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Drift-insensitive dim-target detection using differential correlation

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Outline

- Motivation
- Time-averaged detection with Dark Drift
- Differential Correlation Approach
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- Conclusions

Motivation

- Extending the capability of current remote imaging systems to detect dimmer and dimmer targets is of very high interest to the community in order to expand the possible mission space.
- Conventional methods for target detection using pixellated focal-plane arrays (FPA's) require the target signal to be some multiple larger than the noise signal, typically 5 times, which can be problematic for very dim targets and/or high-noise sensor conditions.
- Therefore, the detection of dim targets with low signal-to-noise (SNR) of less than 2 is challenging and often not possible with current approaches.

Focal Plane Array Signal Detection

Photons: Mean and variance, Poisson Distribution

Photodetector layer

Photogenerated Electrons

Read-out integrated circuit layer

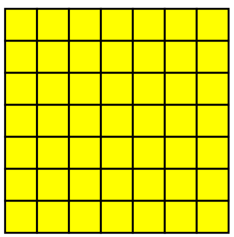
Dark Current

Amplifier Gain and Noise

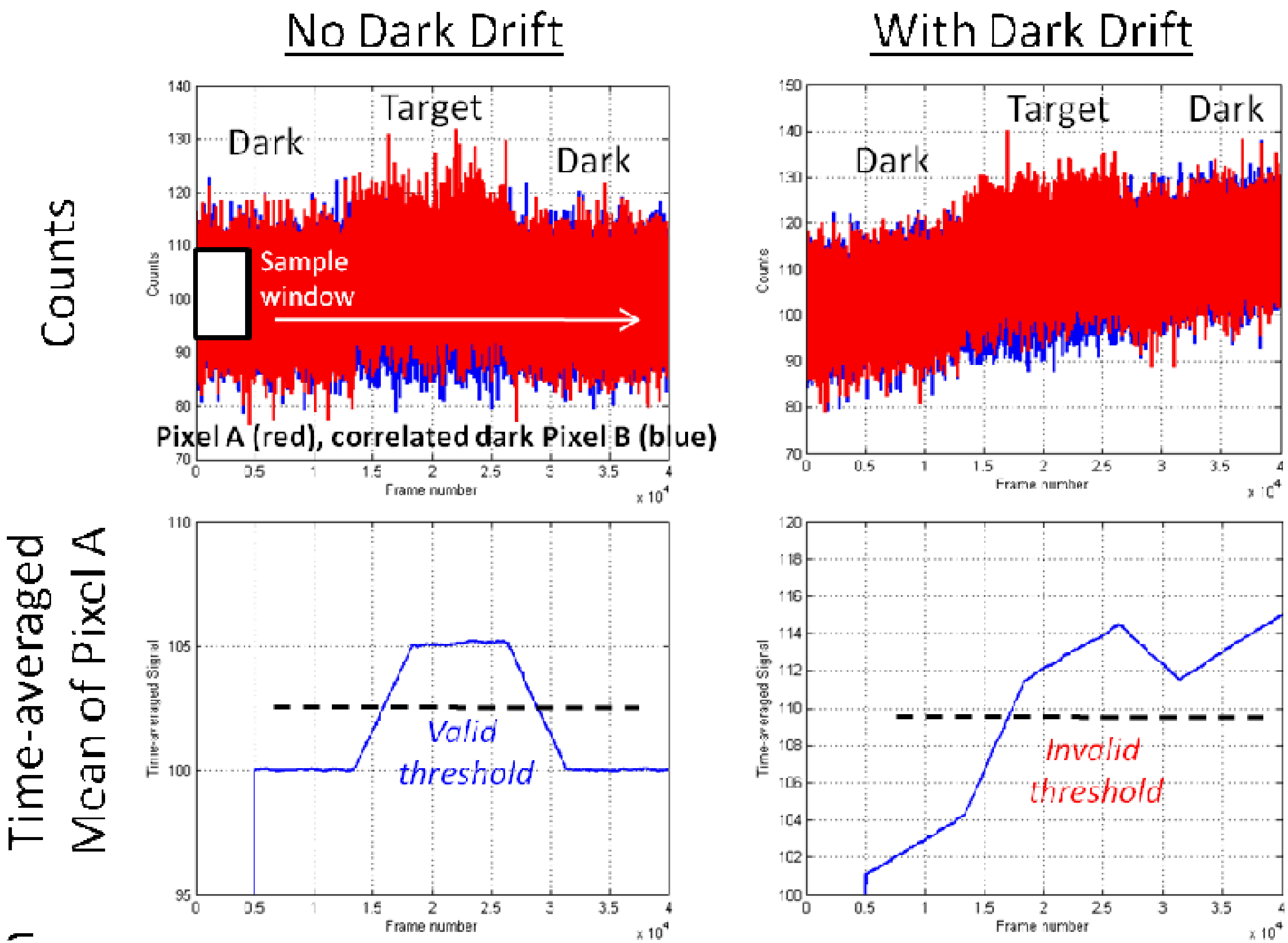
1/f noise

Output signal (V): mean and variance

2-D Focal Plane Array



Time-averaged signal detection



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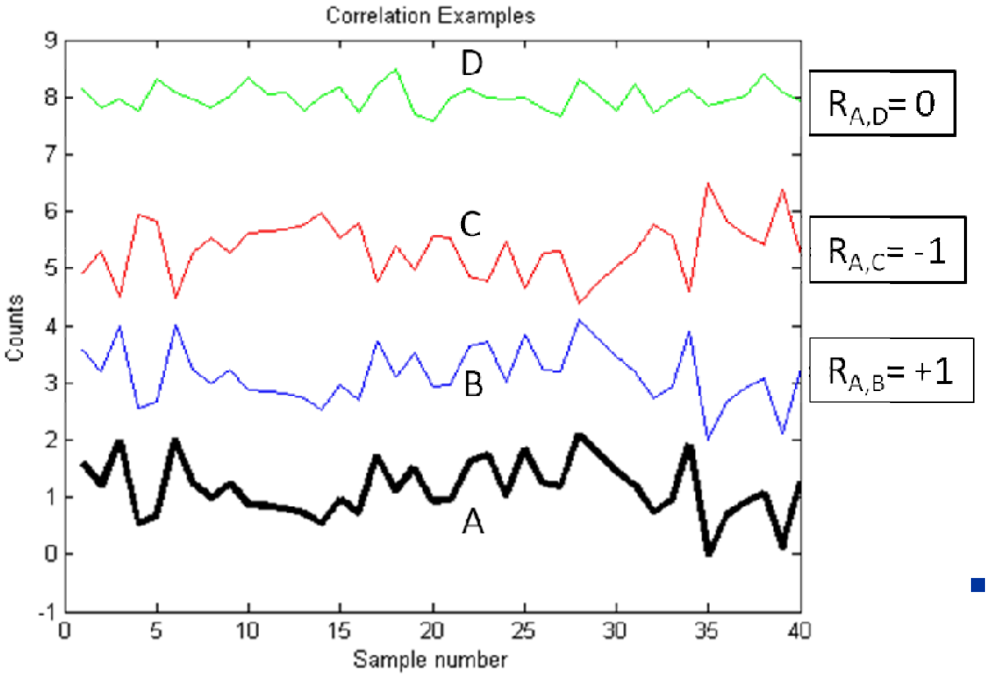
Possible sources of dark signal drift

- Temperature-dependent dark current
- Slight variations in detector bias
- Slow sensor degradation

Cross-Correlation



- **The correlation coefficient between two random variables A and B is given by:**

$$R_{A,B} = \frac{C(A,B)}{\sqrt{C(A,A)C(B,B)}}$$

where

$$C(A,B) = E[(A-\mu_A)(B-\mu_B)]$$

where E[] is the expected value.

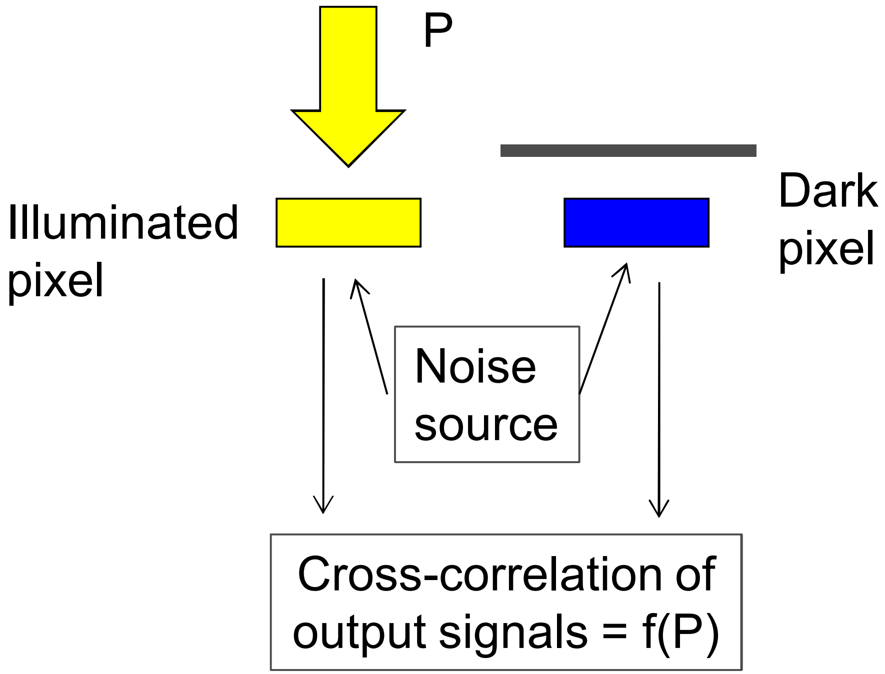
- **For perfectly correlated random variables A and B, the correlation coefficient $R_{A,B}$ = 1.**
- **For perfectly anticorrelated random variables A and C, $R_{A,C}$ = -1.**
- **For uncorrelated random variables A and D, $R_{A,D}$ = 0.**

Correlation for weak-signal detection

- **Cross-Correlation methods have been used for detection of weak signals in many areas such as:**
  - Multipath wireless communications
  - Remote imaging for detecting dim targets in the presence of high background or clutter

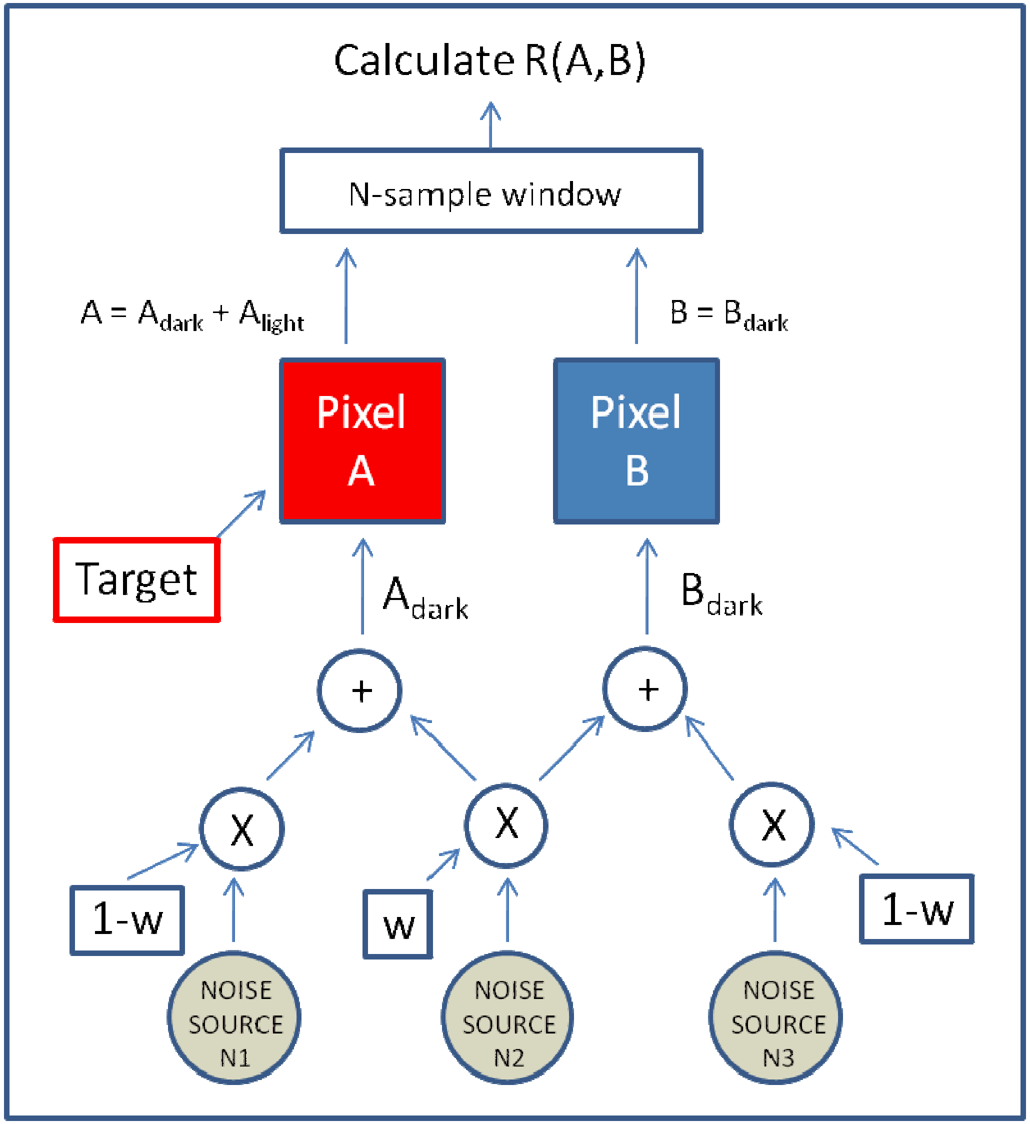
- **These approaches are typically based on detecting correlation enhancement between signals.**

Differential Correlation Approach



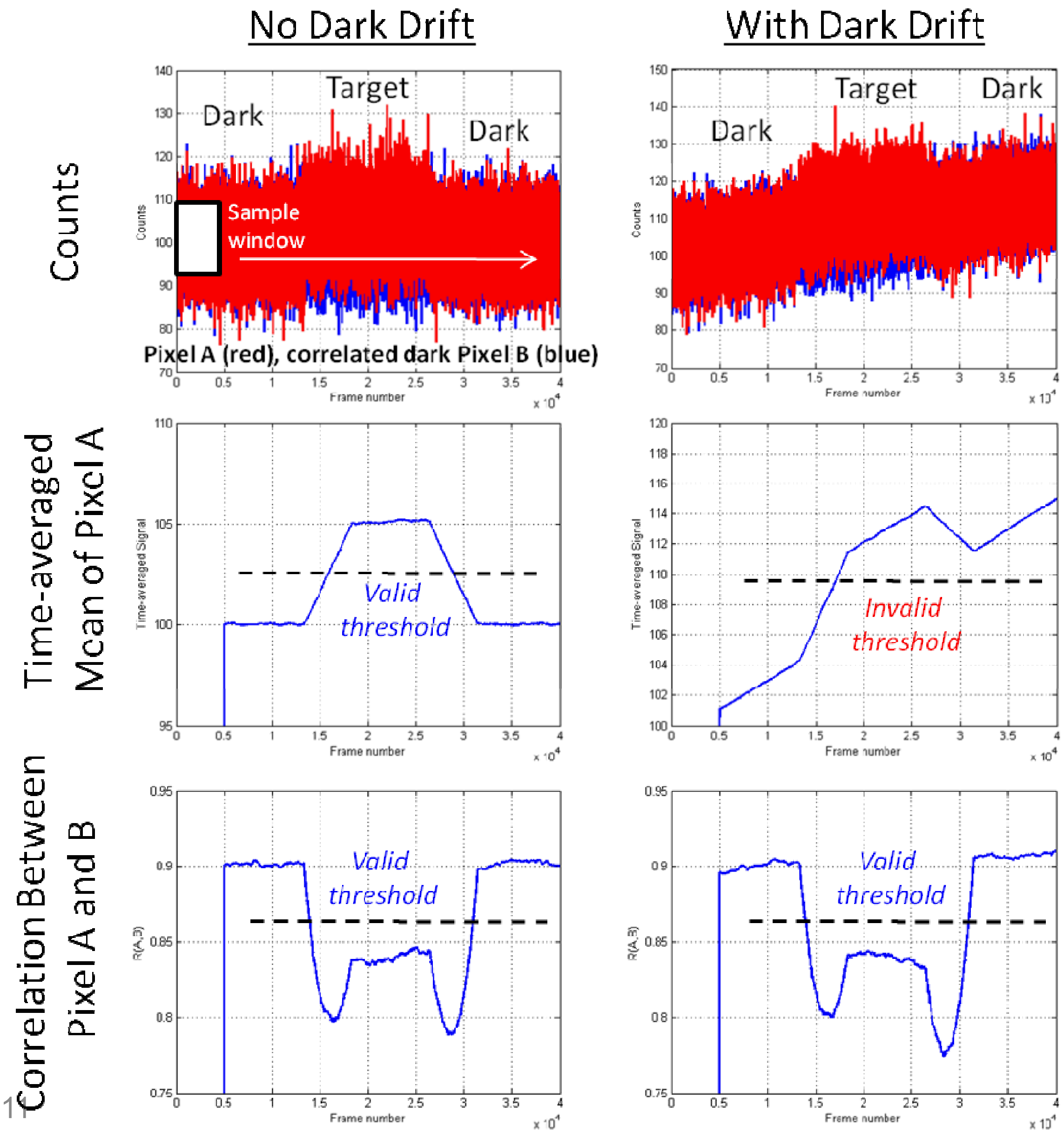
- We propose to investigate a fundamentally different detection algorithm approach based on differential correlation detection where the measured correlation decreases rather than increases with signal.
- The change in the temporal correlation of the output signals between an illuminated pixel and a dark reference pixel is measured in real time over some number of samples and may enable more sensitive detection of dim targets whose signal amplitudes are on the order of the noise levels of the sensor.
- Here, a preliminary investigation of the idea is presented.

Simulation Approach



- **In these simulations, the process for defining the correlation between pixel A and B and calculating R(A,B).**
- **Three independent random variable noise sources N1, N2 and N3 are defined. Pixel A and B share N2 with a weighting factor w which determines the strength of the correlation under dark conditions.**
- **Pixel A additionally includes target signal contributions where a Poisson noise distribution is assumed.**
- **The correlation coefficient R(A,B) is then calculated over an N-sample window.**

Simulation Results



- Simulated example of differential correlation detection compared with conventional detection
- A small positive linear increase is added to the signal to simulate dark drift
- Calculate the correlation coefficient over a 5000-sample window between Pixel A and B and call it R(A,B). Under dark conditions, R(A,B) = 0.9, indicating strong positive correlation. When the target appears, the additional target signal contribution to pixel A is uncorrelated to the dark signal which then reduces R(A,B) while the target is present
- Insensitive to dark drift

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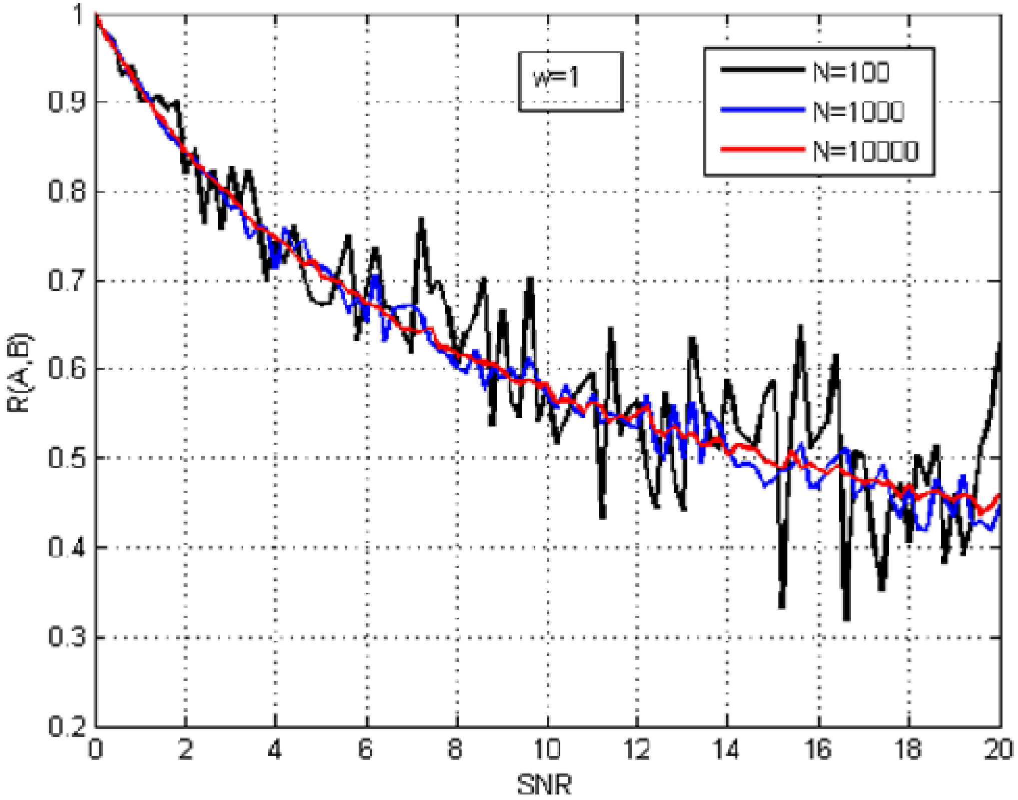
Dependence on Number of Samples



- To understand the impact of the number of samples used for the R(A,B) calculation, R(A,B) was calculated as a function of target signal-to-noise ratio for w = 1 and N=100, 1000 and 10000. In all cases, R(A,B) starts at 1 under dark conditions and decreases in an exponential manner with increasing target SNR.

- As the number of samples N increases, the variability of R(A,B) as a function of SNR decreases which is important if radiometry is to estimated using this method.

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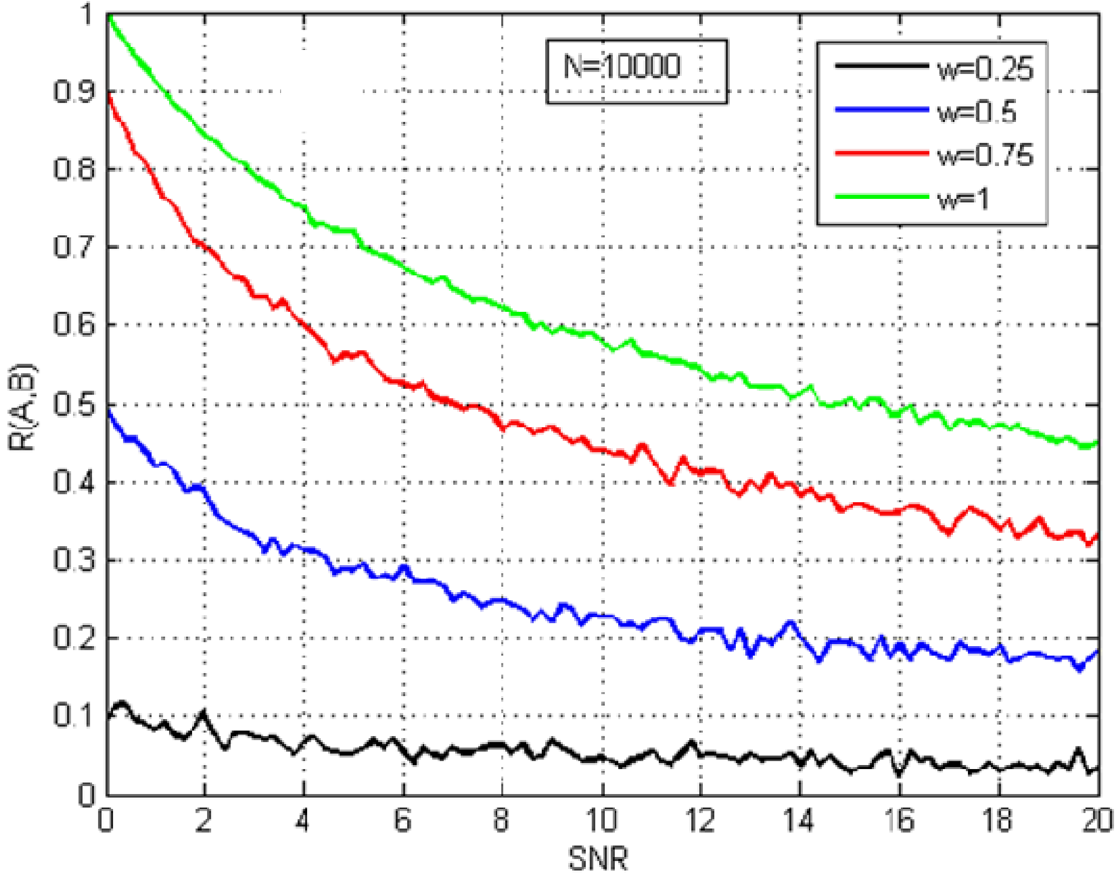
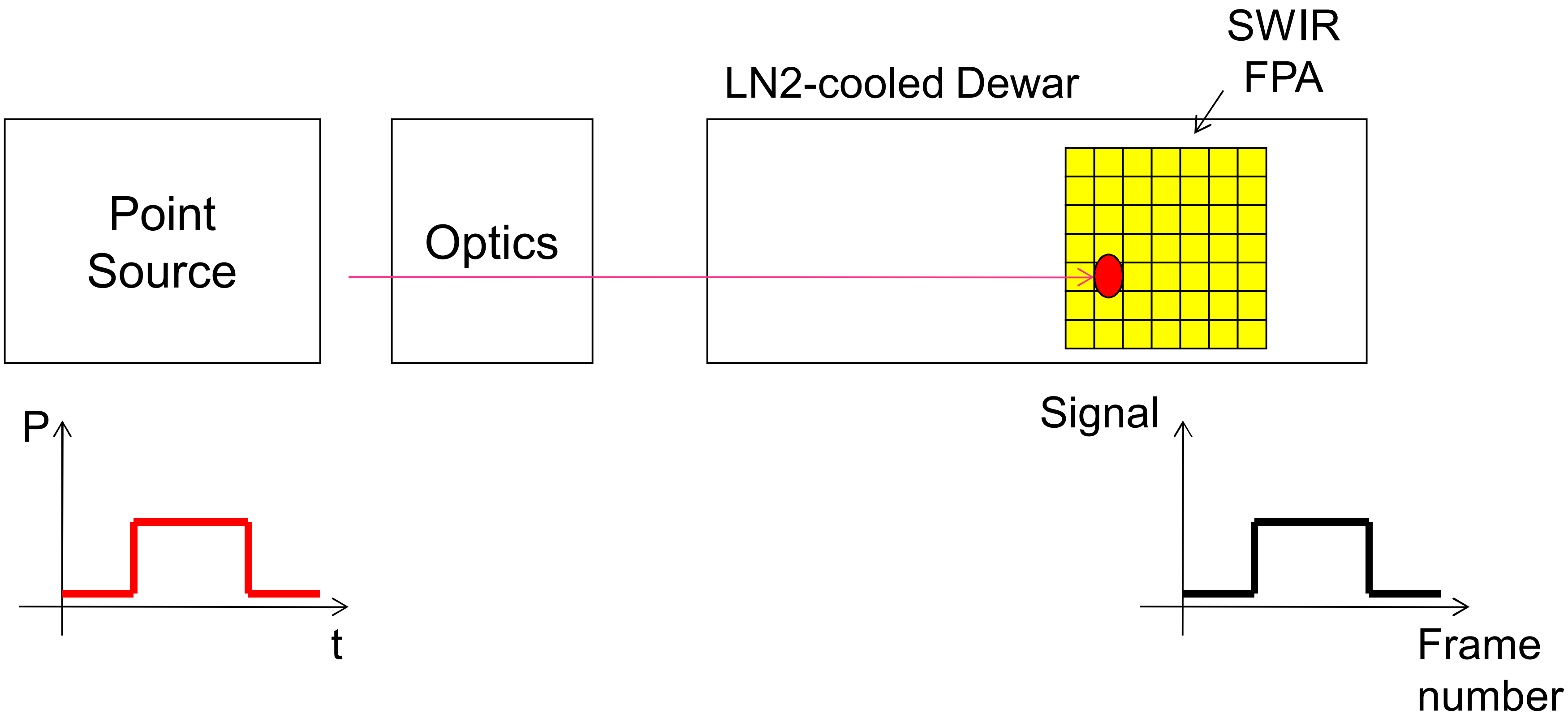
Dependence on Correlation Strength



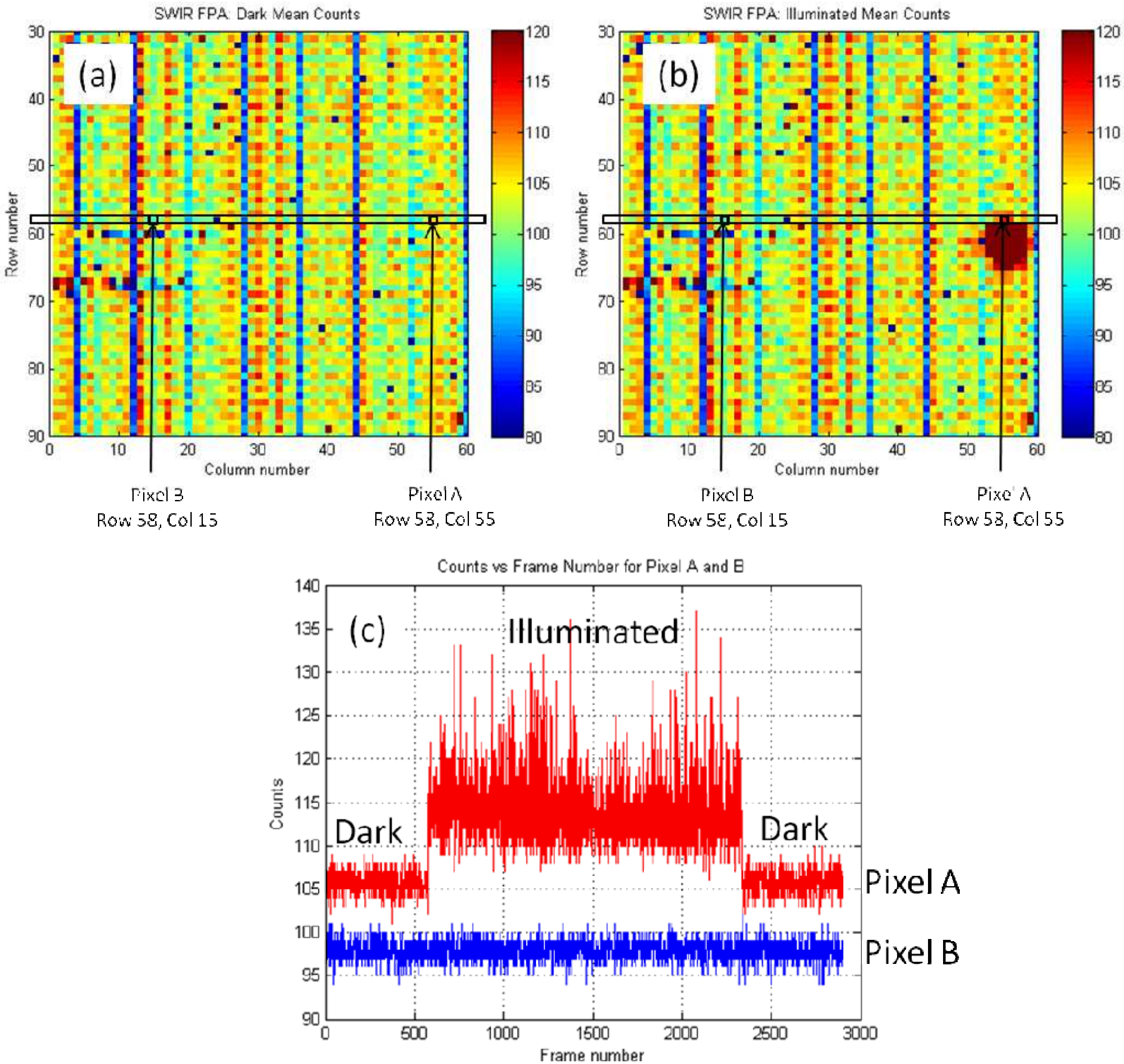
- **The dependence on the weighting factor w is also important. For N=10000 and w = 0.25, 0.5, 0.75 and 1. We can see that in terms of achieving higher dynamic range in R(A,B) vs SNR and reducing variability in R(A,B), higher w values are preferred.**

Experimental Setup for System Data



- **System data from tests with a cooled SWIR 2-D FPA illuminated with a point source is used to demonstrate the differential correlation method**

Demonstration from System Data



- In these system tests, a light spot illuminated the FPA with dark conditions existing before and after.
- A 60x60 pixel area of the FPA during dark conditions and (b) during the light spot illumination on the right side of this area.
- The dark counts vary from 80 to 120 counts.
- We define an illuminated Pixel A (row 58, column 55) and dark Pixel B (row 58, column 15)
- Red and blue traces show the counts for pixel A and B as a function of frame number which illustrates the dark and illuminated periods.

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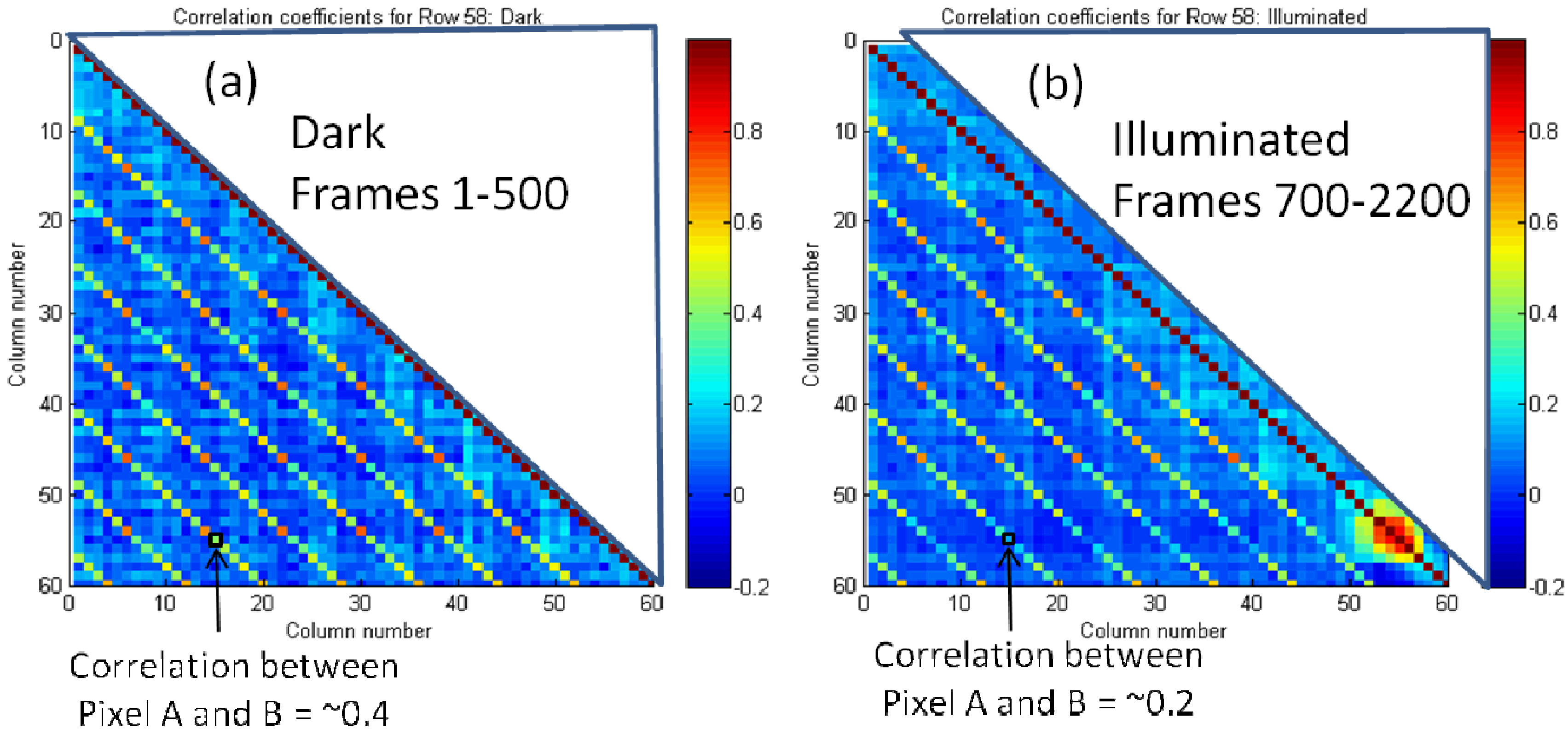
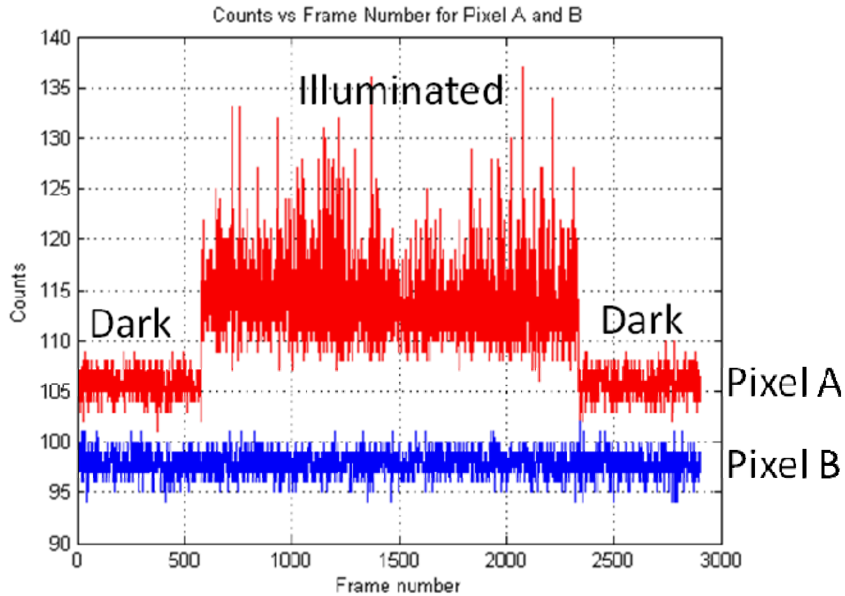
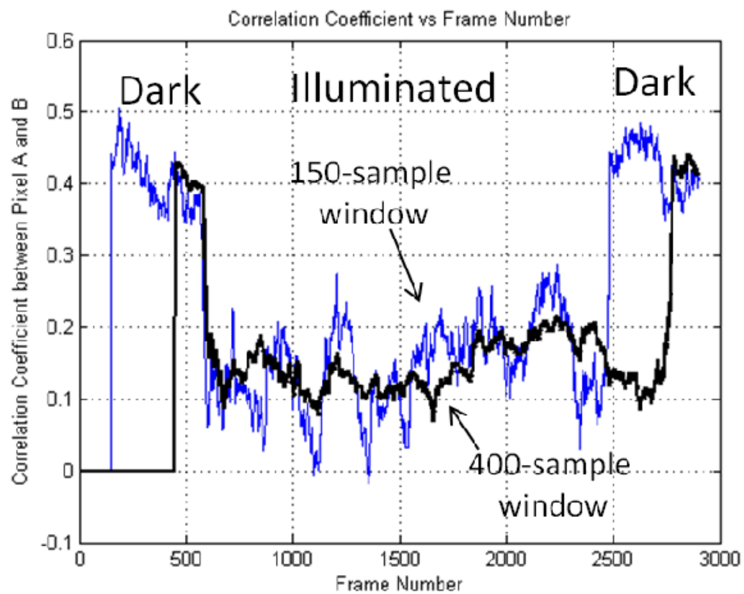
Correlated pixels on FPA



- The reason for this pixel selection was that under dark conditions, the correlation coefficients between every pixel pair along row 58 were calculated.
- While most of the pixels are not correlated to each other (value = ~0, blue color), due to periodicity in the underlying circuitry, pixels separated by integer multiples of 8 columns are correlated to each other with values in the range of 0.3 – 0.6
- The correlation coefficient for this pixel pair under dark conditions (here, defined as frames 1-500) is ~0.4. Under illuminated conditions (here, defined as frames 700-2200), the correlation coefficient for this pixel pair decreases to about 0.2 due to the presence of the uncorrelated light signal.

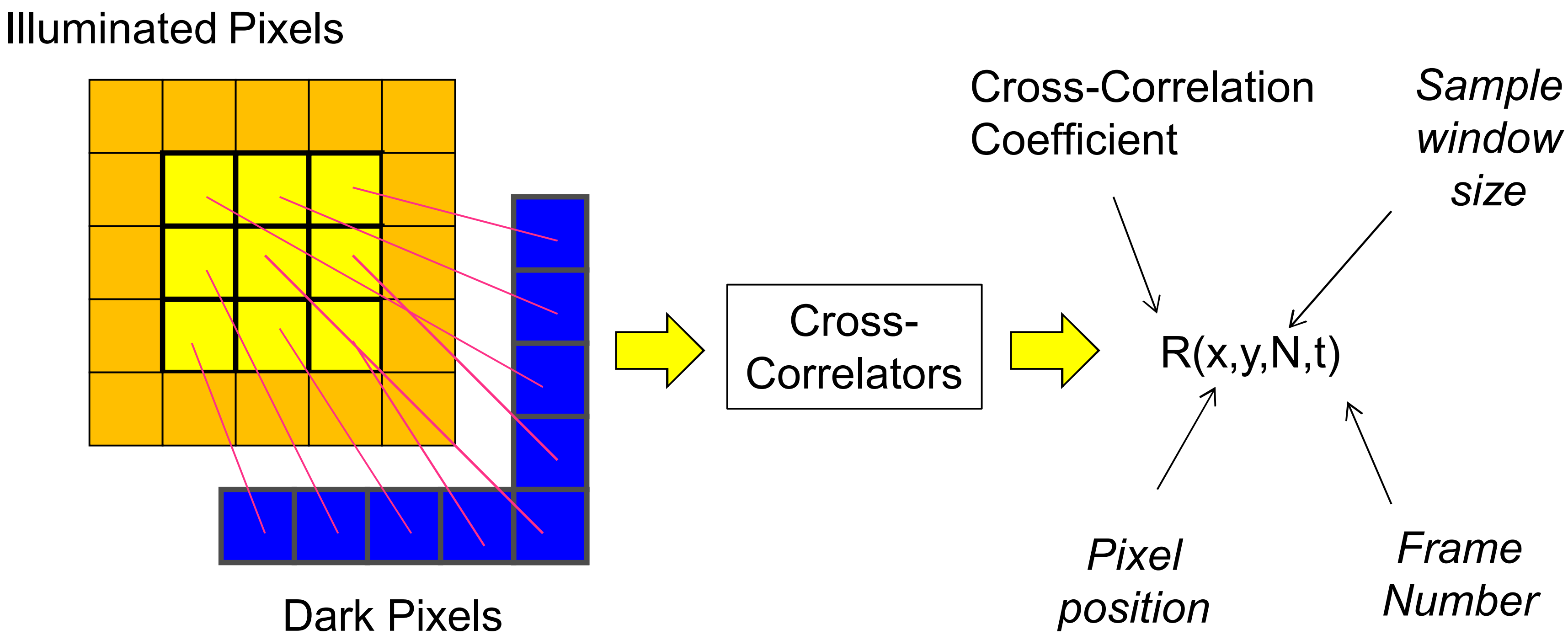
Demonstration from System Data





- The correlation coefficient more clearly as a function of frame number if we define a N-sample window which is used to calculate correlation coefficient between pixel A and B, R(A,B), as a function of frame number/
- Initially in dark conditions, R(A,B) is around 0.4 and as both windows move into the illuminated frames, the value drops to between 0 and 0.25. The higher-sample-number window exhibits less variance R(A,B) as expected.
- As both windows move back into the second dark region, R(A,B) increases back to around 0.4. We can see that if an R threshold value of 0.3 is selected, accurate detection of this signal can be achieved.
- This is by no means an ideal example, particularly since self-emission background flux is known to be significant in this wavelength band, but importantly, it demonstrates the validity of the differential correlation detection concept.

Possible implementation



Mode 1: Standard FPA
Mode 2: Small region correlation detector

Summary and Conclusions

- In summary, Differential Correlation Detection shows promise as a drift-insensitive dim-target detection approach but should be used under the following conditions.

- (1) If the goal is to detect a target signal against some background scene, the integrated background photon signal per frame must be low (a fraction of the dark noise signal) so that any detected correlation changes can be attributed to the target signal of interest.
- (2) A number of samples (100-10000) must be collected and processed for each detection event. Therefore, static target signals that are of long duration relative to the frame rate are required.
- (3) A Differential Correlation Detector should be designed such that the correlation weight between the illuminated and dark pixel be as high as possible to increase sensitivity, reduce the false detection probability and improve radiometry accuracy – preferably, 0.5 or higher.