and in previous efforts.

Appendix C: Homogeneity Criterion

Our recent previous assessments of forward-scatter meters as visibility sensors have used a metric derived from the relative agreement of two crossed-beam transmissometers to establish atmospheric homogeneity. This is particularly important for a comparison between the reference transmissometer(s) and any forward-scatter meters because of the substantial difference in sample volume between the two instruments. Only in conditions where the atmospheric conditions are relatively homogeneous can a forward-scatter meter be reasonably expected to agree with a transmissometer.

As discussed in this report, for this validation effort, which tested one transmissometer against a reference transmissometer, homogeneity was less of a concern. Because the reference transmissometer and the DUT were sited as closely to each other as was feasible, we emphasize the results without applying any homogeneity criteria. We examine results in homogeneous atmospheric conditions primarily to validate the component of the evaluation metric which requires a low fraction of outliers. If the DUT reports a measurement that is an outlier, then, by definition, some factor – including but not limited to homogeneity – is causing the sensors to disagree substantially.

During the primary collection, the DUT (after correction) satisfied the accuracy criterion at the median level without restricting the dataset to homogeneous conditions, but did not satisfy the outlier criterion. In order to assess whether this was some kind of fundamental sensor behavior causing unusually high variability, or whether it was simply related to atmospheric inhomogeneity, which might have affected the measurement comparison despite the care we took to site the DUT and the reference Tasker as closely as practicable, we also applied a homogeneity criterion to restrict the dataset to homogeneous conditions.

This homogeneity criterion was similar to the criterion used in forward-scatter meter evaluations in the past, although it was somewhat more inclusive of data compared to previous evaluations.

In order to determine when conditions are sufficiently homogeneous, we define a uniformity index (UI):

$$UI = 2 * \frac{|\sigma_1 - \sigma_2|}{\sigma_1 + \sigma_2}$$

where σ_1 and σ_2 are the extinction coefficients reported by the 250′ baseline Tasker and the 300′ baseline Tasker, respectively. This is simply the absolute value of the difference between the two crossed-beam transmissometers divided by their average value.

In this evaluation, as we have in previous evaluations, we have defined a homogeneous atmosphere as meeting the criterion UI ≤ 0.1. That is, if the difference between the extinction coefficients of the two Taskers is less than 10% of their average measurement (or, equivalently, the visibilities differ by no more than 10% of their average measurement), the atmosphere is considered to be homogeneous.

We did not apply an additional temporal homogeneity requirement, as has been done in the past for forward-scatter meter evaluations. In those evaluations, it was considered possible that, because of the much larger sample volumes of the Taskers relative to the forward-scatter meters, in an inhomogeneous environment (e.g. patchy fog), it would be possible for the Taskers to agree within the UI criterion. As a result, in the past, we have also required that more than half of the data points (i.e. 15-second interval extinction coefficient / visibility reports) within a given 10-minute interval meet the UI criterion. For this evaluation, it was not considered necessary to apply the temporal homogeneity criterion because of the small spatial separation between the sample volume of the 250’ Tasker and the DUT.

Appendix D: Complete Set of Comparison Box Plots

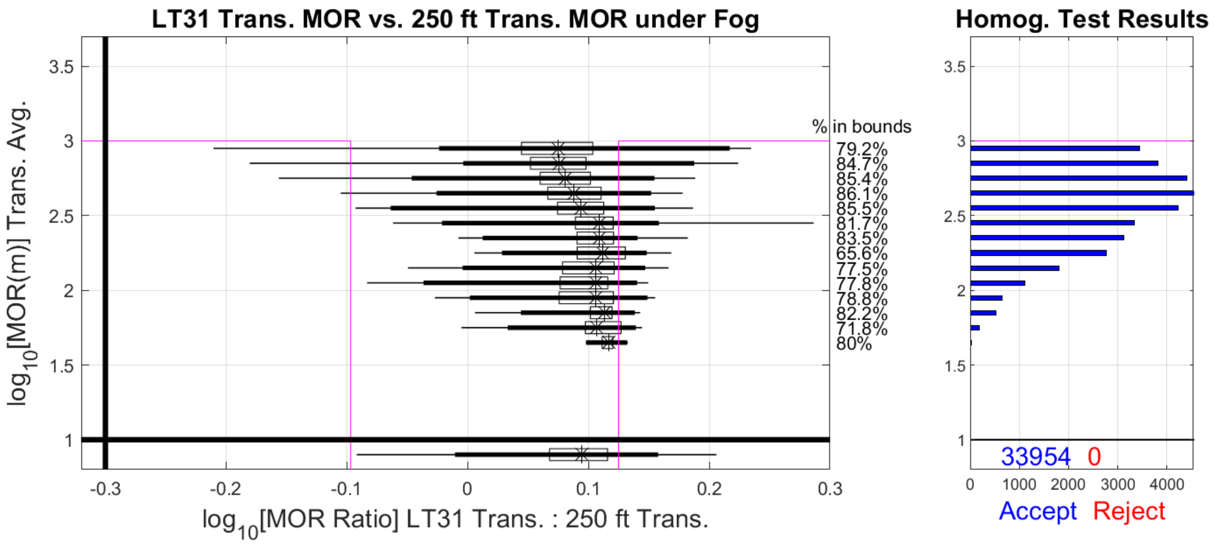
This appendix contains the full set of box plots comparing the performance of the DUT to the reference 250-foot baseline Tasker 500, both without applying any homogeneity criterion, and with the homogeneity criterion described in Appendix C: Homogeneity Criterion applied. These plots are intended to serve as documentation of results and are presented here without any substantial interpretation. In order to serve as full documentation of our results, some plots presented here are duplicative of plots included in the main body of the report. Volpe's interpretation of these results is presented in the main body of the report.

Main Data Collection

Pre-Correction

No Homogeneity Requirement

Fog



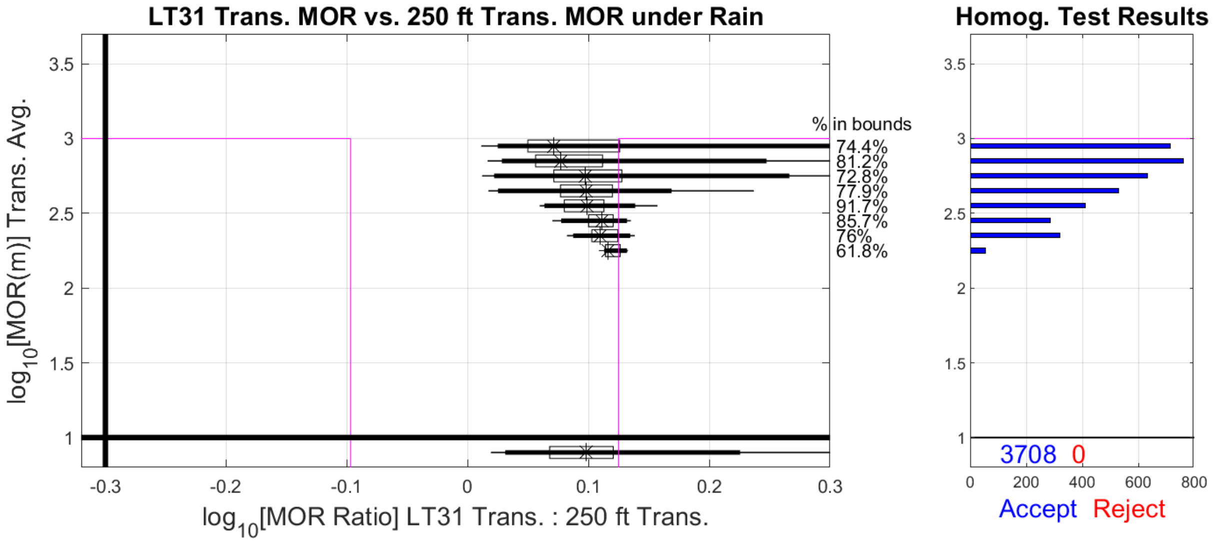
Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.817 Fail

Start Time = 20-Oct-2021 20:59:31
End Time = 05-Oct-2022 15:29:59

Percentage outliers: 0.98% (limit 0.2%)
Fail

Figure D-1: Main Data Collection; Fog; No Homog. Req.; No Correction Applied

Rain



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.787 Fail

Start Time = 25-Oct-2021 06:06:14
End Time = 05-Oct-2022 05:20:03

Percentage outliers: 2.7% (limit 0.2%)
Fail

Figure D-2: Main Data Collection; Rain; No Homog. Req.; No Correction Applied

Snow

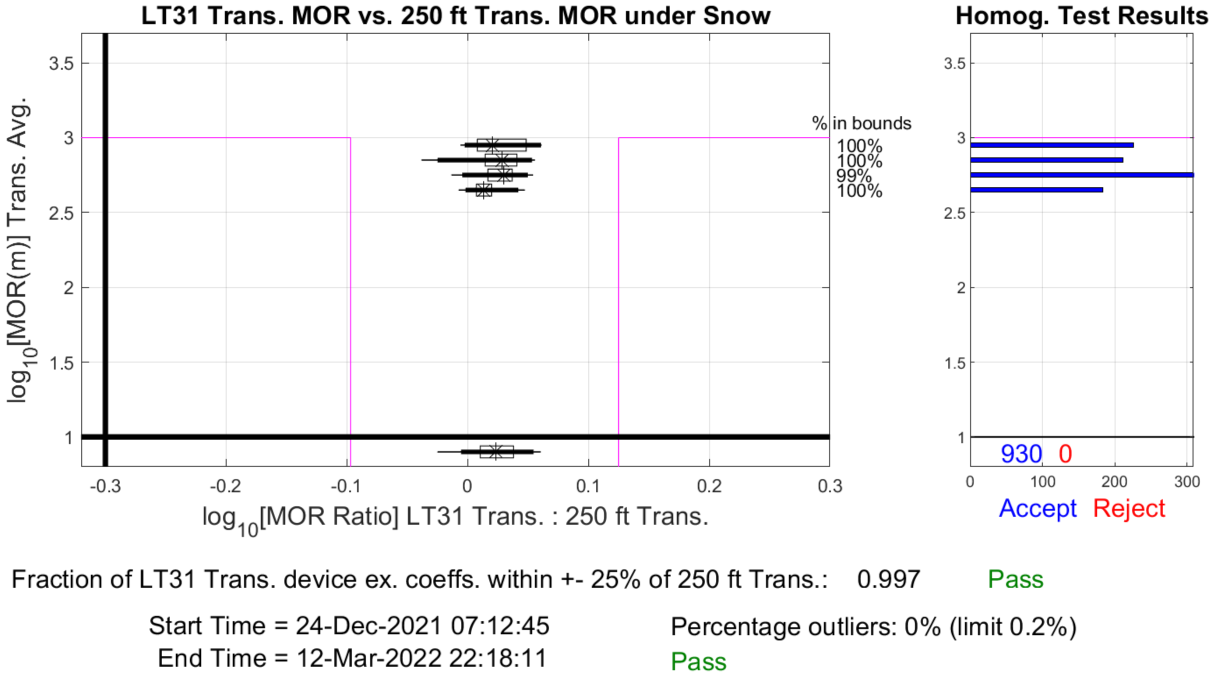


Figure D-3: Main Data Collection; Snow; No Homog. Req.; No Correction Applied

Homogeneous Atmosphere

Fog

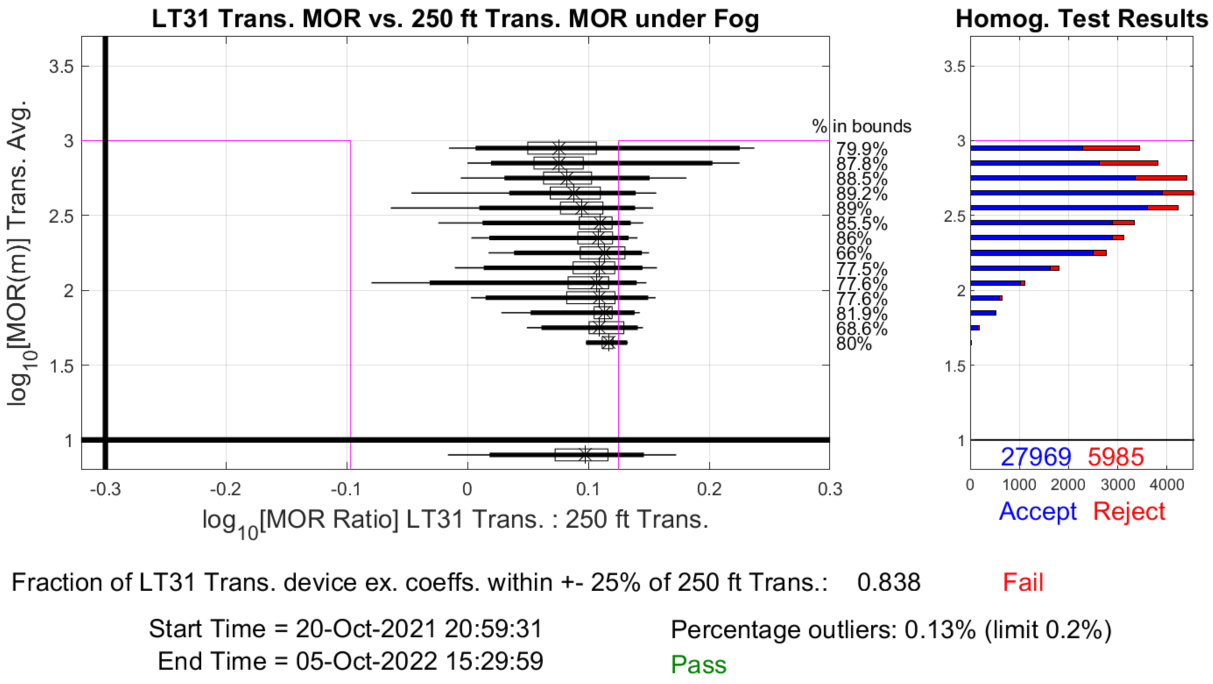


Figure D-4: Main Data Collection; Fog; Homogeneous Atmosphere; No Correction Applied

Rain

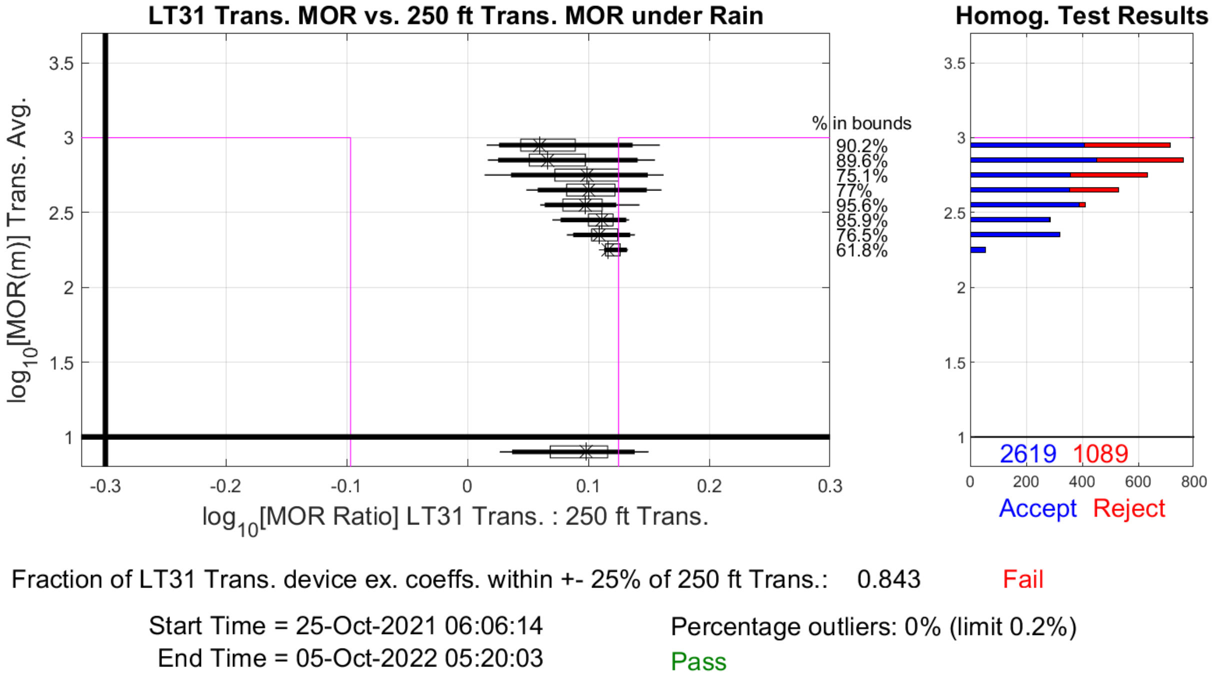


Figure D-5: Main Data Collection; Rain; Homogeneous Atmosphere; No Correction Applied

Snow

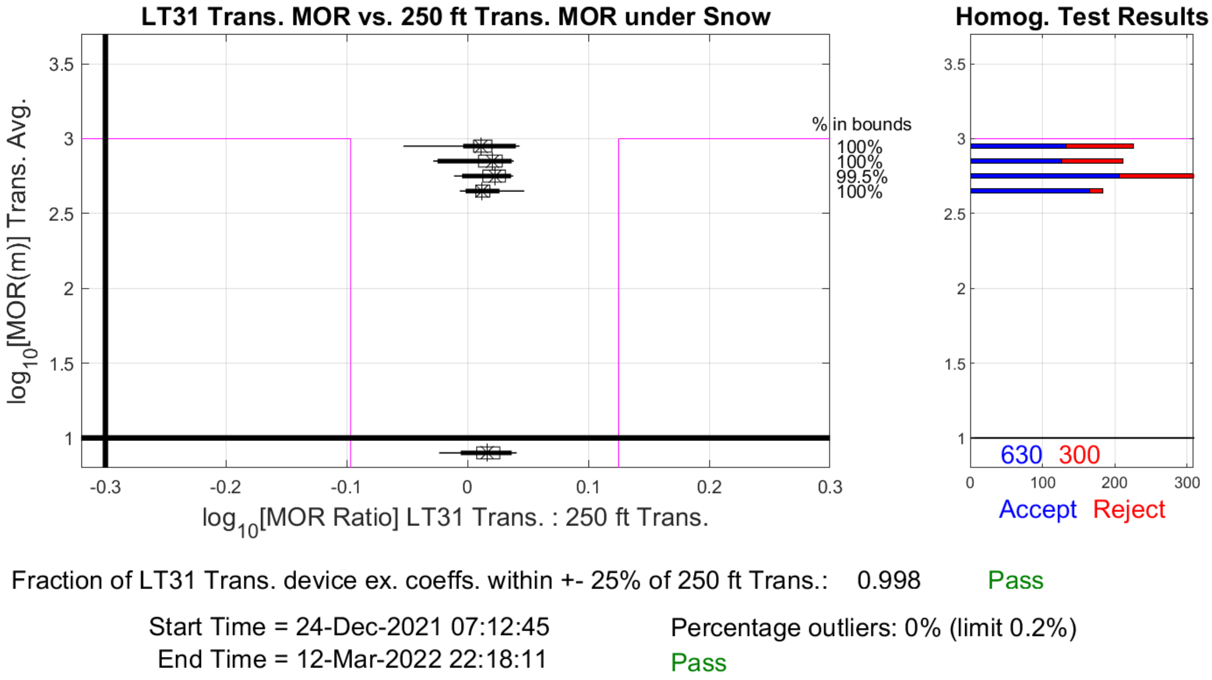
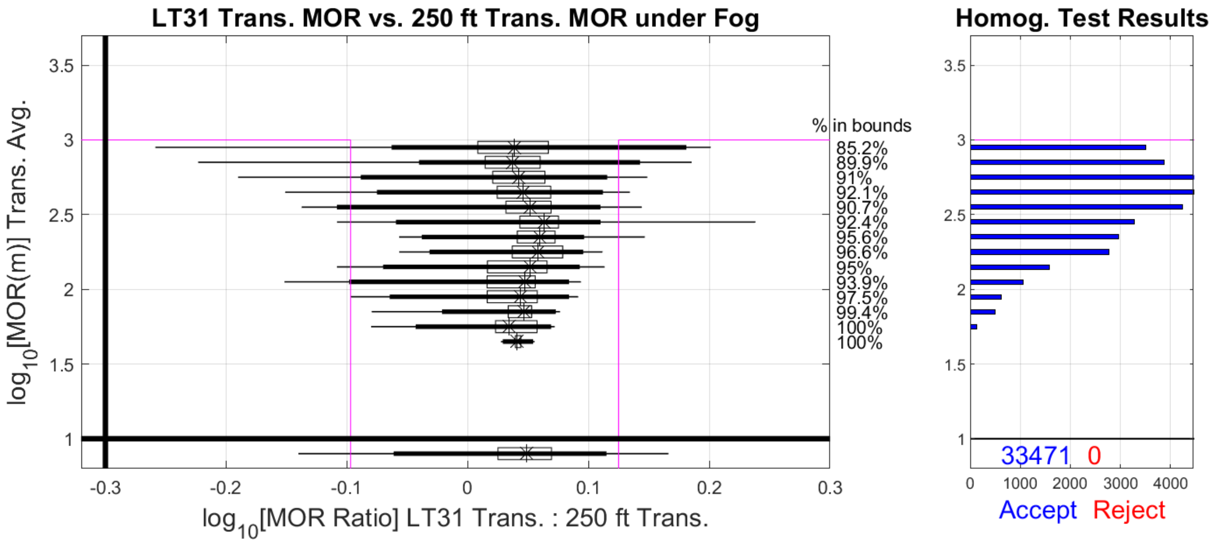


Figure D-6: Main Data Collection; Snow; Homogeneous Atmosphere; No Correction Applied

Post Hoc Correction Applied

No Homogeneity Requirement

Fog



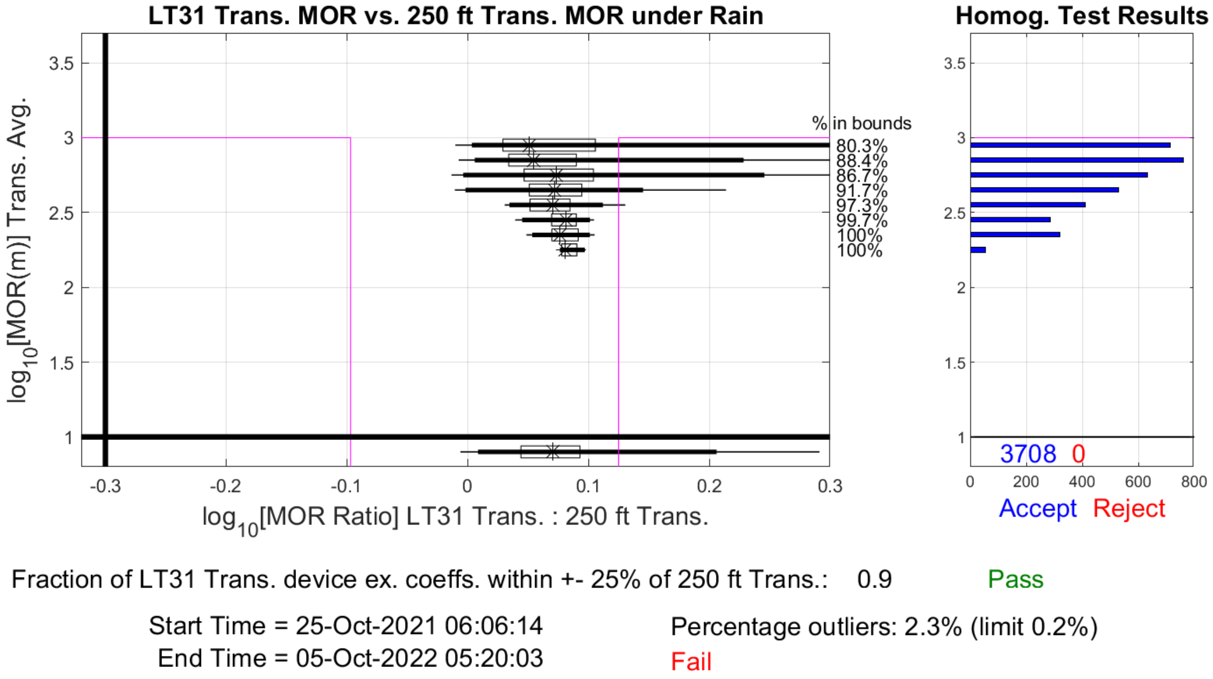
Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.919 Pass

Start Time = 20-Oct-2021 20:59:31
End Time = 05-Oct-2022 15:29:59

Percentage outliers: 0.94% (limit 0.2%)
Fail

Figure D-7: Main Data Collection; Fog; No Homog. Req.; Post Hoc Correction Applied

Rain



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.9 Pass

Start Time = 25-Oct-2021 06:06:14
End Time = 05-Oct-2022 05:20:03

Percentage outliers: 2.3% (limit 0.2%)
Fail

Figure D-8: Main Data Collection; Rain; No Homog. Req.; Post Hoc Correction Applied

Snow

N/A – post hoc correction is not applied to snow data

Homogeneous Atmosphere

Fog

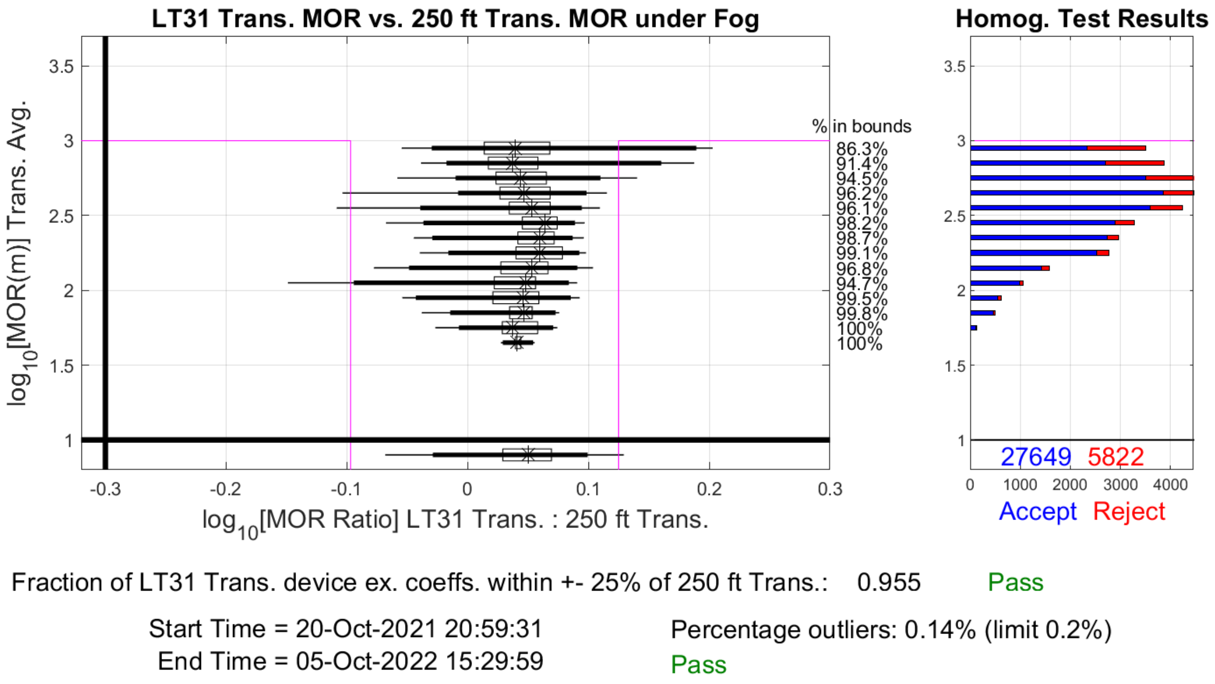
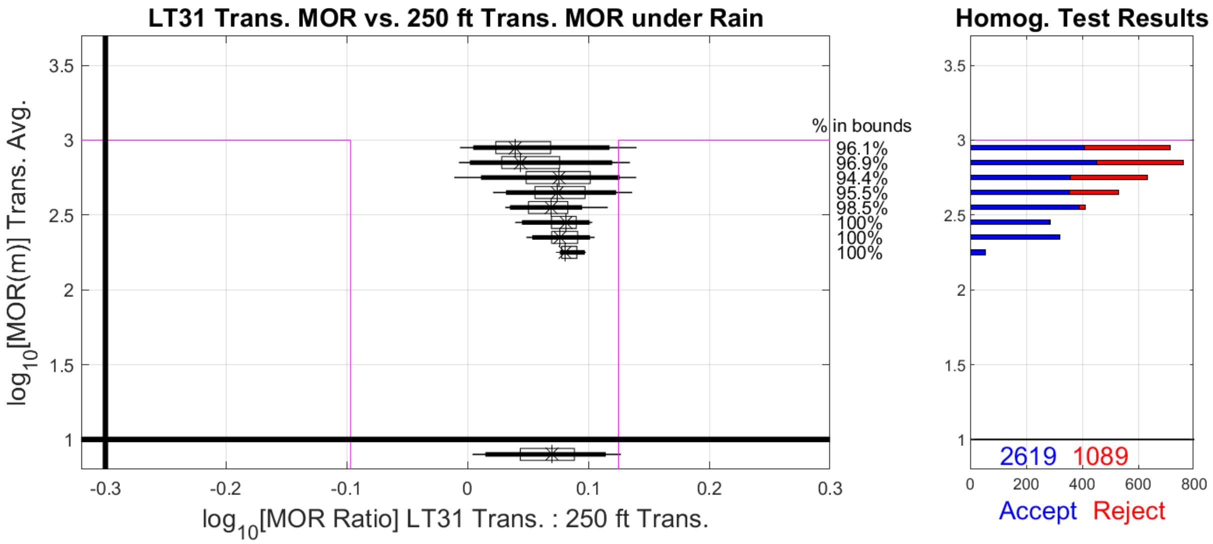


Figure D-9: Main Data Collection; Fog; Homogeneous Atmosphere; Post Hoc Correction Applied

Rain



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.973 Pass

Start Time = 25-Oct-2021 06:06:14
End Time = 05-Oct-2022 05:20:03

Percentage outliers: 0% (limit 0.2%)
Pass

Figure D-10: Main Data Collection; Rain; Homogeneous Atmosphere; Post Hoc Correction Applied

Snow

N/A – post hoc correction is not applied to snow data

Secondary Data Collection

No Homogeneity Requirement

Fog

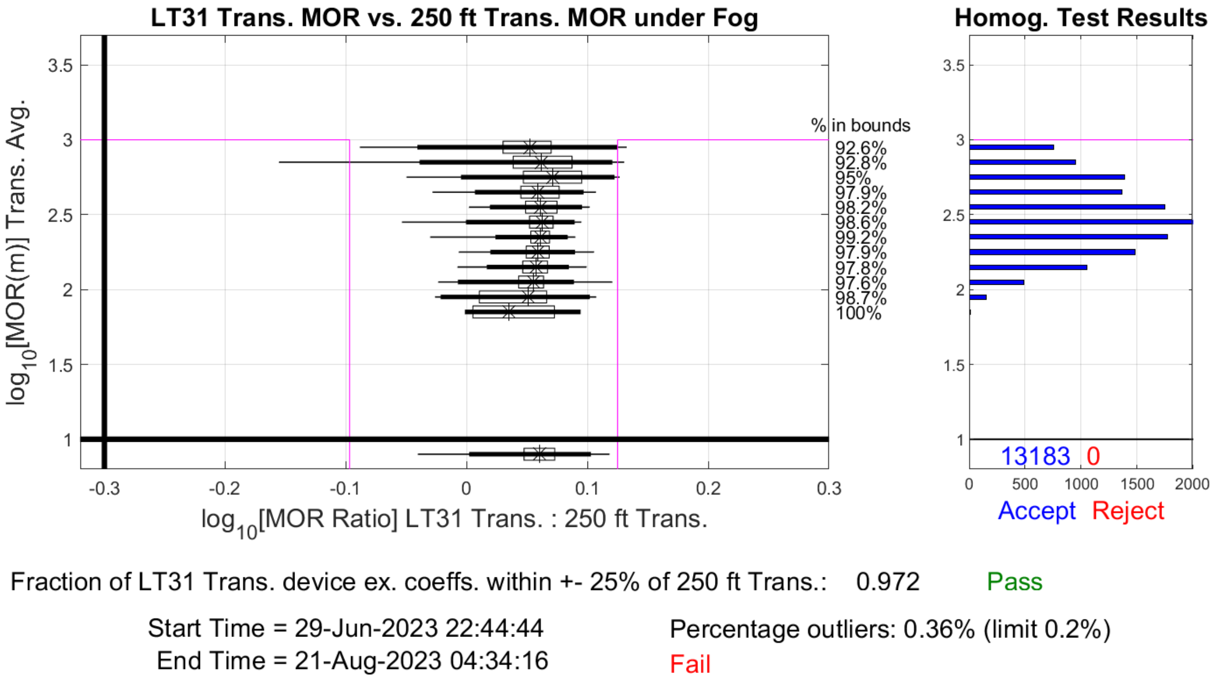
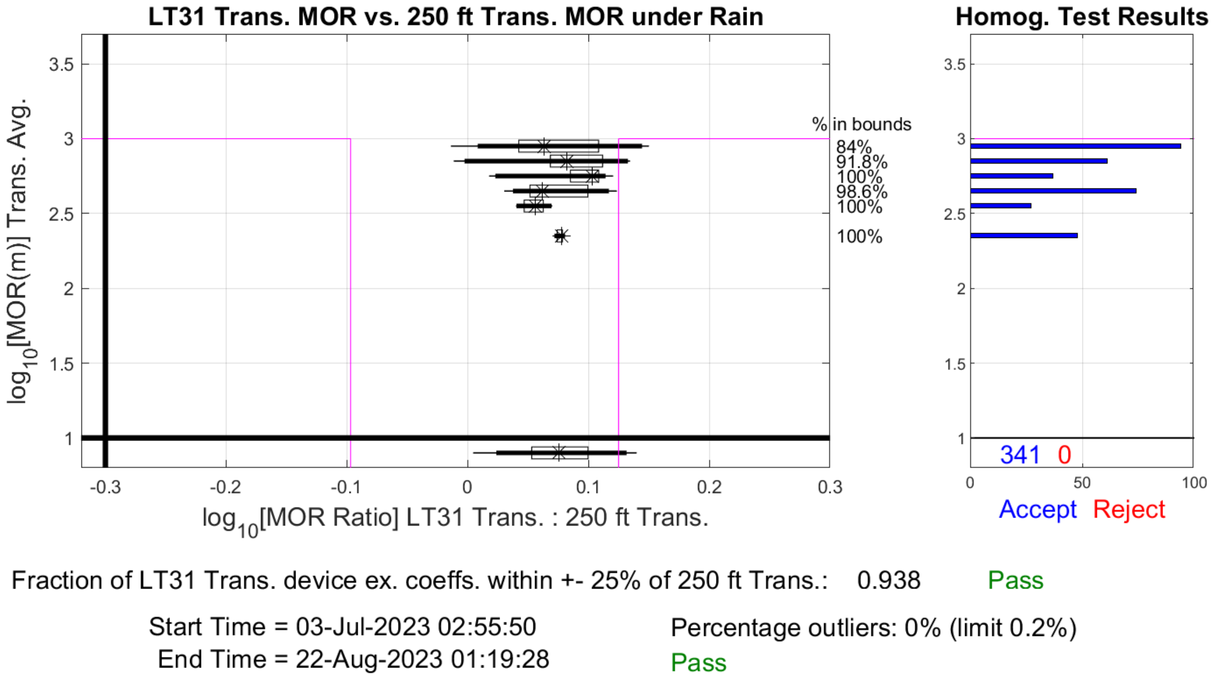


Figure D-11: Secondary Data Collection; Fog; No Homog. Req.; Vaisala Correction Applied

Rain



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.938 Pass

Start Time = 03-Jul-2023 02:55:50

End Time = 22-Aug-2023 01:19:28

Percentage outliers: 0% (limit 0.2%)

Pass

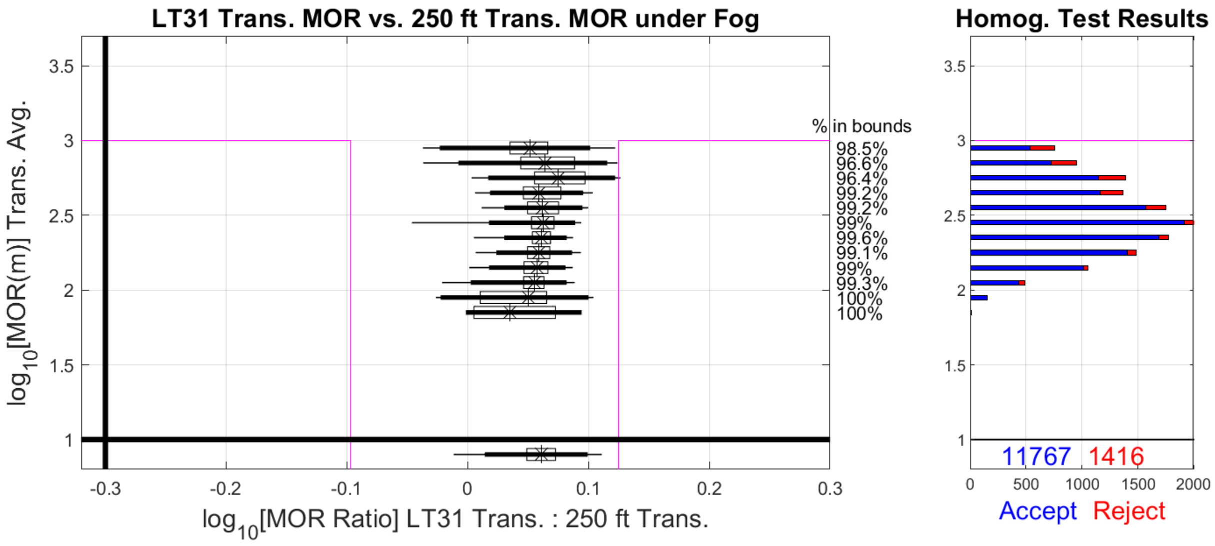
Figure D-12: Secondary Data Collection; Rain; No Homog. Req.; Vaisala Correction Applied

Snow

N/A – no snow data was collected during the secondary data collection

Homogeneous Atmosphere

Fog



Fraction of LT31 Trans. device ex. coeffs. within +- 25% of 250 ft Trans.: 0.988 Pass

Start Time = 29-Jun-2023 22:44:44
End Time = 21-Aug-2023 04:34:16

Percentage outliers: 0.091% (limit 0.2%)
Pass

Figure D-13: Secondary Data Collection; Fog; Homogeneous Atmosphere; Vaisala Correction Applied

Rain

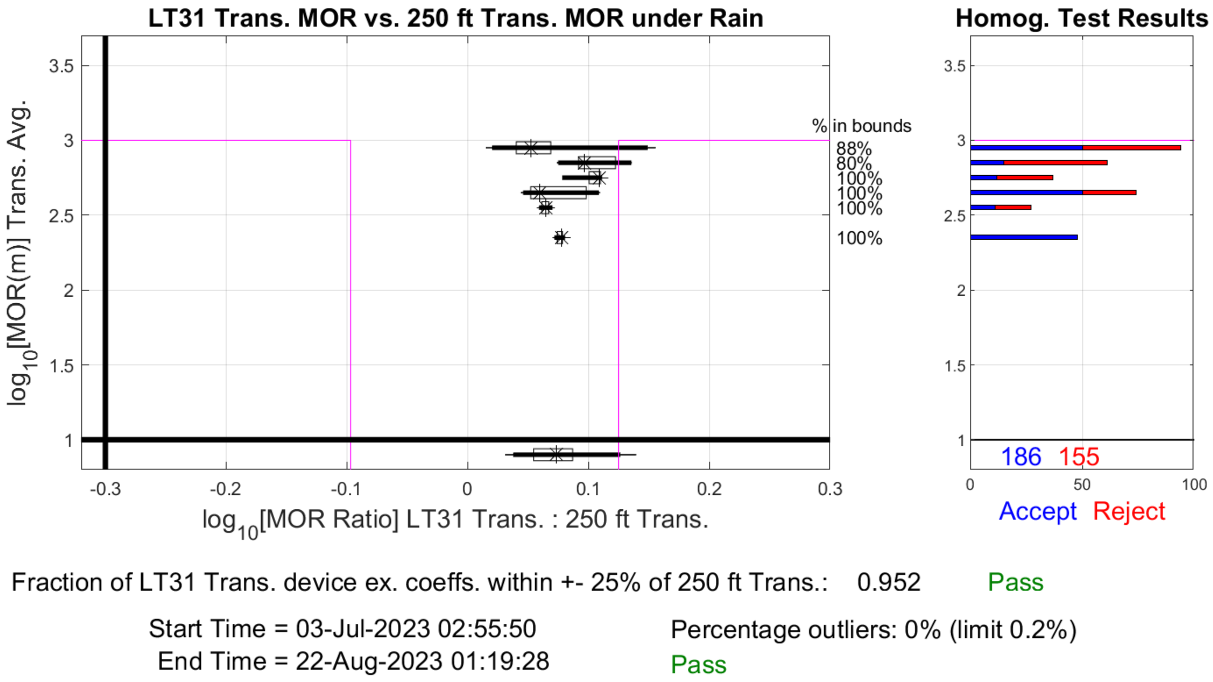


Figure D-14: Secondary Data Collection; Rain; Homogeneous Atmosphere; Vaisala Correction Applied

Snow

N/A – no snow data was collected during the secondary data collection

Appendix E: Possible Alternative Transmissometer Systems – Market Survey

For the reasons stated in Section 2.1, Volpe proposed that the reference transmissometer system (the Tasker 500) should be replaced with another transmissometer system, and the FAA concurred with that proposal. This section provides a market survey of commercially available transmissometer systems, which was conducted in late 2019, and provides a rationale for selecting a particular device to serve as the DUT.

Literature review and direct internet searches were helpful in identifying transmissometer systems that were in either operational or scientific (e.g. sensor validation) use in the relatively recent past, and as a result were potentially viable options. Below is a summary table showing details of the transmissometers that were identified, including manufacturer, model name, source information, and whether the instrument appears to be currently manufactured.

Table E-1: Market Survey of Transmissometers in Recent Use

Manufacturer	Model Name	Source Type	Source	Currently Manufactured?	Notes
Jenoptik Impulsphysik	SKOPOGRAPH II Flamingo	Academic	(Waas, 2006)	No	Out of production as of no later than 2006
Vaisala	LT31	Press release/Periodical	(Metso, 167/2005)	Yes	In production from no later than 2005 to the present; Finnish manufacturer with US subsidiary
Vaisala	MITRAS	Academic	(Bloemink, 2006)	No	Out of production; predecessor to the LT31
CSIR-NAL	Drishti	Academic	(Mohan, et al., 2015)	Yes	Not commercially available; manufactured by Indian government
Degreane Horizon	TR30LED	Internet search	(Degreane Horizon, 2020)	Yes	French company, no US presence
AGI Ltd.	AGIVIS 2000	Internet search	(AGI Ltd., 2020)	Yes	UK company, no US presence
Telvent	Revolver	Academic	(Hosalikar, Mohan,	No	Australian company

Manufacturer	Model Name	Source Type	Source	Currently Manufactured?	Notes
			Vashishta, & Tyagi, 2012)		purchased by competitor and wound down
All Weather Inc.	8364 / 8365 Dual Technology Visibility Sensor	Internet search	(All Weather, Inc., 2020)	Yes	US company, instrument is a hybrid transmissometer/ forward scatter meter

The market survey made clear that the FAA is not the only agency widely replacing its transmissometers with forward scatter meters for operational use. As a result, the market for transmissometers has contracted significantly and many manufacturers of transmissometers that were in business ten or twenty years ago have been acquired, wound down, or simply stopped manufacturing transmissometers in favor of forward scatter meters.

Of the investigated instruments listed in the table, five are still in production: the Vaisala LT31, the CSIR-NAL Drishti, the Degreane Horizon TR30LED, the AGI AGIVIS200, and the All Weather Inc. 8364/8365 Dual Technology Visibility Sensor.

The Drishti can be eliminated from consideration because while the instruments are still being manufactured and are in use, the manufacturer is the Indian government and our inquiries have revealed that the Drishti is not commercially available. The TR30LED appears to be commercially available, but the French manufacturer has not responded to multiple requests for information through their website and via email. The same is true of the AGIVIS2000.

The 8364/8365 Dual Technology Visibility Sensor is a potentially interesting instrument. It is marketed as combining transmissometer and forward-scatter technology to, in theory, combine the strengths of each technology. It is essentially two forward scatter meters yoked together such that the receiver ends can see both the scattering from one projector and the directly emitted light from the other. However, the manufacturer’s documentation indicates that the instruments still ultimately rely on a reference transmissometer for calibration. In addition, the extremely short baseline for the transmissometer component (approximately 1 meter / 3.3 feet or less), when combined with the limitations on visibility measurement for visibility values much larger than the baseline discussed in Section 2.1, means that the transmissometer component can only plausibly provide reliable results for extremely low visibility values – no more than 20 – 40 meters (66 – 131 feet). The forward scatter component must be used for visibility values higher than that. In addition, while the small baseline makes the instrument more compact (similar in size to a forward scatter meter), it removes one of the advantages of a typical transmissometer setup by sampling a small volume of the atmosphere so that the device is less able to accurately characterize visibility through inhomogeneous air. In short, while the device is marketed as a combined transmissometer/forward scatter meter, in practice it must operate almost entirely as a forward scatter meter.

The remaining option – and the one we propose to test – is the Vaisala LT31 transmissometer. The Vaisala LT31 is a modern transmissometer that combines proven, accurate visibility measurement with modern features, discussed in more detail in Section 3.3.2 and Section 3.3.3, that remove many of the operational disadvantages of the older Tasker transmissometers. Vaisala has been manufacturing transmissometers for decades, and the LT31 itself has been in active service for operational use at Zurich airport since 2005 (Metso, 167/2005). Vaisala has a significant US presence and has been very responsive to inquiries about the device itself, installation, and maintenance.

Appendix F: RVR Calculation Methodology

Koschmieder's Law

During the day, or when ambient light conditions are above a given threshold, RVR systems use the atmospheric extinction coefficient to calculate meteorological optical range (MOR). The atmospheric extinction coefficient (σ) is the related value for atmospheric transmittance. This value describes how much light is scattering and/or being absorbed by atmospheric particles. Visibility is inversely proportional to the extinction coefficient; the value of the extinction coefficients are high when visibility is low (Clark & Abbott, 2012). MOR is generally taken to be the distance where the intensity of a light beam has been attenuated to 5 percent of the original intensity (Middleton, 1952), although other values, including 2 percent, have historically been used.

The equation used to calculate RVR during the day is referred to as "Koschmieder's Law", which is nominally based on the detectability of a dark object against a bright background (e.g. an airplane against the bright daytime sky):

$$MOR = \frac{-\ln(0.05)}{\sigma} \cong \frac{3}{\sigma}$$

where MOR has units of distance (e.g. m) and σ has units of $\frac{1}{distance}$ (e.g. m^{-1}).

Allard's Law

When it becomes dark, and ambient light is below a specified luminance threshold, RVR systems use three variables to calculate visual range:

1. Extinction Coefficient
2. Ambient Light
3. Point Source Light

Automated RVR systems take ambient light (e.g. background luminance) measurements using photo-detectors. These detectors have a response to light that is similar to human eye (Clark & Abbott, 2012). Allard's law is used to calculate RVR when the human observer is attempting to observe a bright object against a dark background (e.g. a runway approach light against dark terrain).

Point source light refers to the intensity of the lights on the runway for which visual range is being reported. The intensity of point source light is based on discrete values obtained from Table 3-1 of FAA-E-2772B (Seliga, Weber, Woo, & Badr, 2014) which correspond to specified intensities of runway lighting.

The equation used to calculate RVR at night is referred to as "Allard's Law".

$$E_t(B) = \left(\frac{I}{R^2}\right) \times e^{-\sigma R}$$

where E_t is the visual threshold for a given ambient light in lux, B is the background luminance, I is the runway light intensity in candelas (cd), σ is the extinction coefficient in inverse meters (m^{-1}), and R is the RVR in meters (Federal Aviation Administration, 2006).

In this evaluation, because the VTR is not equipped with a full runway lighting system, and therefore the full RVR calculation cannot be performed, the MOR is used as a proxy for true RVR.