Royal Netherlands
Meteorological Institute
*Ministry of Infrastructure
and Water Management*

Verification of the Vaisala LT31 Transmissometer

Jessica M. I. Strickland en Hannelore I. Bloemink

De Bilt, 2025| Technical report; TR 25-05

Verification of the Vaisala LT31 Transmissometer

Jessica M. I. Strickland and **Hannelore I. Bloemink**
Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201, 3730 AE De Bilt, The Netherlands
email: jessica.strickland@knmi.nl
February 21st, 2025

Abstract

The Royal Netherlands Meteorological Institute (KNMI) is updating its visibility standard which requires a well-maintained transmissometer (TMM) as a reference for their network of present weather forward scatter sensors [1]. The new Vaisala LT31 TMM is verified by comparing the Meteorological Optical Range (MOR) measurements to the current Mitras TMM and FD12P forward scatter sensor observations. We focus on MOR ≤ 1500 m in the interest of high-quality performance during poor visibility conditions. To establish comparable conditions during stable fog events, strict filtering is applied and evaluated. The MOR of each instrument was compared for approximately one year (February 3rd, 2023, to March 18th, 2024) to capture all seasons and retain enough measurements after strict filtering. This verification period was divided into two sub-periods due to impactful instrument adjustments. Additionally, necessary corrections are applied and substantiated to compensate for the differing working conditions of the instruments. The main findings for MOR ≤ 1500 m show good agreement between the visibility instruments. During Period 1, the proportion of LT31 TMM measurements that deviate more than 28 m or 28% from the FD12P sensor is 3.9% without corrections and 2.2% with corrections. During Period 2, the proportion of LT31 TMM measurements that deviate more than 28 m or 28% from the Mitras TMM data is 9.4% without corrections and 3.5% with corrections. Additional analysis provides insight into the performance of the LT31 TMM for MOR higher than 1500 m, emphasizing issues with the current Mitras TMM, but showing good agreement with the FD12P sensor up to 5000 m. Recommendations for operation and further study are provided.

Contents

1. Introduction

Visibility sensors provide valuable information regarding weather conditions and air quality. Although a forward scatter visibility sensor is more cost-effective and labour-efficient compared to a transmissometer (TMM), and is permitted by International Civil Aviation Organization regulations [2], the calibration is non-trivial and must be traceable to a well-defined standard. Therefore, KNMI developed a visibility standard which ensures reliable high-quality measurements by using a well-calibrated TMM to check the calibration of any forward scatter present weather sensors which are installed throughout the measurement network [1]. This standard is maintained by KNMI's calibration laboratory and additional relevant background information related to KNMI's visibility measurements are listed as references [3-5]. The goal of the standard is to regularly check the performance of the FD12P present weather sensors (operational since ~2000) and adjust the scatter plates, if needed, using a developed calibration device, in accordance with ICAO regulations. However, the current Vaisala Mitras TMM (operational since 2006) is end-of-life and is currently being replaced by a new instrument: the Vaisala LT31 TMM (operational since 2022). An extensive (data) verification of the new LT31 TMM is required in order to ensure the quality and applicability of the standard.

Therefore, with traceability in mind, the new LT31 TMM was placed in proximity to the Mitras TMM and FD12P present weather sensor at the test site in De Bilt, The Netherlands, for intercomparison from February 3rd, 2023, to March 18th, 2024. This period encompasses the fog season which is typically October to April. Primarily, we compare the meteorological optical range (MOR) of the LT31 TMM to both available visibility instruments as references: the Mitras TMM and FD12P forward scatter sensor. Comparing the different types of instruments brings about unique challenges due to their different functionality and declining operational condition. The goal is to substantiate that the LT31 TMM is suitable to be used as a reference in the visibility standard within the intended operational range. Therefore, although KNMI reports Runway Visual Range (RVR) up to 2000 m, we primarily focus on quality-controlled visibility data where MOR ≤ 1500 m because quality performance in poor visibility conditions is vital.

This analysis substantiates and verifies that the LT31 TMM is suitable for use as a reference in the visibility standard. Additionally, we investigate the effectiveness of quality-control filtering, focussing on the visibility range of interest MOR ≤ 1500 m. However, we also investigate the performance of the LT31 TMM relative to the reference sensors beyond the primary range of interest (MOR ≤ 5000 m). Furthermore, other aspects which may influence the suitability of the LT31 TMM in the visibility standard are considered, such as maintenance, contamination, and calibrations. The instruments and data/processing are detailed in Sections 2 and 3, respectively, and the results are presented in Section 4. The conclusions are summarized in Section 5 with recommendations for operation and future study discussed in Section 6.

2. Instruments and setup

KNMI's current visibility standard requires a well-maintained transmissometer (TMM) as a reference to ensure that the (FD12P) forward scatter present weather sensors throughout the measurement network are accurately calibrated. The current Vaisala Mitras TMM is being replaced by a the new Vaisala LT31 TMM which will be verified by intercomparing the visibility instruments (Figure 1) which are installed in proximity on the test field (Figure 2). All instruments measure the MOR at a height of 2.5 m above the surface and the FD12P is located halfway between the transmitter and receiver of each TMM. The main relevant specifications of the visibility instruments summarized in the Table 1. For more detail, refer to the respective manuals [6-8].

Figure 1*: Visibility instruments.* ***Left****: Vaisala LT31 transmissometer* ***Middle****: Vaisala FD12P forward scatter present weather sensor* ***Right****: Vaisala Mitras transmissometer.*

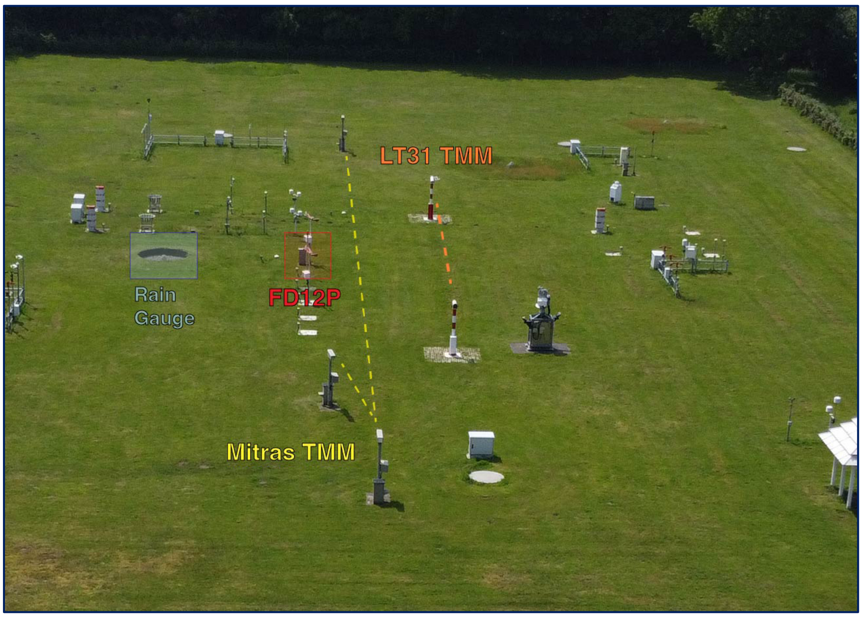

Figure 2*: KNMI test field in De Bilt, The Netherlands. For scale: The Mitras TMM short and long baseline length are 11.4 m and 74.4 m, respectively and the LT31 TMM baseline length is 31.4 m. Photo credit: Rik Noorlandt.*

The visibility instruments average the data in different ways. The Mitras TMM performs an internal 1-minute averaging of the instant transmittance values (30 or 60 values depending on the flashing rate of 2 s or 1 s in low visibility conditions, respectively). The FD12P sensor averages the instantaneous (15 s) MOR values providing 1- and 10-minute averaged output. Specifically, these averages are calculated from the extinction coefficients: σ [1/km] = 3/MOR. Regarding the LT31 TMM, a small present weather detector is attached to the transmissometer and is used for autocalibration and improving the averaged values at higher visibility. The standard output combines the MOR data using "intelligent (moving) averaging" and generates 1-minute averaged output. Further details about the MOR data output of the LT31 TMM can be found in Section 3.2.

Key maintenance notes

FD12P sensor:

- 04/10/2023 – Replaced by another sensor of the same model due to reporting false precipitation events, defective power supply board and connector

Mitras TMM:

- 23/08/2023 – Unsuccessful calibration
- 30-08-2023 – Calibration performed at a maximum visibility of 10km, including a check with the grey filters
- 10-10-2023 – Calibration performed at a maximum visibility of 10km
- 09-01-2024 – Calibration performed at a maximum visibility of 20km

	Vaisala LT31 Transmissometer	**Vaisala Mitras Transmissometer**	**Vaisala FD12P Present Weather Sensor**
Operational since	2022	2006	~2000
Baseline length	31.4 m	Double: - Short: 11.4 m - Long: 74.4 m	N/A
Measuring height	2.5 m	2.5 m	2.5 m
MOR range	10 m (1/3 baseline) – 10 km	7 – 3000 m (MOR) 40 – 3000 m (RVR)	10 m – 50 km
Accuracy	“exceeds ICAO recommendations” (RVR)	“1% of FSR, meets ICAO recommendations in specific ranges”	10%: 10 m – 10 km 20%: 10 km – 50 km
Resolution	0.1 m	1 m	1 m
Sampling rate	1000/s	1/s	update interval: 15/s

***Table 1**: Summary of visibility instrument specifications. Note that the LT31 specifications refer to the entire system including its supplemental present weather detector (PWD).*

3. Data and methodology

3.1. Data streams

Mitras TMM and FD12P sensor:
Data is handled as described in the current visibility standard. The data is collected through operational SIAMs [9,10] and ingested in MetNet (Station # 261) and placed in the KMDS database where it is made available to all users. From there, the data is transferred to the current sensor share (//knmi.nl/data/sensordata/KMDS), and this is the data used in the analysis code. Here, MOR data (denoted as ZM [m]) and precipitation intensity (denoted as NI [mm/hr]) are available as 1-minute averages.

LT31 TMM:
Data is available since 19/12/2022 14:13:57 and can also be found on the sensor share (//knmi.nl/data/sensordata/LT31/). The timestamp is added by KNMI and the raw data is transferred as message format that was finalized on 02/02/2023:

Message 1

2023-01-27 16:49:14 LT1 VIS 15000.0 AL 02000000000000000000 BL ///// AL X 4B4C

Message 9

2023-01-27 16:49:15 LT1 T0TA 0 010 27.02.67 01:14 20.0001 km 0.997 ////// BHBH0000 20000 20000 00 0.00 0 0.9807 699330.1 189649.1 182208.3 0006 0368 0048 0367 0047 0000 0367 0046 0002 +23.8 +20.5 +26.9 +20.0 +19.0 +15.1 +16.3 +19.2 +15.1 +14.6 02000000000000000000 3738 1.016439 0.996780 0.996780 0.980659 1.000303 0.971149 1.010080 028068 0.995484 1.2653 0.995484 0.970855 0.000266 0 0000 1.047019 1.012623 0.0000000 +1.0000000 -27.2 +1.0000000 2 +27.2 -27.2 +1.0000000 +1.0000000 00000 0.0000000 +1.0000000 00000 0.0000000 +1.0000000 -27.2 +1.0000000 2 +27.2 -27.2 +1.0000000 +1.0000000 00000 0.0000000 +1.0000000 00000 3BDD

3.2. LT31 MOR data output

The LT31 TMM generates three different types of MOR output, and this section provides details and insight into the selected MOR output for the remainder of the analysis. The Vaisala LT31 consists of a TMM and a small present weather detector (PWD) which is used for auto-calibration and assisting high visibility observations. The standard output of the LT31 combines the two, with what is called “intelligent averaging”, into a “combined MOR”.

The accuracy of a TMM depends on the visibility itself and therefore the PWD is incorporated to improve observations in the higher visibility range. Figure 3 displays an example of the relative error of a TMM MOR calculation as a function of the MOR. As shown, the relative error drastically increases above 1500 m. At higher visibility, where the TMM is less accurate, information is incorporated from the PWD, which generates a more accurate combined MOR, as illustrated in Figure 4.

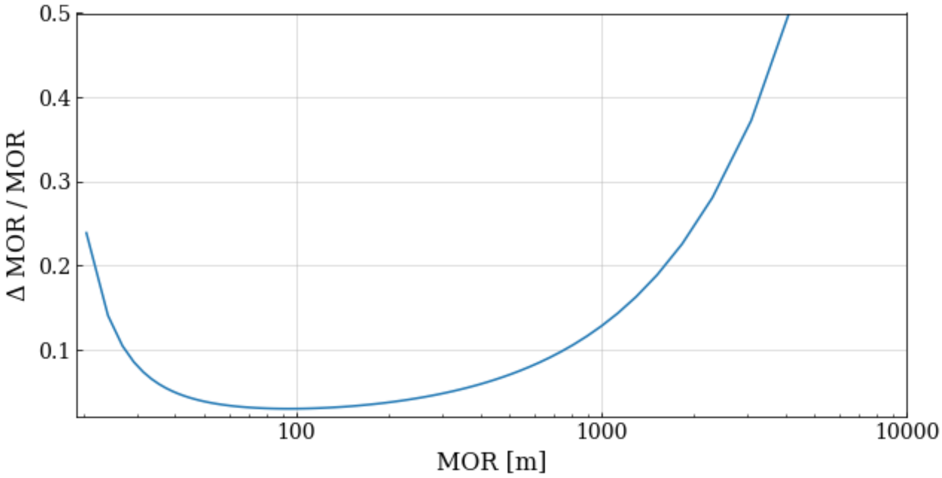

Figure 3: *Example of the relative TMM MOR error as a function of MOR = -3B/ln(T). We assign the baseline (B = 31.4 m) and an error of 0.011 is assumed for determining transmission (T).*

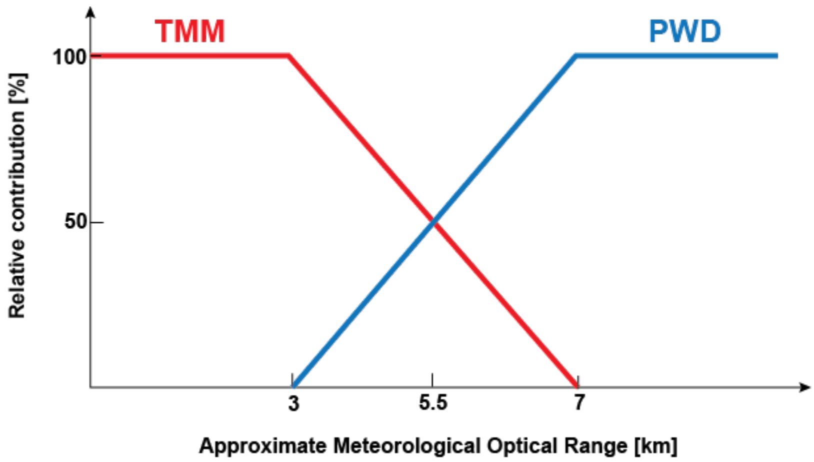

Figure 4: *Sketch illustrating the relative contribution of the LT31 TMM and PWD to the combined MOR output.*

As an example, in Figure 5, we compare the unfiltered TMM, PWD, and combined MOR, alongside the Mitras TMM and FD12P forward scatter sensor as references. Figure 5 confirms that the extent to which the combined MOR incorporates the TMM and PWD depends on the visibility range. At high visibility, the PWD measurement impacts the combined MOR, making it more comparable to the FD12P sensor than LT31 TMM alone. Meanwhile, at low visibility, the PWD is unreliable, and the combined MOR only considers and is equal to the MOR TMM.

In order to be a reference instrument for the visibility standard, the visibility data must be based solely on the TMM. Our primary analysis focusses on MOR ≤ 1500 m because high-quality performance in poor visibility conditions is imperative. Furthermore, the PWD is not calibrated, and this is recommended. Therefore, only the TMM output is suitable for a visibility standard and we proceed with our low-visibility analysis using the LT31 TMM (without PWD combined) based on the transmittance.

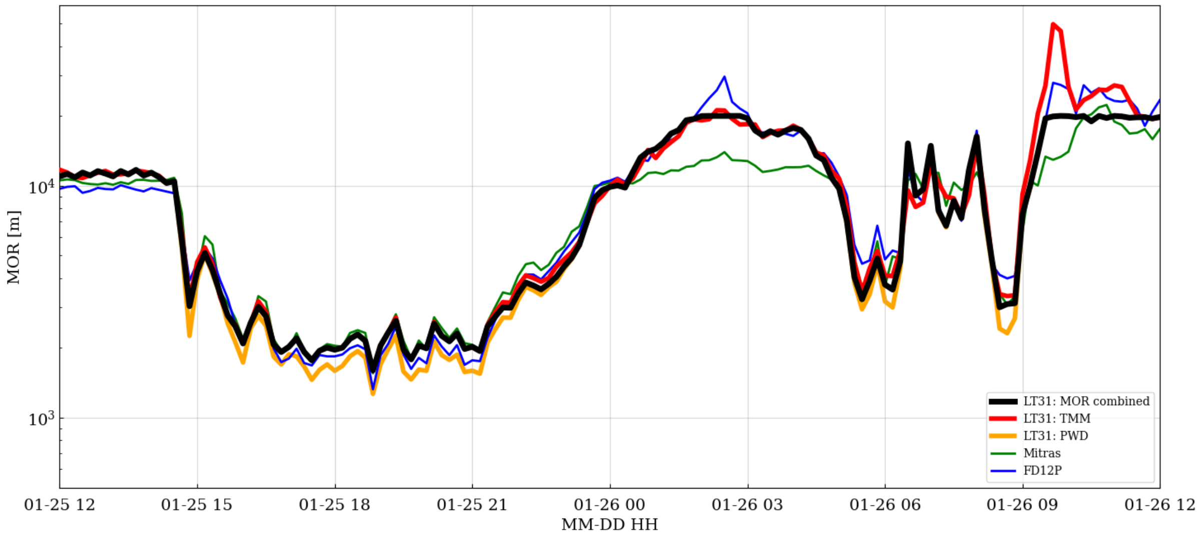

***Figure 5**: Example of the10-minute averaged MOR from the LT31 (combined, TMM, PWD), Mitras TMM, and FD12P forward scatter sensor as a function of time. Note that data points with errors/status warnings have not been removed.*

3.3. Evaluation metrics

The Commission for Instruments and Methods of Observation [11] and the International Civil Aviation Organization (ICAO) [1] state required and achievable accuracies for visibility, MOR, and runway visual range (RVR). The ICAO guidelines require different visibility uncertainty in different ranges: ± 50 m (< 600 m), ± 10% (600 m – 1500 m), ± 20% (1500 m – 3000 m). For the MOR, the achievable accuracy stated by the CIMO guide is the larger of 20 m or 20%.

While a full uncertainty analysis is not within the scope of this verification, we consider these guidelines to evaluate the performance of the LT31 TMM. Specifically, we focus on the achievable measurement uncertainty from the CIMO guidelines but also report what percentage of data fall within the ICAO limits. As such, the LT31 TMM reported MOR should be compared to the known MOR. Therefore, we compare the LT31 TMM reported MOR to two other visibility instruments as references: the Mitras TMM and FD12P forward scatter sensor. Due to the fact that these references are also MOR measurements reported by instruments with errors, we must consider a combined uncertainty.

According to the propagation of errors, when comparing two instruments with uncertainties, the final uncertainty is $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$. Therefore, applying a 20% (or 20 m) limit when comparing both instruments, the uncertainty is approximately σ = 28% (or 28 m), accordingly. Note that this metric assumes both instruments sample the same measuring volume, which they do not. Furthermore, requirements for visibility and RVR differ and are not considered in this analysis. We investigate the impact of substantiated corrections in Section 4.4 and use this limit as a guide to provide indication when comparing the instruments. Ultimately, a more in-depth analysis of the uncertainty is eventually required as part of the operational KNMI visibility standard.

4. Results

Our evaluation of the LT31 transmissometer (TMM) focusses on the meteorological optical range (MOR) at low visibility. Primarily, we compare quality-controlled visibility data of the LT31 TMM to that of an older Mitras TMM and a FD12P forward scatter sensor. After removing data associated with error/warning status messages, the available 10-minute averaged MOR data is shown in Figure 6 for each of the sensors throughout the entire verification period. From this figure, we observe that the MOR data for each sensor is not yet comparable as is, and a wider scope of influences must be considered and addressed.

Therefore, we begin by describing the filtering process and addressing data availability and handling due to maintenance in Section 4.1. Next, in Section 4.2, the quality-controlled data is analysed to evaluate the performance of the LT31 TMM relative to the other instruments during stable foggy conditions (MOR ≤ 1500 m). In Section 4.3, we also explore the capability of the LT31 TMM beyond the range of interest (MOR ≤ 5000 m). Finally, in Section 4.4, relevant corrections and considerations are incorporated after discussions with the manufacturer due to the differing functionality of each instrument.

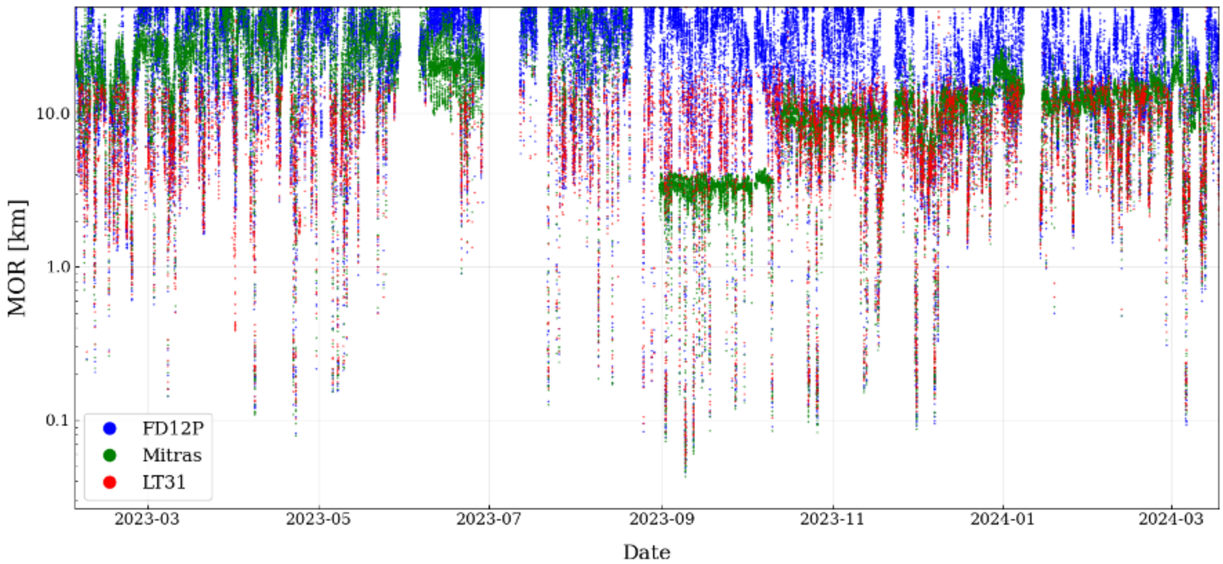

***Figure 6**: 10-minute averaged MOR of the FD12P forward scatter sensor, Mitras TMM, and LT31 TMM as a function of time throughout the entire evaluation period up to 50 km. Data with errors/warning status have been removed.*

4.1. Data filtering and availability

Data filtering is required for quality control and to evaluate the performance of the instruments in comparable conditions. Data availability for this period is roughly 90% and we consider 10-minute averages for comparability to aviation standards [2] and KNMI's visibility standard [1]. Throughout the entire verification period, the LT31 TMM reported foggy conditions, where MOR < 3000 m, for 2.4% of the observations. Figure 6 shows that the MOR data from each sensor exhibits different ranges and significant variability over time with clear shifts during periods of calibration and maintenance.

The data from Figure 6 is displayed as scatter plots in Figures 7, comparing the MOR of the LT31 TMM to the Mitras TMM and FD12P forward scatter sensor, respectively. Even below 3000 m, we observe high variability, particularly when comparing the LT31 and Mitras TMM. Approximately 50% of the data below 3000 m deviates more than 20% from the 1:1 line. Although it is established that the relative error of the TMM MOR increases at higher visibility (refer to Figure 2), there are other conditions which generate poor quality data.

Therefore, the data is quality-controlled by applying the following filters in succession. If any of the below criteria are met, the measurement is **not included** in the remainder of our analysis:

- Status: an instrument gives either an error or warning status message.
- Availability: Less than 7 one-minute data points are available to create the 10-minute average.
- Threshold: TMM MOR values reported higher than 20km.
- Precipitation: Precipitation intensity > 0.0 mm/10min is reported by the FD12P forward scatter sensor. Precipitation detected by rain gauge is explored in Section A1.
- Unstable fog/visibility detected by the LT31 TMM:
    - MOR < 600 m: standard deviation is greater than 50 m.
    - MOR ≥ 600 m: standard deviation is 10% higher than the mean.

This strict filtering targets any potential MOR values that are inaccurately reported, while also limiting the analysis to stable fog conditions without precipitation. Figure 8 shows the quality-controlled data from Figure 7. Clearly, the filtering substantially reduces the number of data points. In fact, due to the high number of error/warning messages from the LT31 TMM, only 30% of the original dataset remains after mutually filtering for status. After the remaining filters are applied, 12% of the original dataset remains. Nonetheless, in Figure 8, we observe that a significant amount of data still falls outside of the shaded region. Below 3000 m, comparing the LT31 TMM to the Mitras TMM, the amount of data that deviates more than 20% from the 1:1 line is roughly 40% before and after filtering. Meanwhile, when comparing to the FD12P forward scatter sensor, the amount reduced from roughly 30% to 20%. These results could be due to the varying conditions of the reference sensors and we consider a more meaningful absolute metric in the following section.

The entire period of data observations available for this study were measured between 03/02/2023 - 18/03/2024, but we will analyse two sub-periods. Throughout that year, various notable maintenance of the reference sensors occurred which can impact the comparison to the LT31 TMM (refer to Section 2.1). More specifically, the working condition of the Mitras TMM is declining and it was calibrated multiple times with varying results, appearing more comparable after 08/2023. Furthermore, the FD12P sensor was replaced on 04/10/2023. Therefore, we consider two main periods before and after this event to ensure comparability. This analysis would benefit from increasing the number of measurement samples and more consistent calibration periods. Various sub-periods were investigated, however, to retain a representative number of data points while isolating comparable conditions, we focus on the following two periods for our analysis:

- **Period 1:** 03/02/2023 - 03/10/2023
- **Period 2:** 04/10/2023 - 18/03/2024

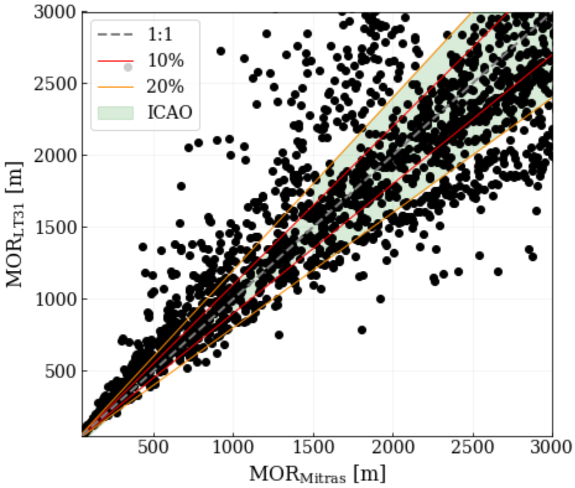

Figure 7: *10-minute averaged LT31 TMM MOR in meters compared to* ***Left:*** *the Mitras TMM MOR and* ***Right:*** *the FD12P forward scatter sensor MOR. Data is shown for observations throughout the entire verification period (03/02/2023 - 18/03/2024), filtered only for errors/warning status. The red and orange lines indicate 10% and 20% deviations from the 1:1 line (gray dashed), respectively, and the green shading indicates the ICAO limits.*

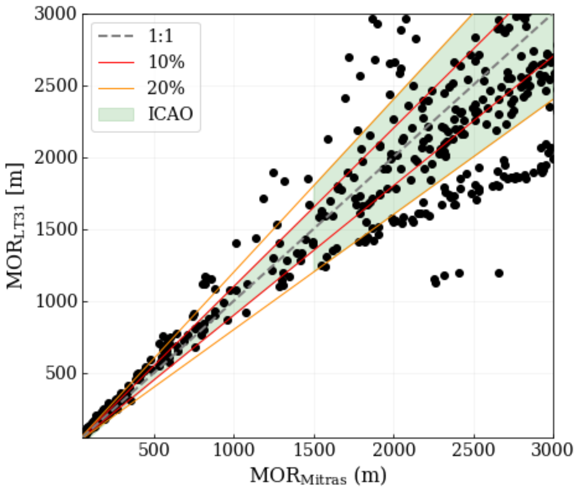

Figure 8: *Filtered 10-minute averaged LT31 TMM MOR in meters compared to* ***Left:*** *the Mitras TMM MOR and* ***Right:*** *the FD12P forward scatter sensor MOR. Data is shown for observations throughout the entire verification period (03/02/2023 - 18/03/2024). The red and orange lines indicate 10% and 20% deviations from the 1:1 line (gray dashed), respectively, and the green shading indicates the ICAO limits.*

4.2. MOR up to 1500 m

In the interest of the sensor applications, we are concerned with ensuring quality performance in poor visibility conditions, and therefore evaluate the performance of the LT31 TMM MOR up to 1500 m. The effectiveness of the filtering method is also demonstrated while comparing the performance of the LT31 TMM to the Mitras TMM and FD12P forward scatter sensor, in Figure 9 and 10, respectively. These figures show the unfiltered and filtered 10-minute averaged MOR data for both periods. In general, a wide range of observations are available below 1500 m, although there are no instances of extremely low visibility (MOR < 100 m) during Period 2. Perfect agreement between the LT31 TMM and the two reference instruments is established if the data points fall along the 1:1 line, which is not the case although we observe a clear linear trend. Overall, after filtering, the quantity of data available for comparison reduces and the points appear closer to the 1:1 line.

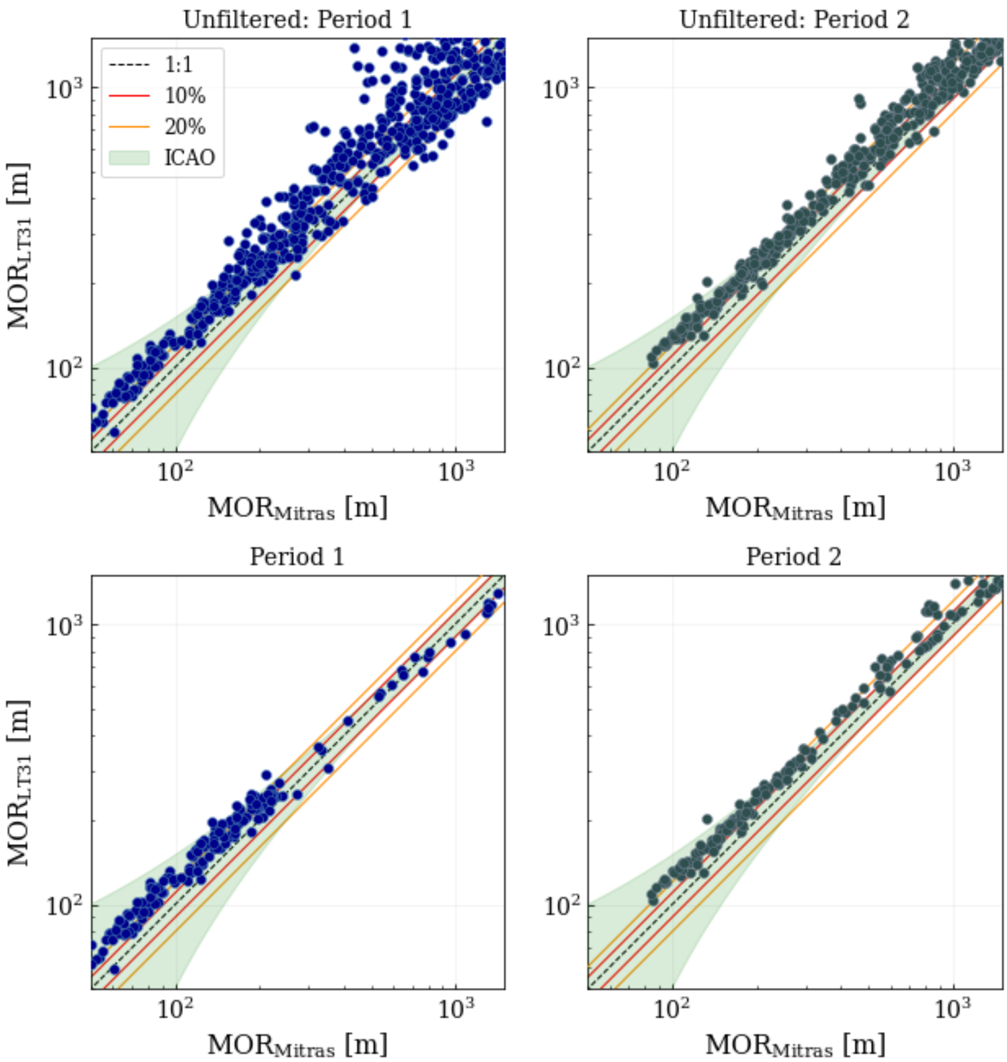

Figure 9: *Status-filtered (**top**) and completely filtered (**bottom**) 10-minute averaged LT31 TMM MOR compared to the Mitras TMM MOR.*

After filtering by all criteria listed in Section 4.1, we observe that the agreement between the LT31 TMM and the reference instruments improves in both comparisons, for both time periods. In Figure 9, we observe that performance of the LT31 TMM relative to the Mitras TMM differs for each period. In Period 1, the LT31 TMM typically measures relatively higher values of MOR in low visibility, but that the Mitras TMM observes higher MOR at higher visibility. We believe this behaviour was due to calibration issues which are further explored in Section 4.3. Although the calibration issues were resolved in Period 2, the LT31 TMM reports a relatively higher MOR than the Mitras TMM overall. This apparent bias may be due to forward scatter effects and an effectively short Mitras TMM baseline. These potential influences are addressed in Section 4.4. Nonetheless, after filtering, 15.0% of the data where MOR < 1500 m deviates by more than 28 m or 28% for the entire period, reduced from 23.7% before filtering. However, for Period 1 and Period 2, this amount is 20.2% and 9.4%, respectively, which is reasonable considering the established calibration issues and declining working condition of the Mitras TMM.

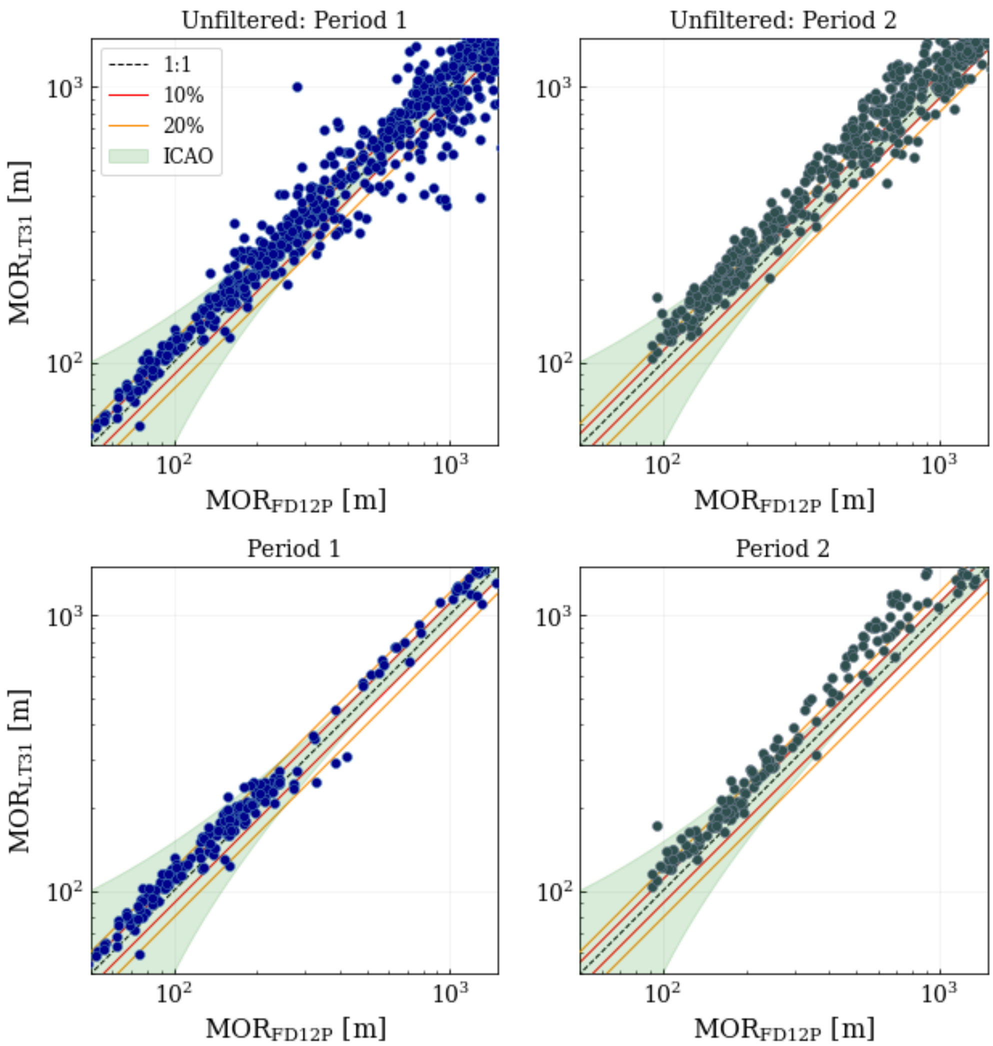

***Figure 10**: Status-filtered (**top**) and completely filtered (**bottom**) 10-minute averaged LT31 TMM MOR compared to the FD12P forward scatter sensor MOR.*

Similar behaviour is observed when comparing the LT31 TMM to the FD12P forward scatter sensor in Figure 10. Although more data variability is observed when comparing the LT31 TMM to the FD12P sensor in this range, the LT31 TMM appears to generally estimate relatively higher MOR values than this sensor as well. Moreover, after filtering, again roughly 15.7% of the data where MOR < 1500 m deviates by more than 28 m or 28% for the entire period, reduced from 23.0% before filtering. However, in this case, for Period 1 and Period 2, the amount is 3.9% and 29.3%, respectively. Therefore, the LT31 TMM had good agreement with the FD12P sensor before it was replaced for Period 2. We investigate this further by considering the statistics.

In Figures 11 and 12, the filtered data is displayed as the ratio of the LT31 TMM MOR and Mitras TMM and FD12P sensor MOR, respectively. Note, that after strict filtering, the number of remaining samples and bin distribution should be considered. Before filtering, 1,256 10-minute samples were available in this range, which is reduced to 451 after filtering. We observe that the mean value of the ratio is greater than one in each case, suggesting that the LT31 TMM is overestimating the MOR in each period, relative to both references. However, the differences we observed in the scatter plots regarding the varying agreement between both periods for each reference sensor becomes more obvious. Moreover, although the mean value of the ratio is greater than 1 for both sensors in both periods, the consistency across the bins varies. The LT31 TMM agrees with the Mitras TMM more consistently in Period 2, while calibration issues may be impacting the higher bins in Period 1. Regarding the FD12P sensor, the comparison in Period 1 exhibits more consistent mean values for each bin. Meanwhile, in Period 2, after the sensor was replaced, the mean is higher, less consistent, and most notably the variance is much higher. This behaviour exhibits a clear change between Period 1 and 2 which is not anticipated because the instruments are the same type and are calibrated prior to instalment. Nonetheless, these results reflect the spread observed in the corresponding scatter plots as well.

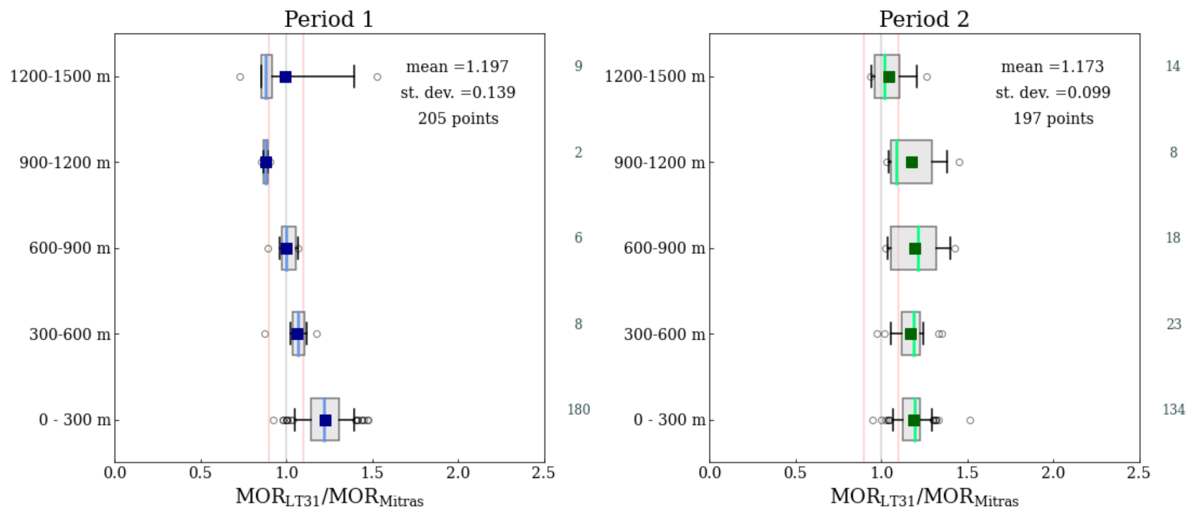

Figure 11: *Filtered 10-minute averaged LT31 TMM MOR relative to the Mitras TMM MOR as box plots for both time periods. The number of data points in each bin are indicated on the right and the vertical red lines indicate 10% deviations. Box plot features: Box: 25 - 75%, highlighted vertical line: median, colored square: mean, fliers: minimum and maximum, 'o' marker: outlier.*

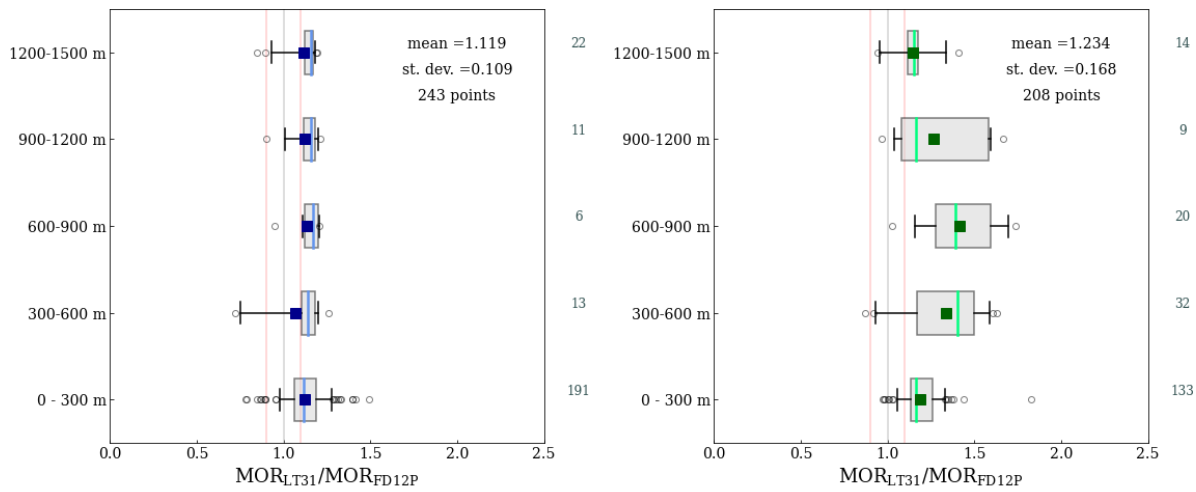

Figure 12: *Filtered 10-minute averaged LT31 TMM MOR relative to the FD12P forward scatter sensor MOR as box plots for both time periods. Refer to Figure 11 for box plot feature description.*

Although we divided the verification period to isolate instrument conditions, the LT31 TMM still appears to measure higher MOR values than both the reference sensors. Superficially, these results suggest that the LT31 TMM may be the common cause for poor agreement. However, intercomparing both reference sensors did not support that there is an underlying issue with the LT31 TMM (refer to Section A2). Therefore, we explore the MOR up to 5000 m, and also consider factors which may further impact the comparison of these sensors in the following sections.

4.3. MOR up to 5000 m

To explore the capability of the LT31 TMM beyond the primary visibility range of interest, we extended our analysis to MOR ≤ 5000 m. The LT31 TMM and Mitras TMM MOR are compared for both periods up to 5000 m in Figure 13. Overall, we observe that the accuracy deteriorates substantially above 1500 m in Period 1, and to a lesser extent in Period 2. This behaviour is expected due to the limitations of TMM instruments above 1500 m (refer to Figure 2); however, we observed a clear divergence in the linear trend in Period 1. Therefore, we also display Period 1 in two sub-periods, before and after 31/08/2023, to show that the trends were caused by differing conditions.

In Figure 13, we observed that the LT31 TMM MOR above 1500 m was reported as either significantly higher or lower than the Mitras TMM MOR throughout Period 1. Moreover, before 31/08/2023, the slope of the trend line above 1500 m decreases meanwhile, after 31/08/2024, it sharply increases. On this date, the Mitras TMM was calibrated at a maximum visibility of 10 km, including a check with the grey filter, after a previously unsuccessful calibration on 23/08/2023. Some remnants of the calibration are also visible in Period 2, as the successful calibration was performed later on 10/10/2024. Performance variability in the reference TMM as its working condition deteriorates poses significant challenges to the accurate validation of the new TMM. By investigating the impacts on the reported visibility during different times, we better understand which periods can provide a valid comparison. Nonetheless, these results highlight the importance of the calibration of the reference TMM, and the limitations of these instruments above 1500 m.

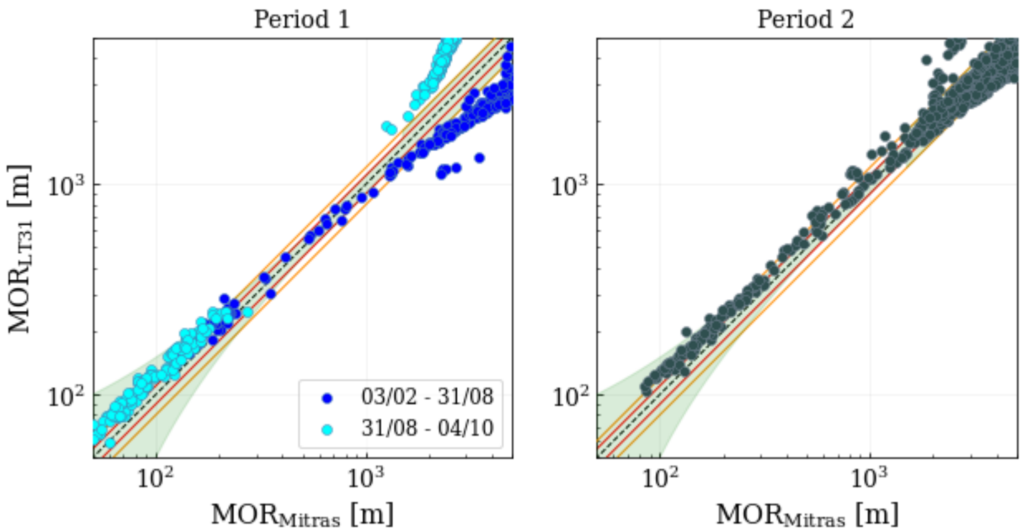

***Figure 13**: Filtered 10-minute averaged LT31 TMM MOR in meters compared to the Mitras TMM MOR up to 5000 m for both time periods where Period 1 (left) is divided into two sub-periods in 2023.*

In Figure 14, the LT31 TMM is compared to the FD12P forward scatter sensor up to 5000 m. This reference sensor is expected to perform better at higher visibilities than a TMM which performs better at lower visibility. In this case, for both periods, we observe relatively good agreement at high visibility. Therefore, we display the ratio of LT31 TMM MOR and FD12P sensor MOR for the entire period up to 5000 m in a boxplot in Figure 15. We observe an increased number of outliers, but overall better agreement at heights above 2000 m. This result is expected due to the nonlinear relationship between a TMM and forward scatter sensor based on how they measure MOR. Still, these findings do not consolidate the performance of the LT31 TMM in the primary range of interest. Therefore, in the next section, we investigate some of the functional differences between the instruments and how they impact the measurements.

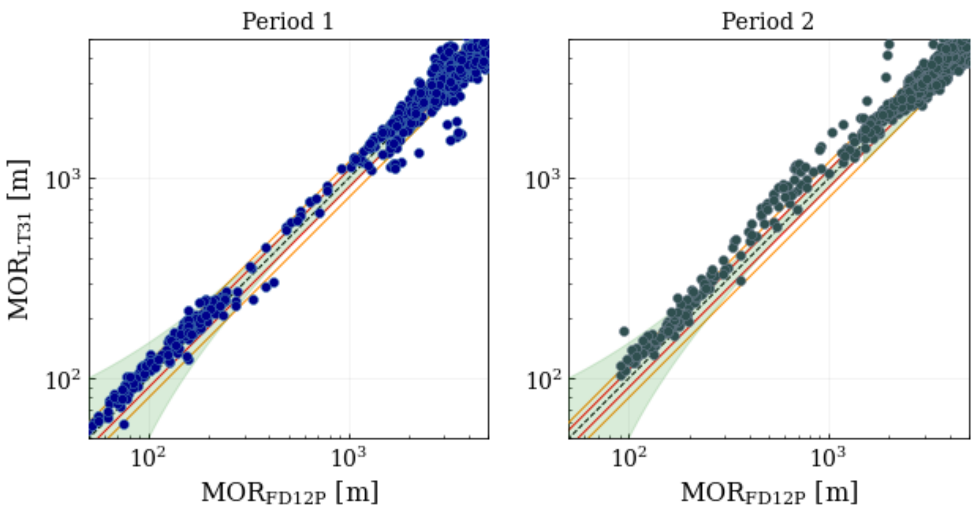

***Figure 14**: Filtered 10-minute averaged LT31 TMM MOR in meters compared to the FD12P forward scatter sensor MOR for both time periods up to 5000 m.*

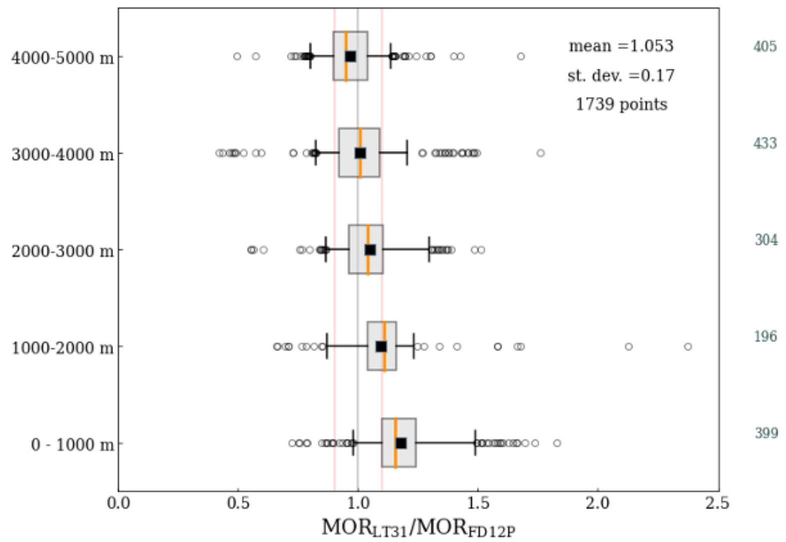

***Figure 15**: Filtered 10-minute averaged LT31 TMM MOR relative to the FD12P forward scatter sensor MOR as a box plot for the entire verification period: 03/02/2023 - 18/03/2024. Refer to Figure 11 for box plot feature description.*

4.4. Data impacts and corrections

Despite strict filtering and examining distinct periods of varying instrument conditions, the initial results show deviations between the visibility instruments that are too large to confirm the suitability of the LT31 TMM. Therefore, after extensive discussions with Vaisala, potential factors and explanations underlying these deviations have been identified and explored. These factors range from fundamental aspects of measuring visibility to practical calibration choices and instrument maintenance issues noted in the previous sections. To this end, estimates of these effects are applied to the filtered data in this section, as described below.

Firstly, the LT31 and Mitras TMM are both expected to experience an artificial increase in MOR due to forward scatter (FS). TMM receivers detect transmitter light which is deflected forward at small angles (< 1 degree) by the atmosphere, artificially increasing the transmittance signal and therefore the reported MOR. While the FS effect for the LT31 TMM is comparable to the long Mitras TMM baseline, this is not the case for the short baseline which is used during for very low visibility (MOR < 200 m). Furthermore, the FS effect is not applicable to the FD12P visibility sensor. This FS effect is exacerbated at low visibility and is therefore particularly relevant during stable fog or precipitation events. Therefore, we apply a FS correction the LT31 TMM when comparing to the Mitras TMM and to the FD12P sensor.

Secondly, the Mitras TMM short baseline may be effectively too long considering the window position and fog penetrating partially within the weather protection hood. Deviations from the effective baseline length of a TMM are expected to have a proportional impact on the reported MOR. Establishing a precise effective baseline is complex and not feasible at this stage. Nonetheless, the potential MOR underestimation of the short baseline should be considered, we investigate the influence by accounting for a slightly shorter baseline (50 cm) when MOR < 200 m, correcting the Mitras TMM observations accordingly.

Thirdly, we apply a calibration correction to the Mitras TMM MOR in Period 1 to exhibit how calibration impacts the MOR above 1000 m. A factor is applied to artificially increase the transmittance reported by the Mitras TMM in what were believed to be clear conditions. However, due to the nature of over- or underestimating the clarity of the conditions corresponding to the transmittance, such a correction must be adapted for each situation and is showcased here only for substantiation.

Finally, the MOR reported by the FD12P forward scatter sensor may be impacted by calibration or window dirt contamination. More specifically, the FD12P forward scatter sensor has a contamination bias to prevent optimistic reporting at low visibility, and this ranges from 0-10%. This correction is assumed to be constant across the visibility spectrum, assuming a linear transfer function between scatter signal strength and attenuation coefficient for forward scatter sensors. Therefore, due to the relative MOR underestimation of the FD12P sensor observed in our preliminary findings, we investigated corrections of 5% and 10% in Period 1 and 2, respectively.

Figures 16 and 17 show scatter and box plots comparing the MOR of the LT31 and Mitras TMM accounting for FS effects, the effective short baseline of the Mitras TMM, as well as a calibration factor in Period 1. Compared to the filtered data without corrections in Figure 9, Figure 16 displays clear improvement in the agreement between the two TMM visibility sensors, especially below 200 m. In fact, the proportion of data below 1500 m that deviates more than 28 m or 28% from the 1:1 line is now only 7% and 3.5% in Periods 1 and 2, respectively. For the entire period, the proportion of data that falls outside of the ICAO limits up to 3000 m is 36.2% without corrections, and 22.6% after corrections. Furthermore, compared to Figure 11, Figure 17 shows that the overall mean of the MOR ratio below 1500 m is closer to 1 after applying corrections. Particularly considering Period 2 as a representative comparison for the TMMs, these improvements verify the performance of the LT31 TMM.

Similarly, Figures 18 and Figure 19 show the LT31 TMM and FD12P forward scatter sensor MOR accounting for TMM FS effects and contamination of the FD12P sensor. Compared to Figure 10, applying the corrections yields clear improvement in agreement between the instruments, but the variability in Period 2 remains. Specifically, the standard deviation for the average ratio of the LT31 TMM and FD12P sensor MOR was 0.1 in Period 1 and 0.153 in Period 2. Below 1500 m, after applying corrections, the proportion of data that deviates more than 28 m or 28% is 2.2% and 11.1%, for Period 1 and 2 respectively. For the entire period, the proportion of data that falls outside of the ICAO limits up to 3000 m was 18.5% without corrections, and 15.3% after applying the FS correction to the LT31 TMM. A dynamic contamination correction could further improve this result. We also observe in Figure 19, that these corrections improve the overall mean in the range of interest, which closer to 1 than in Figure 12.

Therefore, comparing the LT31 TMM to the FD12P sensor before replacement (Period 1), and to the Mitras TMM when successfully calibrated (Period 2), our results verify the performance of the LT31 TMM, contingent on identifying and understanding these causes for deviation. Although deviations from the true MOR due to FS are well-established, corrections are not implemented because the error is considered acceptable, reflecting limitations of human observation. Additionally, we have shown that an appropriate calibration or contamination correction cannot be applied as a constant throughout time and recommend this for further study.

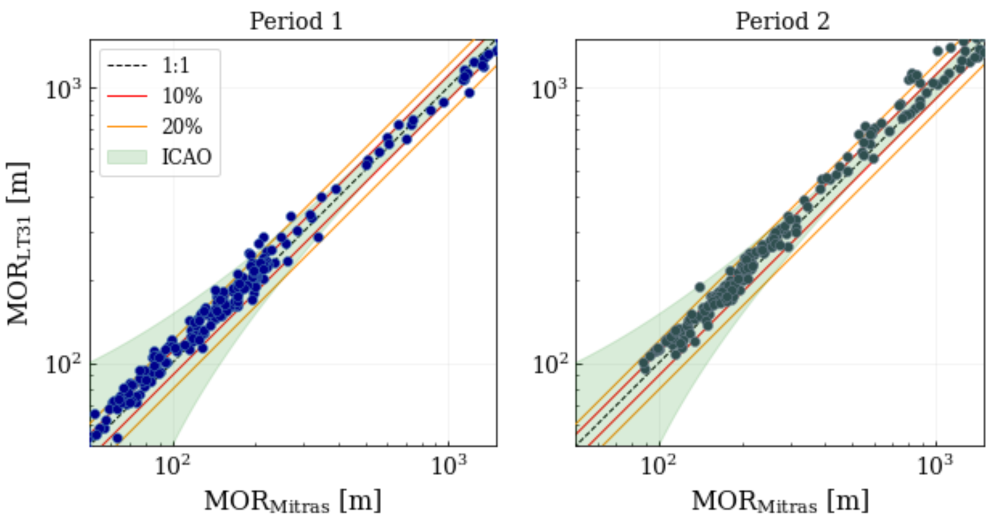

***Figure 16**: Filtered and corrected 10-minute averaged LT31 TMM MOR compared to the Mitras TMM MOR. LT31 TMM is corrected for forward scatter and the Mitras TMM is corrected for effective short baseline. In Period 1, the Mitras TMM is also corrected for calibration.*

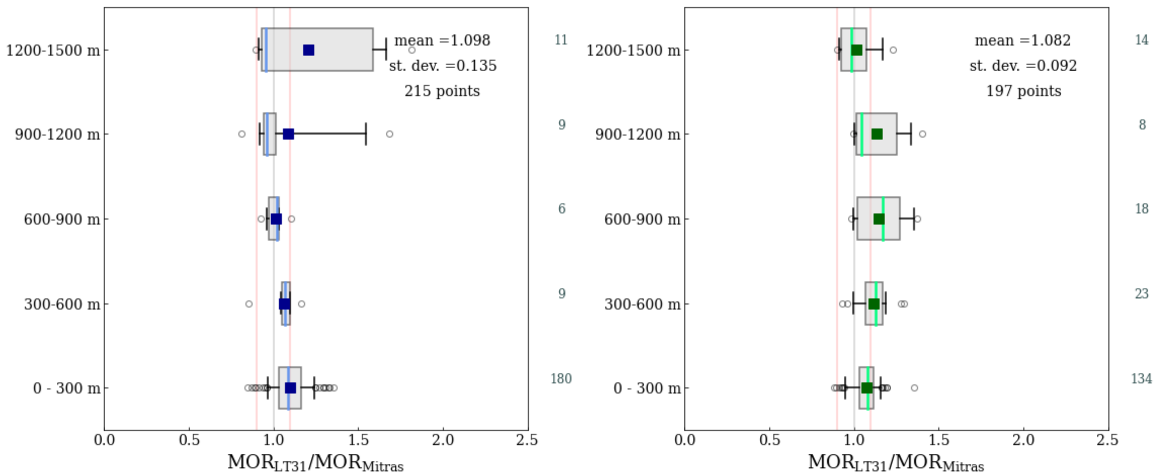

***Figure 17**: Filtered and corrected 10-minute averaged LT31 TMM MOR relative to the Mitras TMM MOR as box plots for both time periods. LT31 TMM is corrected for forward scatter and the Mitras TMM is corrected for effective short baseline. In Period 1, the Mitras TMM is also corrected for calibration. Refer to Figure 11 for box plot feature description.*

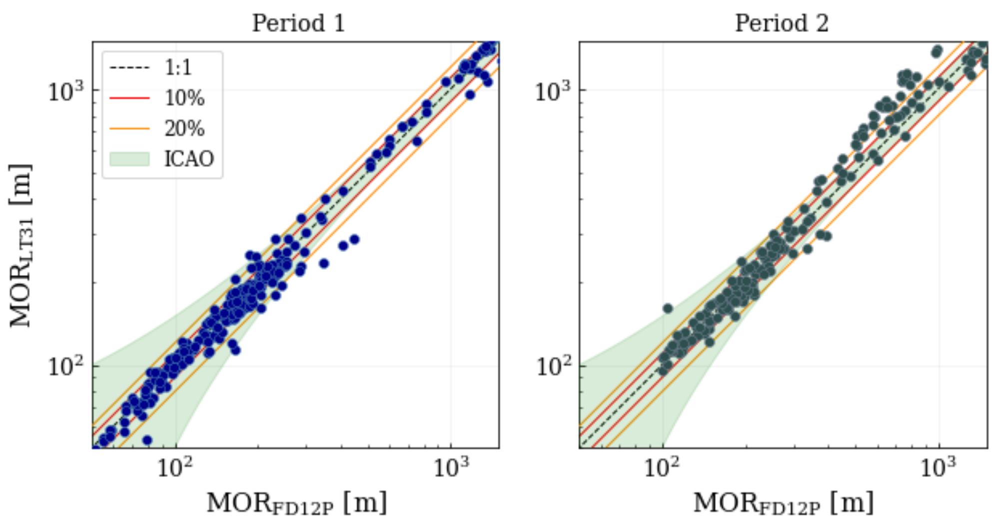

***Figure 18**: Filtered and corrected 10-minute averaged LT31 TMM MOR compared to the FD12P forward scatter sensor MOR. LT31 TMM is corrected for forward scatter and the FD12P sensor is corrected for contamination (Period 1: C = 5%, Period 2: C = 10%).*

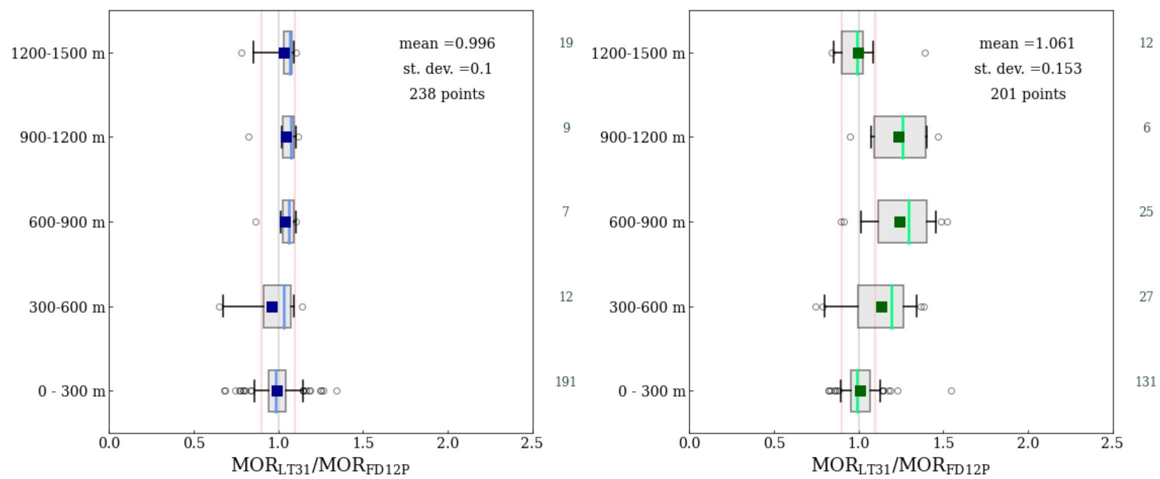

***Figure 19**: Filtered and corrected 10-minute averaged LT31 TMM MOR relative to the FD12P forward scatter sensor MOR as box plots for both time periods. LT31 TMM is corrected for forward scatter and the FD12P sensor is corrected for contamination (Period 1: C = 5%, Period 2: C = 10%). Refer to Figure 11 for box plot feature description.*

5. Summary and conclusions

KNMI has recently acquired a Vaisala LT31 transmissometer (TMM) in order to upgrade their visibility standard. This standard requires a well-maintained TMM as a reference for the forward scatter present weather sensors deployed throughout the measurement network. Replacing the current TMM is necessary, and this report details the verification of the new LT31 TMM. The performance the LT31 TMM has been verified using the current Vaisala Mitras TMM and FD12P forward scatter sensor installed on the test field in De Bilt, The Netherlands. Verification of the new LT31 TMM is not trivial and comparing the various visibility instruments introduces methodological challenges [12]. The meteorological optical range (MOR) of each instrument was compared for approximately one year (February 3rd, 2023, to March 18th, 2024) to capture all seasons and retain enough measurements after strict filtering.

In the interest of practical application, we focused on quality-controlled, 10-minute averaged MOR ≤ 1500 m, prioritizing high-quality data in poor visibility conditions. Strict filtering was applied and evaluated such that the observations from each instrument were comparable with improved agreement during stable foggy conditions without precipitation. Nonetheless, our preliminary findings exhibited persistent irregularities. Therefore, we divided the analysis into two sub-periods due to key instrument adjustments throughout the verification period. When analysing observations beyond the primary range of interest (MOR ≤ 5000 m), clear impacts of calibration and TMM limitations were observable. As expected, the TMM performance deteriorates above 2000 m and the working condition of the Mitras TMM declines. Comparing the LT31 TMM to the FD12P sensor showed better agreement above 2000 m, which is expected considering the operational range of the FD12P sensor. At this stage, the performance of the LT31 TMM could not be verified for MOR ≤ 1500 m. After extensive contact with Vaisala, these deviations are understood and have been investigated and confirmed by applying substantiated corrections to the data.

The differing instrument functionality caused distinct discrepancies when comparing the MOR measurements in the initial dataset. To this end, and after consultation with the supplier of the instruments, four additional corrections were applied to improve the comparison. While the LT31 and Mitras are both TMMs, a key difference is that the Mitras TMM is a double baseline instrument. The short baseline largely impacted the comparison at very low visibility. Therefore, we accounted for forward scatter affecting the LT31 TMM and the effective short baseline length of the Mitras TMM. Clear improvements in agreement were observed after incorporating the corrections, especially in Period 2 when the Mitras TMM was consistently calibrated. During this period, the proportion of MOR observations below 1500 m that deviate more than 28 m or 28%, is 9.4% without corrections and 3.5% with corrections. Furthermore, in this case, the average ratio of the LT31 and Mitras TMM MOR is 1.17 without corrections and 1.08 with corrections. For Period 1, we demonstrate effective improvement through the application of an example calibration correction. The proportion of observations that deviate more than 28 m or 28%, is 31.5% without corrections and 7.0% with corrections including a calibration factor. Although the LT31 TMM appears to measure slightly higher MOR values than its predecessor, small deviations are anticipated, and we accept the reasonable agreement during Period 2 as verification of the LT31 TMM.

Similarly, we substantiated corrections which improved the agreement between the LT31 TMM and FD12P forward scatter sensor. Specifically, accounting for forward scatter affecting the LT31 TMM and applying contamination corrections to the FD12P sensor improved agreement in the primary range of interest. During Period 2 (after the FD12P sensor was replaced), the corrections substantially improve the overall agreement, but the data still showed high variability. Therefore, focussing on Period 1, the proportion of measurements below 1500 m that deviate more than 28 m or 28%, is 3.9% without corrections and 2.2% with corrections. Furthermore, in this case, the average ratio of the LT31 TMM and FD12P sensor MOR is 1.19 without corrections and 0.996 with corrections demonstrating strong agreement.

In conclusion, based on the results comparing the LT31 TMM to the Mitras TMM in Period 2 and the FD12P sensor in Period 1, we support the implementation of the LT31 as a reference TMM for the KNMI visibility standard up to 1500 m. Recommendations for operation and further investigation are summarised in the following section.

6. Recommendations

Although reasonable agreement between the visibility sensors could be exhibited, we discuss notable insights and recommendations for operation and the eventual update of KNMI's visibility standard. In general, we recommend assessing new instruments prior to the onset of deteriorating performance of reference instruments as we have shown that such conditions pose significant challenges to accurately validate a new instrument.

Corrections were implemented to confirm that specific factors impacted the agreement between sensors but are not necessarily recommended for implementation. Firstly, forward scatter affects both TMM instruments, reflective of human observation, and is therefore considered an acceptable error. However, forward scatter does not affect the Mitras TMM short baseline to the same extent which should be considered if this setup is used in the future. Secondly, the precise measurement of the short baseline is critical due to the relative impact on the MOR. More investigation is recommended to better understand the impacts of fog penetrating the instrument weather protection hoods and establish the effective baseline length.

Furthermore, reasonable agreement between the TMM instruments hinges on systematic and accurate calibration of the reference Mitras TMM due to its declining operational condition. While we applied a correction to exhibit the impacts of unsuccessful calibration, applying such corrections is not feasible. Moreover, calibration corrections are not recommended at this time because they require responsive implementation. Again, we emphasize that ensuring consistent calibration and maintenance of a TMM is vital for proper functioning of the instrument. In contrast to the declining working condition of the Mitras TMM, which therefore requires frequent maintenance, the LT31 TMM auto-calibrates using its supplemental present weather detector. Nonetheless, we emphasize that regular cleaning, maintenance, and monitoring to ensure the quality of observations is still necessary and actions must be properly documented. Additionally, the performance and experiences of the visibility reference (now LT31 TMM) should be routinely reported. Future study of the LT31 TMM performance after the autocalibration process (information available in data message) is of interest.

Contamination corrections for the FD12P are also of interest but are not recommended at this stage and require further study. Also, KNMI will soon update the forward present weather sensors within their observation network and such corrections may not be applicable to the new instruments. As is, we do not recommend directly implementing a contamination correction as a standard practice because of the dynamic nature of progressive contamination. However, future studies could monitor, determine, and potentially implement a dynamic correction. In the meantime, we re-emphasize that systematic maintenance and cleaning are essential. Furthermore, these impacts must be considered when verifying a new present weather forward scatter sensor.

As mentioned, KNMI is currently in the process of replacing the FD12P present weather sensors with a new model. Therefore, by upgrading the reference TMM, KNMI will be able to more-accurately calibrate each present weather sensor operating throughout the measurement network across the Netherlands. When comparing to the LT31 TMM to the current candidate, the LT31 TMM measures lower MOR values, as anticipated by the developers. Ultimately, the visibility standard will be upgraded in such a way that complies with current ICAO standards. Therefore, updating the visibility standard will require an uncertainty analysis which will become more difficult as the working condition of the original instruments continues to decline. Investigating the LT31 TMM's accuracy for the runway visual range and during precipitation events is recommended. Furthermore, although we focussed on the raw TMM MOR as a reference, the analysis tools are readily adaptable to the combined MOR as well, which may be of interest for broader applications.

Acknowledgments
The authors would like to thank Mando de Jong, Marijn de Haij, and Wiel Wauben for their contributions to this work. Furthermore, due to the declining working conditions of the reference instruments, this verification hinged on substantial efforts of KNMI's operational staff. Additionally, we thank the Vaisala experts for their knowledge and efforts towards understanding our results.

7. References

[1] Bloemink, H.I., 2006: KNMI visibility standard for calibration of scatterometers, WMO Technical Conference on Instruments and Methods of Observations, Geneva, Switzerland.

[2] International Civil Aviation Organization (ICAO), 2018: Manual of Runway Visual Range Observing and Reporting Practices, Annex 3, 20th edition, Attachment A.

[3] Wauben W.M.F., 2012: Visibility chain Rotterdam The Hague Airport, KNMI Internal Report (IR 2012-02).

[4] Wauben W.M.F., Mathijssen T., and Oudshoorn C., 2016: Field Evaluation of Sensors for Precipitation Type Discrimination, WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observations, Madrid, Spain.

[5] De Haij M., 2008: Assessment of automated quality control of MOR measurements by the FD12P sensor, KNMI Technical Report (TR298).

[6] Vaisala Oyj, 2001, Transmissometer Mitras User's Guide. M210207EN-A. Helsinki, Finland.

[7] Vaisala Oyj, 2001, Transmissometer LT31 User's Guide. M210667EN-E. Helsinki, Finland.

[8] Vaisala Oyj, 2002, Weather Sensor FD12P User's Guide. M210296EN-A. Helsinki, Finland.

[9] Royal Netherlands Meteorological Institute (KNMI), 2009: DZ2 Zicht Mitras SIAM manual (Internal, Document number: ID-30-058).

[10] Royal Netherlands Meteorological Institute (KNMI), 2013: DZ4 Zicht FD12 SIAM manual (Internal, Document number: ID-30-059).

[11] Commission for Instruments and Methods of Observation (CIMO), 2023: Guide to Instruments and Methods of Observation (WMO-No. 8), Volume I – Measurement of Meteorological Variables.

[12] Heyn, K., Lönnqvist, J., and Linna, T., 2018: Uncertainty sources that limit the precipitation identification/quantification and extinction coefficient determination capabilities of optical present weather and visibility sensors, WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observations, Amsterdam, The Netherlands.

[13] Quinlan M., 2022: An Intercomparison of Precipitation Gauges at KNMI in De Bilt, Netherlands, WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observations, Paris, France.

A. Appendices

A1: Filtering precipitation events using rain gauge

We verify the performance of the LT31 TMM in stable fog conditions without precipitation (refer to Section 4.1). Specifically for precipitation, the 10-minute averaged MOR is excluded if the average precipitation intensity reported by the FD12P sensor was non-zero. However, an automated float-type precipitation gauge (manufactured and deployed by KNMI since 1992) is also installed on the same test field which can also be used for this filter [13]. While both instruments report precipitation intensity, the measurement principals and capabilities differ and therefore could produce different filtering results. Therefore, we briefly investigate the impact of using the rain gauge for the precipitation filtering on the overall results. Figure A1.1 shows an example of the precipitation intensity reported by both sensors with different averaging. Minor differences are observed in the 1-minute data as the rain gauge displays more fluctuations and, at times, a delayed response compared to the FD12P sensor, which reports higher values overall. However, as expected, when considering the 10-minute averages, the differences are less pronounced.

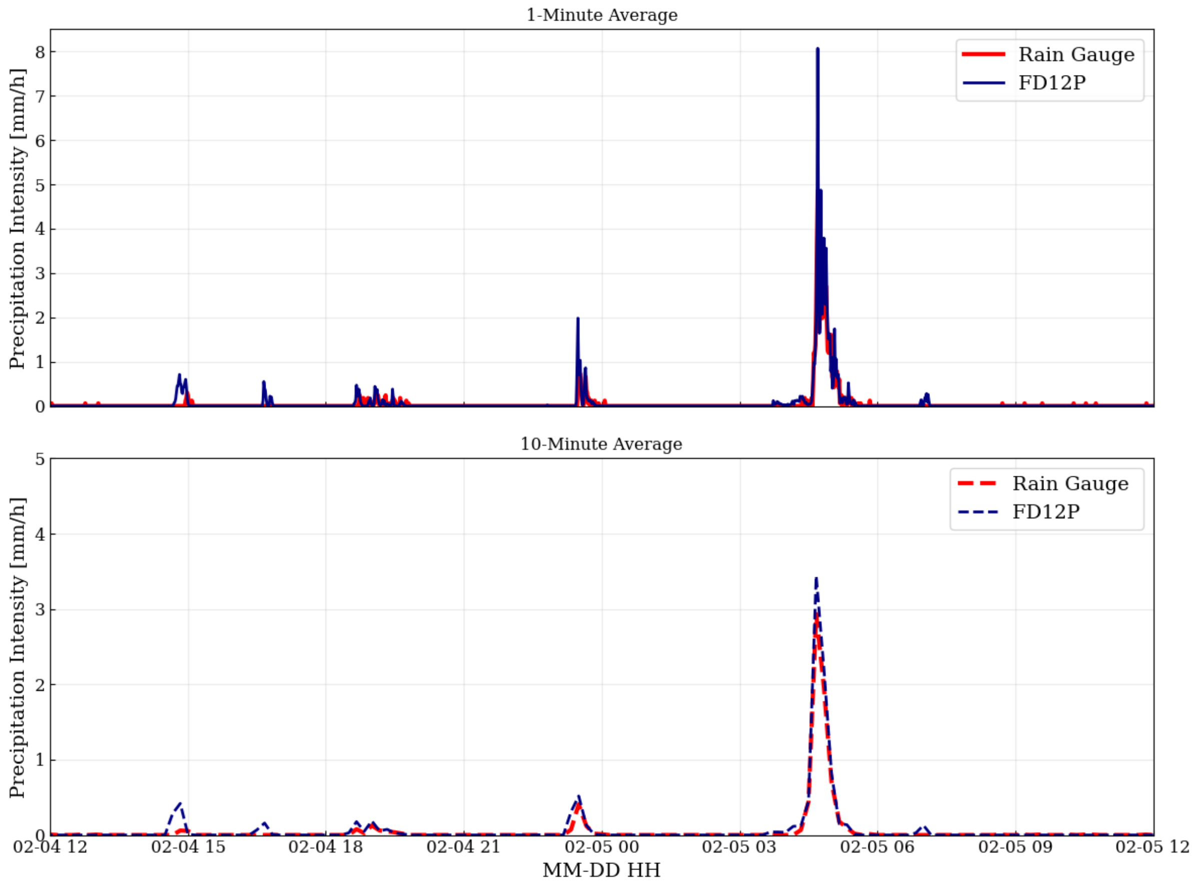

***Figure A1.1**: Precipitation intensity reported by the FD12P forward scatter sensor and KNMI rain gauge resampled to 1-minute (**top**) and 10-minute (**bottom**) averaged values.*

Figure A1.2 shows the 10-minute averaged MOR intercomparison from Section 4.2 but for the entire verification period using the two methods for precipitation filtering. In these scatter plots, the cyan markers represent data that would be removed when the FD12P sensor is used for the precipitation filter as opposed to the rain gauge. We observe that the LT31 and Mitras TMM comparison is not significantly influenced by the precipitation filter instrument choice. However, the comparison between the LT31 TMM and the FD12P sensor appears to benefit more from using the FD12P sensor. In this case, for MOR < 1000 m, many points that deviate farther from the 1:1 line are removed by the FD12P precipitation filter that remain when using the rain gauge precipitation filter. While the quality of samples removed is showcased here, the number of samples that are removed is also relevant.

Box plots are not shown as we observed negligable changes in the statistical data of the relative MOR between the LT31 TMM and the reference insturments. More specifically, the average ratio of the LT31 and Mitras TMM remains roughly 1.2 and the standard deviation remains similar when using the rain gauge for precipitation filtering, despite the fact that the number of samples for MOR < 1500 m increased. Specifically, the number of samples under 1500 m increases from 205 to 211 in Period 1, and from 197 to 248 in Period 2. This behaviour is likely due to the higher sensitivity of the FD12P sensor which will cause more samples to report rain and therefore, be omitted. Above 1500 m, when comparing the LT31 TMM to the FD12P sensor up to 5000 m, the number of sample points reduced by only 19 points and differences in the mean and the standard deviation are negligable when using the rain gauge for the precipitation filter. The limited influence of the different instrument selection for precipitation filtering is likely related to the fact 10-minute averaging smooths out the differences in reported precipitation intensity. We recommend that future visibility studies investigate the effect of filtering the MOR data using the 1-minute precipitation intensity. Furthermore, the precipitation filter was applied to any non-zero precipitation intensity, but we also recommend investigating different thresholds for this filter such as 0.2 mm/h considering the difference in response sensitivity.

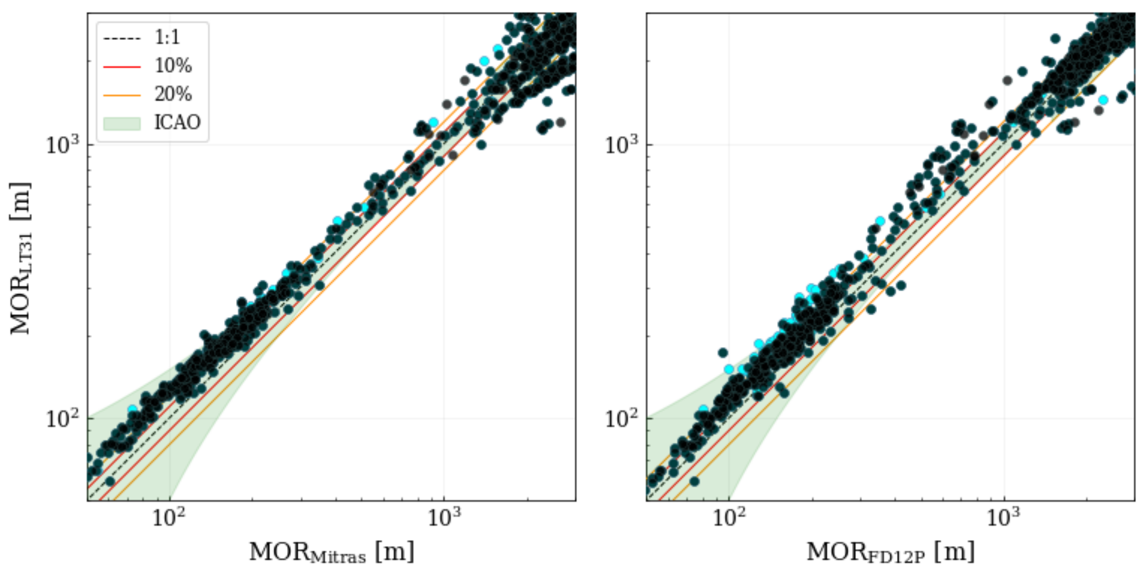

Figure A1.2: *Filtered 10-minute averaged LT31 TMM MOR compared to the Mitras TMM and FD12P forward scatter sensor MOR. Black markers used the FD12P sensor for precipitation filtering while cyan markers used the KNMI rain gauge for precipitation filtering. Data is shown for observations throughout the entire verification period (03/02/2023 - 18/03/2024).*

A2: Mitras TMM and FD12P sensor comparison

We briefly compare the Mitras TMM and FD12P forward scatter sensor because the LT31 TMM showed similar deviations from both visibility instruments in our initial findings (refer to Figures 7 and 8). The LT31 TMM estimated higher MOR values than both references and therefore we compare these two instruments to establish if they are mutually consistent. Figure A2.1 compares the Mitras TMM and FD12P sensor for MOR ≤ 1500 m during both verification sub-periods. We observe that these two sensors do not show better agreement when intercompared than when compared to the LT31 TMM. Below 600 m, the two reference sensors are in relatively good agreement for both periods; however, above 600 m, the FD12P sensor observes lower values than the Mitras TMM. These findings are consistent with our expectations, as we later established that forward scatter influences the results of the LT31 TMM but not the short baseline Mitras TMM at very low visibility (MOR < 200 m). Furthermore, the Mitras TMM calibration issues in Period 1 impacts this comparison similarly as observed in Figures 9. Ultimately, as the Mitras TMM and FD12P sensor do not display clear agreement below 1500 m, we cannot conclude that they observe the true MOR and that the LT31 TMM is the common issue in our primary analysis.

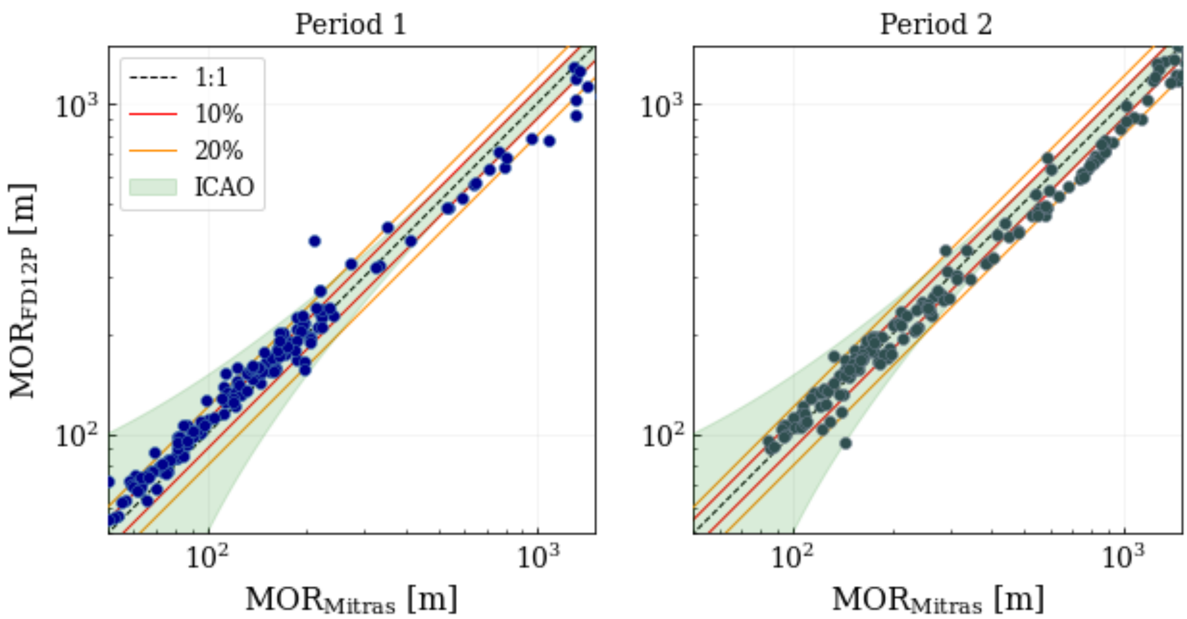

Figure A2.1*: Filtered 10-minute averaged MOR from the FD12P forward scatter sensor compared to the Mitras TMM MOR. The red and orange lines indicate 10% and 20% deviations from the 1:1 line (gray dashed), and the green shading indicates the ICAO limits.*

Royal Netherlands Meteorological Institute

PO Box 201 | NL-3730 AE De Bilt
Netherlands | www.knmi.nl