High Dynamic Range Imaging using FAST-IR imagery

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ABSTRACT

One of the biggest and challenging limitations of infrared cameras in surveillance applications is the limited dynamic range. Image blooming and other artefacts may hide important details in the scene when saturation occurs. Many different techniques such as using multiple exposure times have been developed in the past to help overcome these issues. However all these techniques feature non negligible limitations.

This paper presents a new high dynamic range algorithm developed by Telops, called Optimal Enhanced High Dynamic Range Imaging (OEHDR). It is based on a pixel-wise exposure-time independent calibration as well as a pixel based frame summing with proper interleaved integration times. This technique benefits from the use of a high frame rate camera (> 20,000 fps). Description of the hardware is also included.

Keywords: high dynamic range, HDR, NEDT, infrared camera, high speed camera, MWIR, thermal imaging

1. INTRODUCTION

Typical cryogenically-cooled infrared cameras image at video or a small multiple of video frame rates (30 Hz – 120 Hz) and can achieve very good Noise Equivalent Temperature Difference (NETD) for a given scene when gains, non-uniformity corrections, and integration times are optimized for a particular background flux. However, such an approach cannot achieve excellent NETD over very large ranges of background fluxes. A combination of fast imagery readout and interleaving of integration times, combined with software for dynamic non-uniformity correction and correct radiometric calibration enables a user to achieve excellent NETD over 3 orders of background flux without the need to constantly adjust camera parameters or use mechanical devices like neutral density filters or external variable filter wheels. A new Optimal Enhanced High Dynamic Range Imaging (OEHDR) method works over an extremely large temperature range to achieve low NETD video in scenes from −5 °C to 250 °C with NETD < 35 mK and avoiding sensor saturation in video imagery. At the same time, the user can also sample fast event phenomenology for further temporal image processing applications.

Infrared cameras are capable of detecting very small temperature differences to provide daytime and nighttime imagery as well as being capable of detecting objects of interest. In the Mid-Wave Infrared band (MWIR) (generally 3 µm – 5 µm, although a user might wish to use narrower bands for specific applications), cryogenically cooled cameras based on InSb or HgCdTe focal plane arrays can often achieve effective Noise Equivalent Temperature Difference, NETD, of 20 mK. In these cameras, the electronic gains and integration times are typically set to achieve a high flux density – that is, the detectors are run at 50 % or higher well capacity. In a narrow temperature environment, such as room temperature (20 °C), it is quite easy to optimize camera performances.

In outdoor environments, the MWIR flux levels between −40 °C and 60 °C is a factor of 64. This thermal analysis does not even take into account the potentially large amounts of flux that can arise from solar reflections in the daytime which can occur in sun-loaded hot infrared environments. As a result, the excellent “room temperature” NETD often cannot be obtained outdoors without specifically altering gains and integration times on the fly as the average scene changes. While it is doubtful that one has single scenes of such temperature differences as −40 °C and 60 °C, the average MWIR fluxes can be quite large between cold sky, cool water in shade and hot desert in sun, for example.

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Even these background flux variances do not take into account the desire to often use these cameras in situations where there may be objects of interest to detect. These may include spectral gas emissions (such as oil leaks), fires, soldering irons, and ordnance which may include gunfire, rockets, mortars, and missiles [1]. For applications such as these, it is desired to not only get good quality imagery over a large range of background temperatures with and without solar reflections but also to have a high enough dynamic range for the specific MWIR emissions and ultra-high temperatures in the phenomena to be detected and analyzed.

This paper explore the ability to achieve simultaneously both low NETD and High Dynamic Range by intelligent exploitation of both summing of low integration time imagery and by using interleaved varying integration times in a new Optimal Enhanced High Dynamic Range Imaging (EHDRI) method which takes advantage of hardware and software developed by Telops for high speed imagery. For this paper, the analysis spans an effective scene temperature of 250 °C which represents 3 orders of magnitude flux difference compared with –20 °C. In this large region, both imagery and low NETD can be achieved.

2. **TELOPS FAST-IR CAMERA**

Telops Inc. of Québec, Canada, has come out with a new MWIR camera called the FAST-IR 1500. This camera contains an array of 320 × 256 InSb detectors with 30 µm pitch. The camera is shown in Figure 1.

![Figure 1. Telops FAST-IR MW camera providing 1500 full 320 × 256 frames per second.](image)

The FAST-IR camera has several unique features. It is capable of imaging 1500 full frames (320 × 256) / second. Additionally, it can be windowed down to substantially higher frame rates such as 20,000 frames/sec in a 128 × 32 or a 64 × 64 format. Even higher frame rates can be obtained with smaller formats. The camera has real-time onboard processing including non-linearity compensation, Non-Uniformity Correction (NUC), temperature compensation, and radiometric calibration. A patent-pending Telops calibration technique assures accurate NUC and calibration for any exposure time. This enables an Automatic Exposure Control (AEC) mode, which provides real-time calibrated images through continuously optimized integration time. An obvious advantage of high speed imaging is that one can use the camera to gather data on high-speed phenomena. For example, Telops has done fast imaging of muzzle flashes in the infrared as seen in Figure 2. A muzzle flash lasts only approximately 2 ms. and therefore a high-speed imager is ideal to examine the entire phenomena of primary and secondary flash phenomena [2]. Telops has done that as shown in Figure 2.

Telops FAST-IR 1500 exposure times can be varied from around 5 µs to full frame exposures and controlled by computer software. Thus, one has the capability of interleaving or alternating frames times. Thus, in addition to being useful as a fast framing instrument, it can also perform extremely High Dynamic Range (HDR) imaging. The Telops FAST-IR 1500 also comes equipped with two neutral density filters that can be switched in at 25 ms. and an option for an external 100 Hz 8-color warm filter wheel. Thus, the camera has inherently very large HDR. Nevertheless, there are situations where one might not wish to use either an external filter wheel or to have manually switchable internal neutral density filters. Therefore, the purpose of this paper is to explore the intrinsic HDR capabilities of the Telops without resorting to internal or external mechanically switched filters.
3. HIGH DYNAMIC RANGE (HDR) THROUGH AVERAGING

Infrared cameras are the perfect instruments to capture fast events exhibiting high temperature targets. Both reasons, fast events and high temperature targets, thus large photon fluxes, are dictating the use of short exposure times. Determining the exposure time to ensure proper imaging of hot targets without saturation obviously leads to very low signal levels for all the cooler parts of the scene. These lower flux levels turn into low filling of the IR detector wells, causing much larger noise levels.

The present section summarises 2 methods to overcome the limitations described in the preceding paragraph in applications where the user requests an effective lower acquisition frame rate, enabling efficient combination of images to improve dynamic range. The first basic idea is to average images with short exposure time to extend the image dynamic range and to increase it further by combining the result with an image taken with a long exposure time to ensure a good quality image of the cool background. The second algorithm fully exploit the camera capabilities by coupling HDR techniques, thus multiple exposure times, and proper frame averaging for each exposure time in order to ensure excellent quality through the complete temperature dynamic range.

3.1 Averaging short-integration time acquisitions

As mentioned earlier, the first algorithm uses averaged image acquired with short exposure time, combined with an image acquired over a long exposure time, whose value is selected to ensure a good quality image of the background. This approach enables to get good quality data for image areas also showing high temperatures, and acceptable quality for the cool background. This approach also does keep the advantage of short exposures which can be good for temporal identification of rapid events.

In order to estimate the basic capabilities of the averaging related to noise reduction, we first study how the noise performances of an acquisition made at a short exposure time are improving with increased averaging. Figure 3 shows the impact of averaging on the noise of acquisitions of a cool scene with an exposure time of 15 µs. Such scene with a low photon flux results in a small well filling of 2,8 %.
As expected, averaging a pixel value reduces its standard deviation following the ideal $1/\sqrt{N}$ behavior (i.e. improvement achieved when averaging uncorrelated samples), even over a full decade of improvement. One can thus expect the same improvement in dynamic range. However it is only partly true. Low averaging levels are bringing their benefits as seen in Figure 3 (red points), conversely the spatial uniformity does not improve as expected from the reduced temporal noise level. Increasing averaging finally reveals deterministic NUC artifacts caused by peculiar IR detector characteristics at low well filling, precluding further increase in dynamic range. The latter reduced improvement may even be impossible to reach as seen on some camera models where the manufacturer limits the availability of the data at low well filling.

An earlier experiment compared the NETD vs. the number of frames summed for different integration times. This is summarized in Figure 4. When the wells exhibited very low fillings, readout noise contrition made it such that 200 integrations of 10-µs frames was not better than a single 400-µs integration although the “effective” exposure time was 2 ms. Nevertheless, it was still possible to reduce NETD with frame summing. If it is desirable to use very rapid exposure times (for interrogation of fast events), then one can still recover a reasonably decent image (NETD < 40 mK), as indicated in Figure 4.

Figure 5 illustrates the typical gain in performances when performing averaging. Camera performances are described in terms of signal-to-noise ratio (SNR) or in terms of NEdT (or NETD equivalently). At first the normal behavior of the camera is observed, the performances are at their best for the higher temperatures since they ensure the best well filling (here 90 % is achieved at a scene temperature of 250 °C). The performances decreased as the temperature is lowered, down to 84 °C where the well filling is insufficient to ensure good NUC quality. Use of averaging thus enables to improve the SNR and the NEdT in a similar way for all scene temperatures. Operating the camera at an effective acquisition frame rate of 100 Hz leaves the room for the averaging of 16 consecutive images (full frame), thus resulting in a performances improvement of a factor 4 (magenta curves). It is finally observed in the graphs that averaging does not have the capability of extending the low well filling limit (here set at 5 %).

In order to avoid the dynamic range limitations of sole averaging, addition of HDR techniques can be used to combine the result of averaging with an image acquired with a sufficiently large exposure time to get good well filling for the scene cool background. Appropriate selection of the latter exposure time enables a good image quality for the cool background, but the user has still to determine which maximum temperature this single acquisition it is supporting, and which noise level will be observed. Moreover if the temperature difference between the cool background and the hot targets is large, the data quality in the intermediate temperature zone may still be poor. This is due to the fact that, for such mid-range temperatures, the single acquisition at large exposure time may be saturated, while the images acquired with the short exposure time still exhibit very low well filling.
Figure 4: NETD vs. number of frames summed ranging from 400 $\mu$s exposure times (bottom curve) to 10 $\mu$s exposure times (top curve) showing reduction of NETD as more frames get summed up.

Figure 5. Performances of data averaging with a maximum scene temperature (blackbody) of 250 °C. The Exposure Time is set to $ET = 5.1 \mu$s. Upper graph shows signal-to-noise ratio, while the lower graph presents the NEdT (or NETD equivalently). The variable $K$ denotes the number of consecutive images that are averaged together.
3.2 Optimum Enhanced HDR Imaging (EHDRi)

Considering a given effective acquisition frame rate, thus a given amount of time available, what is the best combination of images that will lead to the largest dynamic range? So how can HDR techniques, thus multiple exposure times, and frame averaging techniques be amalgamated to get the most over a limited observation time? Having this question in mind we developed a new algorithm to optimally combine images acquired at distinct interleaved exposure times, each using dedicated averaging, under a uniform performances constraint.

Before going further into the method, let first look at a typical graph showing the performances of a camera with operating with a given exposure time (5.1 µs) and averaging a certain number of images (\(K = 4\)) (see Figure 6). To characterize any specific combination of exposure time and averaging, a set of 4 particular scene temperatures is used:

- \(T_l\) represents the scene temperature providing the lowest allowed well filling, so the minimum scene temperature to ensure good NUC quality;
- \(T_p\) represents the minimum scene temperature ensuring a given level of performances (stated in terms of maximum NEdT or minimum SNR); this temperature may not exist if the desired performances level is not reached for any temperature in the possible range (from \(T_l\) to \(T_h\));
- \(T_n\) represents the scene temperature providing the nominal well filling, thus the preferred operating point;
- \(T_h\) represents the scene temperature providing the highest allowed well filling, avoiding saturation.

Figure 6. Definition of characteristic scene temperatures illustrated on a typical NEdT plot (e.g. averaging of 4 images taken at 5.1 µs). “Low” represents the scene temperature providing the minimum allowed well filling. “Performances” indicates the minimum scene temperature meeting the noise constraint. “Nominal” stands for the scene temperature corresponding to the nominal well filling, e.g. that corresponding to the normal maximum operating point. Finally “High” finally designates the scene temperature at maximum well filling.

As mentioned in a preceding paragraph, we developed an algorithm to determine the best combination of averaging and multiple exposure times in order to ensure a given level of performances over the largest dynamic range. Such technique is also used with visible images [3]. In order to constrain the performances, we decided to use either a minimum SNR level or a maximum NEdT level. We use the latter as an example to illustrate the method throughout the current section of the paper. Figure 7 shows the scene temperature limits to ensure meeting the constraint of an NEdT lower than 35 mK.

The way Figure 7 has to be interpreted is simple. For a given exposure time, let say 100 µs, nominal well filling (dashed line) is achieved with a scene temperature of 80 °C. Without any averaging, the minimum allowed well filling (blue line) is reached when the scene temperature is 55 °C. These mean that an operating range of scene temperatures between 55 °C and 80 °C, ensuring NEdT values lower than 35 mK, is achieved without averaging. However averaging 3 images (red line) ensures an enlarged operating range of 25 °C up to 80 °C, under the very same NEdT constraint. So for any combination of frame summing and exposure time the permitted scene temperature range covers the horizontal line between the limits set by the averaging (continuous line) and the dashed line (\(T_n\)). As introduced in the current paragraph, the lower end of this range does always increase as the number of averaged frames grows.
Figure 7. Limit temperature ranges permitted while meeting the NEdT constraint of a maximum value of 35 mK. Dashed line represents the nominal temperature limit \( T_n \), imposed by the nominal well filling selected by the user. The minimum temperature limit \( T_p \) is determined by the level of averaging allowed: the blue line shows the limit value without averaging, the green line gives this limit while averaging 2 frames, the red line illustrates the limit when averaging 3 images, and so on up to an averaging of 16 images.

The graph shown in Figure 7 reveals a lot of information regarding the way the camera has to be operated to ensure a given level of performances (here illustrated in terms of NEdT). Looking at the points where the performances limit without averaging (blue curve) intersects with the nominal limit (dashed curve) indicates that the performances constraint is met between scene temperatures of 15 °C (at an exposure time of 420 µs) up to 172 °C (at an exposure time of 16 µs). However at these limiting points the performances criterion is only met at the nominal well filling, leaving no room for operation at these specific exposure times under the desired constraint. The only solution to extend the scene temperature range, while preserving the performances, is thus to use frame averaging. The latter brings improvements at both ends of the temperature range, as observed when comparing the continuous blue \((K = 1)\) and green \((K = 2)\) lines (thus extending the ultimate range from 15 °C to 172 °C up to −2 °C to 268 °C).

Operation of the camera at an effective acquisition rate of 100 Hz means that an overall time interval of 10 ms is available to get the best combination of frame summing and exposure times. This time interval must then be efficiently employed by allocating the proper time to integrate the photon flux and to read all the images (here considering full frame operation, other frame sizes may be considered as well and different sets of optimum configurations can then be obtained). Under the constraint of a maximum NEdT of 35 mK and with a maximum scene temperature of 250 °C, the best combination uses 14 images acquired with 4 different exposure times as detailed at the bottom of Figure 8. It enables to extend the scene temperature range down to −5 °C, meaning that the photon flux covers 2 decades without sacrificing performances! This method developed for Telops IR cameras is called optimum EHdRI (EHdRI).

The “path” describing the optimum combination for a maximum scene temperature of 250 °C is depicted by the dotted blue line in the upper graph of Figure 8. Each horizontal segment represents the scene temperature range of the corresponding exposure time. This graph presents in a very elegant fashion the way the optimum combination does make use of the proper amount of averaging with each exposure time, as well as the number of different exposure times that are required. It is noted that the best selection of exposure times (5.1 µs, 19.6 µs, 89.1 µs and 263 µs), along their dedicated frame summing, enables to split the overall scene temperature range across optimally allocated fractions of the flux dynamic range.

The lower graph of Figure 8 illustrates the predicted NEdT for the 4 exposure times of the optimum solution (along their associated averaging conditions). This demonstrates how the NEdT constraint is met all over the full contiguous scene temperature range from −5 °C to 250 °C. Despite the inherent NEdT disadvantage of the highest temperature range (the one with the shortest exposure time), the constraint is met by employing the appropriate averaging level.
Figure 8. Upper graph shows the representation of the path followed by the optimum solution (detailed at the bottom of the figure) enabling to cover a full scene temperature range from −5 °C to 250 °C, with a maximum NEdT level of 35 mK. This is made out of a total of 14 images acquired during 9.8 ms. Lower graph depicts the NEdT achieved for the 4 exposure times (blue curve at 5.1 µs, green curve at 19.6 µs, and so on) over all possible scene temperatures, showing how the constraint is reached over all the contiguous temperature range. Optimum solution is only possible through the best combination of multiple exposure times, each benefiting from its specific averaging level.

Keeping the maximum scene temperature of 250 °C, we finally determined the best solutions for a set of different constraints. For each maximum NEdT constraint we found the lower scene temperature that can be reached, as function of the total time interval allowed (that is the inverse of the effective acquisition frame rate) to make the acquisitions (see Figure 9). The 35-mK constraint considered in the preceding paragraphs corresponds to the red line. It shows that increasing the overall speed from 100 Hz to 200 Hz reduces the available time to 5 ms, thus enabling instead a minimum scene temperature of 53 °C. A minimum scene temperature of −5 °C can still be achieved at an effective frame rate of 200 Hz, but with the lowered constraint of keeping the NEdT below 50 mK. Exploring this graph shows how the user can trade performances and acquisition speed with high level criteria that do not involve strong knowledge of hardware constraints.

The larger is the total time interval allowed for the entire acquisition; the lower is the minimum scene temperature since more time is available for best exposure times / averaging combinations. Figure 9 depicts well the compromise that the user must do: *the more he reduces the speed, the larger becomes the scene temperature dynamic range and/or the better are the noise performances*. Such figure can be produced for any frame size to accommodate higher frame rates. Telops GEHDR algorithm enables the user to better determine the way he trades acquisition speed and performances, while considering the dynamic range he needs.
4. CONCLUSIONS

Telops Inc. has made a very fast frame imager capable of full frame (320 × 256) imaging of 1500 frames per second or partial frame (64 × 64) imaging at 20,000 frames per second. Along with the high speed output, there is effective radiometric and NUC for a variety of integration times ranging from 5 µs to > 500 µs. In theory, the shortest exposure times can be summed such that one can have good NETD in cold scenes while the shorter exposures will not saturate in hot scenes with fires, gas emissions, or military ordnance. External color filter wheels and mechanical neutral density filters can be used to achieve HDR imagery but these involve mechanical changes and are inherently slower than using a variable frame rate.

A more optimal way of obtain HDR imagery over 3 orders of magnitude (e.g., from −5 °C to 250 °C with NETD < 35 mK) of background flux in the MWIR is the Optimized Enhanced High Dynamic Range Imaging – ŒHDRI technique. The ŒHDRI uses 14 frames with a set of 4 integration times varying from 5.1 µs to 263 µs. Every “image” at an effective 100 Hz frame rate is made of de-facto readout rate of 1400 Hz, which is within the full-frame readout capability. Extension to lower scene temperatures with low NETD is possible at a lower effective frame “image” rate than 100 Hz. The camera can thus have the ability to sample fast events for temporal processing of “fast events” (such as muzzle flash detection or rapid moving target indication) while presenting 100-Hz HDR “display” video in an optimal matter such that it has both sensitivity and avoids saturation. The user can benefit from this technique without the need to re-set parameters between hot and cold backgrounds or between day and night uses.

ŒHDRI algorithm results from the optimum combination of HDR and frame summing. It enables the user to better determine the way he compromises acquisition speed and performances (constraining NEdT or SNR), while ensuring the largest scene dynamic range. ŒHDRI algorithm benefits from unique patent-pending permanent Telops calibration technique ensuring accurate NUC/calibration for any exposure time. All Telops IR cameras actually enable the acquisition of images at different exposure times (up to 4) combined with frame averaging in any sequential order.

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