Range accuracy of a Gated-Viewing system
as a function of the number of averaged images

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ABSTRACT

Primarily, a Gated-Viewing (GV) system provides range gated imagery. By increasing the camera delay time from frame to frame, a so-called sliding gates sequence is obtained by which 3-D reconstruction is possible. Scintillation caused by atmospheric turbulence degrades each Gated-Viewing image and thus, the range accuracy that can be achieved with the sliding gates method. By averaging a certain number of images per range, this degradation can be reduced.

In this paper we have studied the influence of the number of averaged images on the resulting range accuracy. Therefore, we have combined the Intevac Gated-Viewing detector M506 with a pulsed 1.57 μm laser source. The maximal laser pulse energy was 65 mJ. The target was a 1-m²-plate at a distance of 500 m. The plate was laminated with a Spectralon layer having Lambertian reflection behavior with a homogeneous reflectance of 93 %. It was orientated diagonally to the line of sight of the sensor in order to provide a depth scenario. We have considered different combinations of the four parameters »detector binning mode« (1x1, 2x2), »optics« (f = 250 mm, f/2.1; f = 500 mm, f/3.3; f = 2032 mm, f/10), »gate length« (13.5 m, 23.25 m, 33 m) and »signal-to-noise ratio« (SNR) (1 dB, 2 dB, ..., 9 dB). For each considered set of parameters, a sliding gates sequence of the target was recorded. Per range, 20 frames were collected. Finally, the range accuracies were derived as a function of the number of averaged frames per range.

Keywords: Gated-Viewing, Range gating, Sliding gates method, Range accuracy, Atmospheric turbulence, Temporal frame averaging, SWIR

1. INTRODUCTION

In the past few years, a lot of work has been done concerning the 3-D capability of gated imaging systems. Basically, two approaches can be recognized. The first, intuitive technique is the so-called »sliding gates« method\(^{1-5}\). Simply, by increasing the distance of the range gate during the measurement, a range sampled sequence of the scenery is obtained. By sticking together images showing consecutive range gates, 3-D reconstruction of the objects in the field of view (FOV) is achieved. The second, sophisticated approach makes use of multiple exposures of range gated images in order to create coded images\(^{6}\). A direct control access to the sensor gate is required. The 3-D reconstruction is based on the comparison of pixel grey levels in a certain number of coded images.

Both methods are based on the detected laser intensity and thus, they suffer from the scintillation effect induced by atmospheric turbulence. A common technique to mitigate this degrading effect is to reduce the standard deviation of this intensity fluctuation by averaging, pixel by pixel, several images before processing. But dynamic scenarios allow no long measuring times because the observed object could move during the measurement. And from a military point of view, it is not desired to emit a large number of laser pulses because each laser pulse can reveal the own position. So, concerning a practical use of a range gated system as 3-D sensor, the total number of images should be kept as small as possible.

Within the framework of this paper, the influence of the number of averaged images on the range accuracy derived from the sliding gates method is investigated. Additionally, different combinations of the four parameters »detector binning mode«, »optics«, »gate length« and »SNR« are considered. In Section 2 the experimental set-up for data collection is illustrated. Section 3 shows data examples and gives an overview of all captured data. The methodology that was employed for the range accuracy analysis of the data is described in Section 4. The main results of the range error analysis are contained in Section 5. Finally in Section 6, conclusions are drawn.

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2. EXPERIMENTAL SET-UP

A flash lamp pumped Nd:YAG Q-switched laser with a maximal pulse energy of 65 mJ, a wavelength of 1.57 µm (OPO shifted) and a pulse width of 7.1 ns was synchronized with the Intevac GV detector LIVAR® M506 with a full resolution of 1280x1024 pixels and a detector pitch of 6.7 µm. The laser was equipped with a beam shaper with a transmission of 70 % producing speckle-reduced illumination with a homogeneous flat top profile. The divergence of the outgoing laser pulse was 1°. With an additional attachment, a divergence of 0.25° was possible. During the measurements, optics with focal lengths of 250 mm, 500 mm and 2032 mm and F-numbers of 2.1, 3.3 and 10, respectively, were mounted in front of the GV detector. Additionally, the Scintec Boundary Layer Scintillometer (BLS) 900 receiver was mounted next to the GV system. At a distance of 500 m the Scintec BLS900 transmitter and a 1-m²-plate were positioned next to each other. The plate was laminated with a Spectralon layer having Lambertian reflection behavior with a homogeneous reflectance of 93 %. The plate was orientated diagonally to the line of sight of the GV system in order to provide a depth scenario. A scheme of the experimental set-up is depicted in Figure 1.

![Figure 1](attachment:image.png)

Figure 1. Scheme of the experimental set-up for the measurements. Left: GV system (laser and GV camera) and scintillometer receiver. Right: Scintillometer transmitter and target (plate) at a distance of 500 m.

The BLS900 provides measurements of the refractive index structure parameter \( C_n^2 \) [m\(^{-2/3}\)] and the crosswind \( v_\perp \) [m/s] during the GV data collection. The GV detector can be operated in a binning mode where 2x2 pixels are binned together. The three optics that were mounted in front of the GV detector result in horizontal FOVs of approximately 2°, 1° and 0.25°, respectively. In the first configuration (2° horizontal FOV), the GV system is nearly diffraction-limited with an Airy disc diameter of 8 µm (6.7 µm pixel size). In the second configuration (1° horizontal FOV) it is diffraction-limited for the 2x2 binning mode with an Airy disc of 13 µm (13.4 µm pixel size). In the third configuration (0.25° horizontal FOV) it is optics-limited with an Airy disc diameter of 38 µm.

3. DATA

For the data collection, the frames rate was always set to 10 Hz. The gate was always shifted by 0.75 m. For each range, 20 images were captured for subsequent averaging. Different combinations of the following parameters were considered:

- **Optics**: f = 250 mm, f/2.1; f = 500 mm, f/3.3; f = 2032 mm, f/10
- **Detector binning mode**: 1x1 pixel (unbinned mode), 2x2 pixels (binned mode)
- **Gate length (number of ranges / gate start)**: 13.5 m (35/488 m), 23.25 m (50/478.25 m), 33 m (65/464 m)
- **Divergence of the outgoing laser pulse**: 0.25°, 1°
- **Laser energy transmission**: 2.5 %, 5 %, 10 %, 25 %, 50 %, 75 %, 100 %

The divergence of the outgoing laser pulse (parameter 4) and the laser energy transmission (parameter 5) can be combined into a single value describing the maximal brightness of the target in the sliding gates sequence compared to its noise floor. The resulting value is defined as SNR [dB] by

\[
SNR = 10 \cdot \log_{10} \frac{G_{\text{max}}}{G_{\text{min}}},
\]

where \( G_{\text{max}} \) and \( G_{\text{min}} \) denote the maximal and minimal value of the average target grey levels after averaging 20 frames per range. Exemplarily, in Figure 2, the average target grey levels are plotted against the range number in the sliding gates sequence after averaging 20 frames per range. Three curves are depicted for the gate lengths mentioned above.
Figure 2. Plots of the average target grey level against the range number in the sliding gates sequence after averaging 20 frames per range. From the maximal and minimal values of these curves, the SNR is derived by Equation (1). Optics 3 with \( f = 2032 \) mm, \( f/10 \) was used. The gate lengths were 13.5 m (left), 23.25 m (middle) and 33 m (right). The gate was shifted 35 times (left), 50 times (middle) and 65 times (right) by 0.75 m and the divergence of the outgoing laser pulse was 0.25°. The laser energy transmissions were 50 % (+), 25 % (O) and 10 % (□).

In the upper right corner of the plots in Figure 2, the resulting SNR values are given for the 9 exemplary curves. These SNR values are calculated for all sliding gates sequences and will replace the two parameters »divergence of the outgoing laser pulse« and »laser energy transmission« mentioned above. They are rounded to the closest integer and take the following values.

- **SNR:** 1 dB, 2 dB, 3 dB, 4 dB, 5 dB, 6 dB, 7 dB, 8 dB, 9 dB

Exemplarily, Figure 3 shows three GV images of the target that were captured with the GV system equipped with the three different optics mentioned above. The gate length was set to 13.5 m and the SNR was 7 dB.

Figure 3. GV images of the target captured with different optics mounted in front of the GV detector. The gate length was set to 13.5 m and the SNR was 7 dB. Left: Optics 1 with a focal length of \( f = 250 \) mm and a F-number of 2.1. Middle: Optics 2 with a focal length of \( f = 500 \) mm and a F-number of 3.3. Right: Optics 3 with a focal length of \( f = 2032 \) mm and a F-number of 10.

Figure 4. Overview of all captured sliding gates sequences grouped by the optics in three tables. Each table contains the information if the detector was operated in the 2x2 binned mode (B) or in the 1x1 unbinned mode (U). A dash (-) indicates that no data was collected.

<table>
<thead>
<tr>
<th>f = 250 mm</th>
<th>Gate length</th>
<th>f = 500 mm</th>
<th>Gate length</th>
<th>f = 2032 mm</th>
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<td>13.5 m</td>
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<td>U/B</td>
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<td>9</td>
<td>B</td>
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<td>B</td>
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</tbody>
</table>
The three measuring matrices in Figure 4 give an overview of all captured data. During the GV data collection, the BLS900 provided $C_n^2$ values between $0.2 \cdot 10^{-14}$ m$^{-2/3}$ and $3 \cdot 10^{-14}$ m$^{-2/3}$ and crosswind values between 3 m/s and 12 m/s. The Greenwood time constant $\tau_G$ is the time interval over which turbulence stays constant. Under the assumption of constant $C_n^2$ and crosswind values along the propagation path of the laser pulse, $\tau_G$ can be estimated by

$$\tau_G = \frac{(2.91 \cdot k^2 \cdot C_n^2 \cdot L)^{-3/5}}{v_L},$$

where $k = 2\pi/\lambda$ [m$^{-1}$] is the wavenumber, $\lambda$ [m] is the laser wavelength and $L$ [m] is the length of the laser pulse propagation path. For a wavelength of $\lambda = 1.57$ μm, a path length of $L = 500$ m and the weakest turbulence and crosswind conditions of $0.2 \cdot 10^{-14}$ m$^{-2/3}$ and 3 m/s, respectively, during the GV data collection, the Greenwood time constant is calculated with Equation (2) to $\tau_G = 33$ ms. Thus, a frame rate of 10 Hz is sufficient to capture images with pairwise uncorrelated intensity disturbances due to scintillation. So, they are suited for frame averaging.

4. METHODOLOGY

All sliding gates sequences from the Section 3 are processed with the same algorithm to derive a range value for each pixel. First of all, a region of interest (ROI) within the target area is defined. The size of the ROI is 10x30 pixels for all collected data. By plotting the intensity values of a ROI pixel against the range number in the sliding gates sequence, the intensity profile is obtained that is the convolution of the sensor gate and the laser pulse. This intensity profile is approximated by the symmetric, piecewise polynomial function $\Pi_p$ in Figure 5 with $p = (p_1, p_2, p_3, p_4, p_5)$, $p_1 \leq p_2 \leq p_5$.

$$\Pi_p(x) = \begin{cases} p_4 & \text{if } x < p_1 \text{ or } x > p_5 + p_2 - p_1 \\ p_5 & \text{if } p_2 < x < p_5 \\ p_3 - p_4 & \begin{cases} -2\left(\frac{x - p_3}{p_3 - p_4}\right)^3 + 3\left(\frac{x - p_3}{p_2 - p_4}\right)^2 + p_4 & \text{if } p_1 \leq x \leq p_2 \\ 2\left(\frac{x - p_5}{p_2 - p_4}\right)^3 - 3\left(\frac{x - p_3}{p_2 - p_4}\right)^2 + p_5 & \text{if } p_3 \leq x \leq p_3 + p_2 - p_1 \end{cases} \end{cases}$$

Figure 5. Equation (left) and plot (right) of parameterized symmetric function $\Pi_p$ with the parameters $p_1, \ldots, p_5$ as approximation of the intensity profile.

In the first step, this function is fitted to the measured intensity values for each pixel by the least squares method:

$$\min_p \sum_{k=1}^{n} (\Pi_p(k) - g_k)^2,$$

where $g_k$ are the pixel grey levels ($k \in \{1, 2, \ldots, n\}$) and $n$ is the number of different ranges in the sliding gates sequence.

Exemplarily, some results of these curve fits are shown in Figures 6 and 7. For Figure 6, no frame averaging was applied. For Figure 7, 20 frames per range were averaged. It can be seen that the curve fitting step works quite well and that the spread of the grey levels – particularly in the plateau region – was significantly reduced by frame averaging. But it also turns out that the simple approach from Figure 5 for the intensity profile is not an optimal choice. Especially Figure 7 shows a rounded edge at the transition from the plateau to the falling slope. This rounded edge is not modeled with $\Pi_p$. However, the other parts of the intensity profile can be modeled quite well by $\Pi_p$. So, this approach will be used in the following. Another conclusion that can be drawn from Figure 6 and 7 is that a gate length of 13.5 m is too short because the curves in the left plots do not reach the plateaus of the curves in the middle and right plots although the divergence of the outgoing laser pulse (0.25°) and the laser energy transmission (50 % (+), 25 % (O) and 10 % (□)) are the same. The corresponding SNR values reflect this fact: 8 dB compared to 9 dB (+), 5 dB compared to 7 dB (O) and 3 dB compared to 4 dB (□). The reason for this is that the high-voltage (HV) between the photocathode and the CMOS sensor is switched off before reaching its maximum. The time that is required for the HV rising and falling slope is 65 ns each. Thus, the minimal integration time without a cutoff like above is 130 ns corresponding to a gate length of 19.5 m.
Figure 6. Plots of the grey levels (markers) for ROI pixel (1,1) against the range number in the sliding gates sequence without frame averaging. The solid lines are the fitted intensity curves \( I_0 \). Optics 3 with \( f = 2032 \) mm, \( f/10 \) was used. The gate lengths were 13.5 m (left), 23.25 m (middle) and 33 m (right). The gate was shifted 35 times (left), 50 times (middle) and 65 times (right) by 0.75 m and the SNR values were 8/9 dB (+), 5/7 dB (○) and 3/4 dB (□).

Figure 7. Plots of the grey levels (markers) for ROI pixel (1,1) against the range number in the sliding gates sequence with 20 frame averaged per range. The solid lines are the fitted intensity curves \( I_0 \). Optics 3 with \( f = 2032 \) mm, \( f/10 \) was used. The gate lengths were 13.5 m (left), 23.25 m (middle) and 33 m (right). The gate was shifted 35 times (left), 50 times (middle) and 65 times (right) by 0.75 m and the SNR values were 8/9 dB (+), 5/7 dB (○) and 3/4 dB (□).

From the optimal parameters \( p_2 \) and \( p_3 \), the range is derived by calculating their mean value and converting this real-valued number into the corresponding range by:

\[
R = \text{gate start} + \left( \frac{p_2 + p_3}{2} - 1 \right) \cdot 0.75 \text{ m} + \frac{\text{gatem length}}{2}.
\]  

In the second step, the range accuracy (or range error) was derived. Therefore, a plane was fitted to the resulting point cloud of the ROI. Let \( R(x,y) \) be the calculated range map. \((x,y)\) denotes the horizontal and vertical pixel number in the ROI. The approach for the plane is \( P(x,y) = ax + by + c \), where the parameters \( a, b \) and \( c \) are again determined by the least squares method:

\[
\min_{a,b,c} \sum_{x=1}^{30} \sum_{y=1}^{30} (P(x,y) - R(x,y))^2 .
\]

Finally, the standard deviation of the difference array \( D(x,y) = P(x,y) - R(x,y) \) is defined as range error \( \sigma_R \):

\[
\sigma_R = \sqrt{\frac{1}{300} \sum_{x=1}^{30} \sum_{y=1}^{30} (D(x,y) - \mu_D)^2} ,
\]

where \( \mu_D \) is the mean value of \( D \):

\[
\mu_D = \frac{1}{300} \sum_{x=1}^{30} \sum_{y=1}^{30} D(x,y) .
\]
In the case of a plane-like point cloud $R$ and a good fit of $P$ to $R$, $\mu_P$ should be zero. The minimizations in Equations 3 and 5 were realized with the MATLAB® function `fminsearch` that uses a derivative-free simplex search method. The entire procedure for deriving the range error from a sliding gates sequence was carried out for all data and, additionally, for $1, 2, \ldots, 20$ averaged images per range in order to study to influence of frame averaging on the range error.

5. RESULTS

In Figures 8 and 9, the range errors are plotted as functions of the number of averaged images per range. Figure 8 contains the results for the 1x1 unbinned mode of the detector. Figure 9 contains the results for the 2x2 binned mode of the detector.

As expected, the curves in Figure 8 are basically monotonically decreasing which means that the range error goes down with the number of averaged images per range. Additionally, an asymptotic behavior of the curves can be observed, i.e. the higher the number of averaged images per range, the smaller the reduction of the range error. Roughly, it can be said that 5 – 7 averaged images per range are sufficient and reduce the range error by approximately 50 %. The greatest absolute range error enhancement was achieved in the lower right graph for a SNR of 4 dB. With only 2 averaged images per range, the range error was reduced by 5 cm (from 14 cm without averaging to 9 cm).
Concerning the influence of the SNR on the range error, there is no statement possible for the first optics (upper row) due to a lack of data. For the second optics (middle row), there is a small range error improvement when increasing the SNR from 4 dB to 8 dB. The greatest range error improvement was achieved in the right graph when increasing the SNR from 6 dB to 7 dB. For the third optics (lower row), the range error was significantly improved when increasing the SNR from 3 dB to 6 dB (left) and 4 dB to 7 dB (middle and right). There is only a small dependence of the gate length on the range error for medium SNR (< 8 dB in the middle row, 4 dB in the lower row) and no dependence of the optics. The best range errors with values below 2 cm were achieved in the lower left graph for more than 8 averaged images per range.

Figure 9. Plots of the range error $\sigma_R$ as functions of the number of averaged images per range for the 2x2 binned mode of the detector. The range error values were calculated with the procedure described in Section 4. The gate lengths were 13.5 m (left column), 23.25 m (middle column) and 33 m (right column). The optics focal lengths were $f = 250$ mm (f/2.1) (upper row), $f = 500$ mm (f/3.3) (middle row) and $f = 2032$ mm (f/10) (lower row). Each graph shows the range error functions for several SNR values (1 dB – 9 dB). The markers are equal for equal SNR values.

The curves in Figure 9 are also basically monotonically decreasing with an asymptotic behavior. The statements concerning Figure 8 are also true for Figure 9, i.e. 5 – 7 averaged images per range result in a range error enhancement of about 50 %, and a higher SNR yields better range accuracies. Additionally, in the lower row it turns out that a longer gate length significantly increases the range error for low SNR up to 21 cm. The reason for this could be that the curve fitting is more difficult for a low and – at the same time – long intensity profile. A significant influence of the binning mode is not observable.
6. CONCLUSION

The conclusions that can be drawn from this analysis concerning the practical use of a GV system as a 3-D sensor are as follows. An obvious conclusion is to keep the gate length as small as possible because this reduces the required number of range steps in the sliding gates sequence and a longer gate length offers no advantages. Due to the strong impact of the SNR on the range error, enough energy per laser pulse should be sent to the target in order to achieve a SNR greater than 4 dB. Then, in Figures 8 and 9, the range error was always below 8 cm. Averaging 2 images per range, decreases the range error below 6 cm regardless of the optics and binning mode. For instance, 35 ranges with 2 images per range and a frame rate of 20 Hz result in total number of images (and laser pulses) of 70 and a required measuring time of 3.5 s.

Without frame averaging, only 1.75 s are required. If these two numbers have to be further reduced and if the low range errors below 8 cm are not necessary, the step size of the range shifts can be increased. In this paper, only a step size of 0.75 m was investigated. Future work will be to analyze the influence of increased step sizes (1.5 m, 2.25 m,…) on the range accuracy of GV systems.

REFERENCES