Quantum limit of photon-counting imaging based on compressed sensing

XUE-FENG LIU,1 XU-RI YAO,1 CHAO WANG,1 XIAO-YONG GUO,1,2 AND GUANG-JIE ZHAI1,3

1Key Laboratory of Electronics and Information Technology for Space Systems, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China
2xyguo@nssc.ac.cn
3gjzhai@nssc.ac.cn

Abstract: We experimentally demonstrate that the sensitivity of photon-counting imaging can be improved by 2 orders of magnitude with the compressed sensing (CS) theory. The maximum sensitivity of CS imaging under the quantum limit, which is approximately 1 photon in each pixel during one measurement, is quantitatively obtained through theoretical derivation and proved experimentally. The influences of dark noise and shot noise on photon-counting imaging are also studied to confirm the fundamental constrains on the imaging sensitivity of different imaging methods, which can guide the effort for further enhancing the ultra-weak light imaging ability.

© 2017 Optical Society of America

OCIS codes: (110.1758) Computational imaging; (270.2500) Fluctuations, relaxations, and noise; (110.3000) Image quality assessment; (110.2970) Image detection systems.

References and links
1. W. Becker, A. Bergmann, M. A. Hink, K. Konig, K. Bemmdorf, and C. Biskup, “Fluorescence lifetime imaging by time-correlated single-photon counting,” Microsc. Res. Tech. 63, 58–66 (2004).
2. J. Skottfelt, D. M. Bramich, M. Hundertmark, U. G. Jorgensen, N. Michaelsen, P. Kjaergaard, J. Southworth, A. N. Sorensen, M. F. Andersen, and M. I. Andersen, “The two-colour EMCCD instrument for the Danish 1.54 m telescope and SONG,” Astron. Astrophys. 574, A54 (2015).
3. M. A. Albota, R. M. Heinrichs, D. G. Köcher, D. G. Fouche, B. E. Player, M. E. O’Brien, B. F. Aull, J. J. Zayhowski, J. Mooney, and B. C. Willard, “Three-dimensional imaging laser radar with a photon-counting avalanche photodiode array and microchip laser,” Appl. Opt. 41, 7671–7678 (2002).
4. H. M. Qu, Y. F. Zhang, Z. J. Ji, and Q. Chen, “The performance of photon counting imaging with a Geiger mode silicon avalanche photodiode,” Laser Phys. Lett. 10, 105201 (2013).
5. A. Kirmani, D. Venkatraman, D. Shin, A. Colaco, F. N. C. Wong, J. H. Shapiro, and V. K. Goyal, “First-Photon Imaging,” Science 343, 58–61 (2014).
6. P. A. Morris, R. S. Aspden, J. E. C. Bell, R. W. Boyd, and M. J. Padgett, “Imaging with a small number of photons,” Nat. Commun. 6, 5913 (2015).
7. L. Neri, S. Tudisco, L. Lanzan, F. Musumeci, S. Privitera, A. Scordino, G. Condorelli, G. Fallica, M. Mazzillo, D. Sanfilippo, and G. Valvo, “Design and characterization of single photon avalanche diodes arrays,” Nucl. Instrum. Method A 617, 432–433 (2010).
8. D. U. Li, J. Arlt, J. Richardson, R. Walker, A. Buts, D. Stoppa, E. Charbon, and R. Henderson, “Real-time fluorescence lifetime imaging system with a 32 × 32 0.13 µm CMOS low dark-count single-photon avalanche diode array,” Opt. Express 18, 10257–10269 (2010).
9. M. F. Duarte, M. A. Davenport, D. Takhar, J. N. Laska, T. Sun, K. F. Kelly, and R. G. Baraniuk, “Single-pixel imaging via compressive sampling,” IEEE Sign. Process. Mag. 25, 83–91 (2008).
10. R. M. Willett, M. F. Duarte, M. A. Davenport, and R. G. Baraniuk, “Sparsity and structure in hyperspectral imaging,” IEEE Sign. Process. Mag. 31, 116–126 (2014).
11. G. R. Arce, D. J. Brady, L. Carin, H. Arguello, and D. S. Kittle, “Compressive coded aperture spectral imaging,” IEEE Sign. Process. Mag. 31, 105–115 (2014).
12. B. Sun, M. P. Edgar, R. Bowman, L. E. Vittert, S. Welsh, A. Bowman, and M. J. Padgett, “3D Computational Imaging with Single-Pixel Detectors,” Science 340, 844–847 (2013).
13. G. A. Howland, P. B. Dixon, and J. C. Howell, “Photon-counting compressive sensing laser radar for 3D imaging,” Appl. Opt. 50, 5917–5920 (2011).
14. C. Q. Zhao, W. L. Gong, M. L. Chen, E. R. Li, H. Wang, W. D. Xu, and S. S. Han, “Ghost imaging lidar via sparsity constraints,” Appl. Phys. Lett. 101, 141123 (2012).
1. Introduction

Sensitivity is a basic performance characteristic of optical imaging systems. In biological and astronomical research, high-sensitivity imaging is often required to realize low-concentration component detection or distant star observation [1, 2]. To realize high-sensitivity imaging, the Geiger-mode avalanche photodiode (APD), which has the ability of single-photon detection, is widely used to perform photon-counting imaging [3, 4], and many new imaging schemes based on single-photon detection have been developed to improve imaging sensitivity [5, 6]. However, at present, the resolution of APD arrays is relatively low, the highest being only 32 \times 32 pixels for commercial products; this limitation greatly restricts the practical applications of photon-counting imaging [7, 8]. Conventionally, it is necessary to scan with a point or small-array APD detector to obtain a high-resolution image, but this technique suffers from mechanical instability. Single-pixel imaging based on the compressed sensing (CS) theory was proposed recently, and it has attracted much attention owing to its abilities of point detection and subsampling [9–12]. Therefore, CS imaging is also widely applied in the photon-counting region and related applications to resolve the problem of poor detector resolution [13–16].

Besides the advantage of point detection, CS imaging can be greatly advantageous for imaging sensitivity. Because in each measurement of CS imaging photons from many randomly selected image pixels are focused into a single point detector, the photon number to be detected is much greater than that in point scanning detection, resulting in measurements with large signal-to-noise ratios (SNRs). Therefore, the imaging sensitivity achieved with CS imaging can be higher than that achieved with traditional scanning imaging using the same detector. In a classical imaging system, the main source of noise is the detector dark noise, while in the photon-counting region, the shot noise caused by quantized photons plays an important role in the imaging performance. The influence of various types of noise on CS-based photon-counting imaging has been theoretically discussed in some previous studies [17]. However, the SNR improvement of CS imaging has not been proved in a real experiment, and the imaging sensitivity of CS imaging under the quantum limit is still unclear in terms of quantitative accuracy.

In this study, we experimentally prove the effect of SNR improvement of CS photon-counting imaging. By studying the influences of both dark noise and shot noise, the quantum limit of sensitivity is quantitatively obtained. The remainder of this paper is organized as follows. In Section 2, we theoretically derive the quantum limit of both CS-based and traditional scanning imaging. Section 3 presents the results of photon-counting imaging experiments conducted with various strategies. Section 4 presents exhaustive simulations and discussions for the analysis of the effect of different types of noise. Conclusions are drawn in Section 5.
2. Theory

The basic principle of CS-based imaging is shown in Fig. 1. The original image of a target \( x \) is randomly modulated in space according to a matrix \( A_i \), the most easily implemented of which in an optical system is the 0-1 random matrix. This modulation randomly selects light in several pixels of the image, the total intensity of which is then measured using a point detector to obtain a measurement result \( y_i \). This process of modulation and measurement is repeated many times, and as the following equation is obtained:

\[
y = Ax,
\]

where \( y \) is a column matrix composed of the measurement results \( y_i \) and \( A \) is the measurement matrix with each row equal to unfolded \( A_i \). The CS theory mathematically proves that, even if the modulated number is less than the image pixel, which means Eq. (1) is an ill-conditioned problem, the image \( x \) can still be reconstructed with a proper optimization algorithm as long as two conditions are satisfied. The first condition is that the image should be sparsely expressed in a certain basis, which is satisfied for most practical images. The second one is that the measurement matrix must obey the restricted isometry property (RIP), which indicates that the random matrix should be composed of \( \pm 1 \) rather than \((0,1)\). Under these conditions, the error in the reconstruction can be bounded by the noise in the measurement \([18,19]\).

For CS imaging with a measurement number \( M \) and random measurement matrix composed of \( \pm 1 \), the reconstruction error is \([20]\)

\[
\|\hat{x} - x\|_2 < C_N \varepsilon,
\]

where \( \hat{x} \) is the reconstructed result, \( \|\cdots\|_2 \) denotes the 2-norm operation, and \( C_N \) is a constant. \( \varepsilon \) denotes the noise in the measurement and is defined as

\[
\varepsilon^2 = \frac{1}{M} \|\hat{y} - y\|_2^2 = \sigma_y^2,
\]

where \( \hat{y} \) is the measured intensity with noise and \( \sigma_y^2 \) denotes the variance of the measurement result. The second half of Eq. (3) is accurately true only for zero mean measurement noise, while a fixed deviation of \( y \) can be ignored without impact on the imaging application.

\[
y_1 = Ax \\
y_2 = (1 - A)x
\]

in which \( A \) is a Bernoulli matrix with elements of 0 and 1. Then, the two equations are subtracted to form a new one with measurement matrix elements of \( \pm 1 \).

\[
y_1 - y_2 = (2A - 1)x.
\]
Therefore, to realize $M$ measurements with ±1 modulation, the complementary modulations should be performed $M$ times. For a fixed imaging time $T$, the measurement time for each modulation is $\tau = T/2M$. In photon-counting imaging, the main noise source contains the dark noise of the detector and the shot noise induced by the quantized photons. If the photon flux in the nonzero pixels of the image is $P$ counts/s on average and the dark rate of APD is $P_d$ counts/s, the average photon number in each measurement is

$$y_1 = y_2 = \left( \frac{N_k P}{2} + P_d \right) \frac{T}{2M}.$$  

(6)

The variance of the measured photon numbers induced by shot noise is

$$\sigma^2_{y_1} = \sigma^2_{y_2} = \left( \frac{N_k P}{2} + P_d \right) \frac{T}{2M}.$$  

(7)

With the operation in Eq. (5), the variance of $y = y_1 - y_2$ is

$$\sigma^2_y = \left( \frac{N_k P}{2} + P_d \right) \frac{T}{2M} \cdot 2 = \left( \frac{N_k P}{2} + P_d \right) \frac{T}{M}.$$  

(8)

To calculate the SNR of the image reconstructed by the CS algorithm, we define the signal of the image as the difference value between pixels with mean grey scale and zero grey scale:

$$Signal = P \tau = \frac{PT}{2M}.$$  

(9)

The noise of the image is defined as the standard deviation between the original and reconstructed images:

$$noise = \sqrt{\frac{1}{N} \| \hat{x} - x \|^2} < \sqrt{\frac{1}{N} C_N^2 \sigma^2_y}.$$  

(10)

Then, the lower limit of SNR of CS imaging is

$$SNR_1 = \frac{signal}{noise} = \frac{1}{C_N} \sqrt{\frac{PT}{2M}} \frac{1}{\left( \frac{N_k P}{2N} + \frac{2P_d}{N} \right)}.$$  

(11)

We notice that $P_{n1} = \frac{PT}{2M}$ is the photon number of one pixel during one measurement, and $k = N_k/N$ is the sparsity of the image. As in most situations the imaging pixel $N$ will be a large number, as long as the photon flux $P$ is not too less compared to dark noise $P_d$, Eq. (11) can be simplified to

$$SNR_1 = \frac{signal}{noise} = \frac{1}{C_N} \sqrt{\frac{P_{n1}}{k}}.$$  

(12)

Therefore, for a fixed target, the SNR of CS imaging is mainly determined by the photon number of one pixel during one measurement. In CS-based photon-counting imaging, the key factor influencing the imaging SNR under the quantum limit is the photon flux during one measurement, rather than that in unit time; therefore, we can call the quantity $P_{n1}$ as the effective photon number. Considering the typical values of $C_N$ and $k$ [21], the sensitivity of photon-counting imaging based on CS expressed with effective photon number will be in the order of one photon.

For comparison, we also analyze the SNR of photon-counting imaging based on point scanning under the quantum limit. With the same imaging time $T$, the average photon numbers in the pixels with a transmissive function of 1 and 0 are

$$y_1 = (P + P_d) \frac{T}{N}, y_2 = \frac{P_d T}{N},$$  

(13)
respectively. Similar to the case of CS imaging, the variances of measurement results in the two regions are

\[ \sigma^2_{y_1} = (P + P_d) \frac{T}{N}, \sigma^2_{y_2} = P_d \frac{T}{N}. \]  

(14)

The SNR of the scanning imaging is

\[ SNR_2 = \frac{y_1 - y_2}{\sqrt{\sigma^2_y}} = \sqrt{\frac{PT}{N} \cdot \left( \frac{1}{N} + \frac{P_d}{P} \right)} = \sqrt{P_{n2} \cdot \frac{1}{k \cdot \left( 1 + \frac{1}{k} \frac{P_d}{P} \right)}}. \]  

(15)

where \( P_{n2} \) is the photon number of one pixel during one measurement similar to \( P_{n1} \), which can be considered as the effective photon number in scanning imaging.

Compared Eqs. (12) and (15), if the photon level in one pixel of the image \( P \) is similar to or less than the dark noise \( P_d \) of the detector, the term \( \frac{1}{k} \frac{P_d}{P} \) will not be negligible, and the SNR of scanning imaging will be less than that of CS imaging more and more remarkable along with decreasing photon flux. From Eq. (11), this advantage of CS imaging is brought by the detection of random modulated image instead of single image pixel, which makes a high-flux detection with average photon number be \( N_k \frac{P}{2} \) and then the term containing dark noise be negligible. Therefore, the CS theory has an important advantage in terms of the sensitivity of photon-counting imaging under ultra-low photon flux.

3. Experimental results

We establish a photon-counting imaging setup based on a digital micromirror device (DMD) and APD to investigate the quantum limit of imaging sensitivity, which is shown in Fig. 2. The DMD (Texas Instrument DLP7000) is a spatial light modulator containing 1024 × 768 micromirrors with size 13.68 μm × 13.68 μm. The rotating angles of micromirrors can be individually controlled to reflect light into different directions, realizing the intensity modulation of light. With different modulation matrices, photon-counting imaging based on CS and point scanning can be realized. As shown in Eq. (10), to obtain the imaging error accurately, the original image should be known, which is difficult in the imaging of a real object. Therefore, in our experiment, we apply the concept of an imaginary object. This means there is no real object in the light path, and the random or scanning modulation matrix is multiplied with the transmission function of an imaginary object before it is loaded on the DMD. The resulting effect is the same as the imaging of an object on the DMD. A halogen lamp is used as the light source, which directly illuminates the DMD through several diaphragms to reduce the noise caused by a light spot outside the micromirror region. As the modulation matrix contains the imaginary mask, the reflected light of DMD is equivalent to a modulated image, which is then collected by the lens and fiber collimator and transmitted to a fiber-input APD detector (PerkinElmer SPCM-AQRH-13-FC). The output of APD is then transferred to a pulse counter to obtain the photon number during each DMD measurement.

The photon-counting imaging experiments are implemented in three ways: CS with 0-1 modulation, CS with complementary modulation, and point scanning. The imaginary object is the Chinese character of “light” with 64 × 64 pixels, as shown in the bottom right of Fig. 2. The object has a binary transmission function with a transparent area of 1000 pixels. In the 0-1 modulation CS imaging, 4096 random binary matrices are used for modulation on the DMD. We do not employ the sub-sampling ability of CS to make the modulation numbers of three imaging strategies the same; thus, we guarantee that the difference in imaging quality under the quantum limit is caused only by the difference in imaging method. For complementary-modulation CS imaging, 2048 pairs of complementary binary matrices are loaded successively on the DMD so that the total sampling number remains the same with that in 0-1 modulation CS imaging.
In point-scanning imaging, we use 4096 modulation matrices with only one position-scanned pixel being “1” in each matrix.

In a real experimental system, the noise on the APD is not entirely uncorrelated with the signal from the object, as the environmental scattering of the light source also contributes to the imaging noise. Therefore, it is difficult to change the signal intensity while keeping the detection noise fixed. From Eqs. (12) and (15), it can be inferred that the effective photon number $P_n$ is the most important factor influencing the imaging SNR of both CS and scanning imaging. Thus, in the experiment, we change the working frequency of DMD to adjust the photon number on APD in each measurement. In this case, the ratio of signal and noise intensities $P/P_d$ is fixed, and the imaging SNR based on CS and point scanning is only related to the effective photon number $P_n$, according to Eqs. (12) and (15). For each certain working frequency of DMD, the photon number levels on object during once measurement are the same for CS and scanning imaging, and then we can compare the performances of these imaging methodologies with the same sampling time and target intensity.

In our experiment, the noise level on the APD is approximately 2.2k photons/s, and the signal intensity in the transparent part of object is 800 photons/pixel/s on average. We adjust the DMD frequency from 5 Hz to 2k Hz at some discrete points, and therefore the effective photon number varies from 160 photons to 0.4 photons. The imaging results based on three strategies with different effective photon numbers are shown in Fig. 3. The imaging SNRs are also marked below the images based on the definition in Eqs. (9)-(11). It is obvious that, for every imaging method, the SNR will be decreased with the decrease of the effective photon number. For CS imaging in Fig. 3(a, b), the decrease is remarkable especially for low photon fluxes being approximately $P_n = 1$, while the imaging quality is still dramatically improved compared to that with point scanning, as shown in Fig. 3(c), in which the image is totally indistinguishable at this level of photon flux.

The variation trends of imaging SNRs for different strategies can be clearly observed in Fig. 4, which plots the imaging SNRs as functions of the effective photon number in each pixel. The squares, circles, and crosses are the experimental results, while the curves are mathematical fits to the experiment data. In the high-photon-flux region, the SNR of complementary CS imaging is greater than that of 0-1 modulation CS imaging as the ±1 modulation matrix in complementary CS is more coincident with the RIP criterion [22]. It is noticed that, in both complementary and 0-1 modulation CS imaging, the SNRs have upper boundaries, which means the SNRs cannot be infinitely increased even if the photon flux becomes increasingly greater. This is because the CS algorithm we used cannot reach the ideal state and the reconstruction is not absolutely accurate even if the measurement noise is zero, which restricts the continuous increase of the...
imaging quality.

The advantage of CS imaging in terms of sensitivity is more obviously reflected in the low-photon-flux region, in which the imaging SNRs are much greater than that of scanning imaging. From Eq. (15), as the photon flux in each pixel is relatively less than the dark noise of the detector in our experiment, the SNR of scanning imaging will be less than that of CS imaging mainly because of the existence of dark noise. According to Fig. 3, we choose SNR=5 as the acceptance quality of imaging results, and the demanded photon flux levels can be obtained from Fig. 4. With 0-1 modulation CS and complementary CS imaging, the effective photon number is as low as $P_n = 1.3$ and $P_n = 0.9$ photons, respectively, which can be considered as the imaging sensitivity of CS imaging under the quantum limit. For the same imaging SNR=5, scanning imaging demands an effective photon number of $P_n = 114$, which is more than 100 times that in CS imaging. This implies that the sensitivity of photon-counting imaging decided by the quantum limit can be improved by 2 orders of magnitude with the use of CS sampling.
4. Simulations and discussions

4.1. Effects of CS imaging with a grayscale-object

In the above experiment the effects of CS theory on the sensitivity of photon-counting imaging are proved with a simple two-value target, while in fact this imaging method is also applicable for grayscale-objects. Fig. 5 shows the simulated photon-counting imaging results of a microscopic image of cells with three methods, complementary CS, 0-1 modulation CS and point scanning imaging. For all simulations the dark noise in each measurement is 20 photons and the average effective photon numbers on the object vary from 1 to 100. From the imaging results in Fig. 5(b) and SNR variation trends in Fig. 5(c), the behaviors of the three schemes on imaging a grayscale-object are basically the same as imaging a two-value target. CS-based imaging has obviously enhancement in the SNR performance under ultra-low photon flux compared with scanning imaging, which proves that the imaging sensitivity for complex grayscale-objects can also be improved by CS methodology. Although the superiority of CS imaging is lessened when the photon flux becomes larger, the development of CS-based imaging is mainly aimed to detect the targets with extremely weak signals which are invisible with traditional photon-counting imaging scheme.

4.2. Analysis of fundamental constraints on photon-counting imaging sensitivity

To clarify the fundamental constraints on the sensitivity of photon-counting imaging, we quantitatively investigate the effects of different types of noise on the sensitivity of photon-counting imaging through simulations. The object in the simulation is the Chinese character of “light” with $64 \times 64$ pixels, as in the experiment. The measurement times of complementary CS, 0-1 modulation CS, and point-scanning imaging are all 4096, and the SNRs of imaging results are calculated with Eqs. (9)-(11).

First, we analyze the effect of dark noise on the sensitivity of photon-counting imaging. Two simulations are performed in which the dark noise during one measurement set as $P_d = 50$ and $P_d = 0$, respectively, and the effective photon number from each pixel in the object varies from 1 to 100. The proportion of SNRs under the two different levels of dark noise is calculated as plotted in Fig. 6, which can indicate the effect of dark noise on the imaging quality. For scanning imaging, the difference of SNRs is enormous between imaging with and without dark noise, showing that dark noise plays an important role in the imaging quality. In scanning imaging, the signal in one measurement consists of the photons from one pixel of the object, and this signal should be greater than the fluctuation of dark noise to obtain a distinguishable image. Therefore,
the dark noise is closely connected with the photon number demanded for a high-quality image in scanning imaging. However, in CS imaging, photons from approximately half the pixels in the object are collected at the detector; consequently, the signal is usually much greater than dark noise. Therefore, the level of dark noise does not have a great impact on the imaging SNR in CS imaging, and the image quality is almost unaffected by the introduction of dark noise, as shown in Fig.6. The resistance to dark noise is one of the important advantages of CS imaging over traditional scanning imaging.

Second, the influence of shot noise on the quality of photon-counting imaging is analyzed. Compared with dark noise, which has a vastly different effect, shot noise is the main factor that impacts the sensitivity of CS imaging. The shot noise in photon detection can be equivalently considered as photon fluctuations on the object pixels. This means that, in CS imaging, the image of the object varies in grey scale throughout the large number of measurements, violating

---

**Fig. 5.** Simulation results of grayscale-object photon-counting imaging. (a) The grayscale and pseudo-color images of original object. (b) Imaging results of photon-counting imaging with three methods under different effective photon numbers \( P_n \). The images are 64 × 64 pixels and the modulation numbers are all 4096. (c) Imaging SNRs as functions of \( P_n \). Squares, circles, and crosses are the simulation results; curves are mathematical fits.
the accuracy of linear equations in Eq. (1). At a low photon level, this fluctuation becomes more violent and degrades the imaging quality.

Fig. 7 shows the increasing factors of imaging SNRs in the case where no shot noise exists in the photon detection; here, the dark noise is 5 photons in one measurement. It is remarkable that, without shot noise, the quality of complementary CS imaging is dramatically improved, especially in low light level of several effective photons in each pixel. If the photon number is too low, the dark noise begins to exert an influence, and the increase of SNR is weakened to a certain extent. In 0-1 modulation CS imaging, the SNR can also be improved by 2-3 times without the existence of shot noise at a low photon level.

The dramatically impact of shot noise on complementary CS imaging reflects the lower robustness using complementary modulation compared with 0-1 CS imaging. As the measurement values corresponding to different matrices fluctuate around half of total photon numbers from the object, the absolute value of $y = y_1 - y_2$ in Eq. (5) will be lower than the photon number measured with 0-1 modulation. Meanwhile the subtraction makes the standard deviation of random measurement noise be increased by a factor of $\sqrt{2}$, leading to the decrease in the measurement SNR. This will have significant effect on the imaging quality especially if the
photon number is ultra low, as the shot noise will be relatively high compared with the absolute value of signal $y$, and makes a sharp decline in the reconstruction SNR. In 0-1 CS imaging the photon number fluctuation induced by shot noise is still obviously less than the signal intensity when $P_n$ is several photons, and therefore shot noise will not have an impact as large as in complementary CS imaging. This can also explain why in Fig. 4 the reconstructed image SNR of complementary CS trends to be similar with 0-1 modulation CS imaging under ultra-low photon flux.

For scanning imaging, at a low photon level, shot noise has little impact on the SNR as the imaging quality is already extremely low because of the dark noise. This shows that in traditional scanning photon-counting imaging, dark noise is the dominant factor deciding the imaging sensitivity.

5. Conclusion

In conclusion, we experimentally demonstrated the SNR improvement of photon-counting imaging with CS theory. The sensitivity of CS imaging is up to 1 photon on each object pixel during one measurement, which is about 2 orders higher than that of traditional scanning imaging under our experimental conditions. This approach of increasing imaging sensitivity is proved to be applicable for both two-value and grayscale targets. The quantum limits of photon-counting imaging based on different imaging strategies were studied to clarify the fundamental constrains on the imaging sensitivity. Dark noise is the main factor that influences the quality of scanning imaging, while in CS signal photon imaging, the shot noise plays the most important role in imaging SNR. To improve the sensitivity of photon-counting imaging further, the effects of shot noise should be mitigated through modification of the signal detection or image-reconstruction algorithm. We hope this work can promote the development of ultra-weak optical imaging and its related application fields such as biology and astronomy.

Funding

National Natural Science Foundation of China (61601442, 61575207, 61605218); Science and Technology Innovation Foundation of Chinese Academy of Sciences; National Major Scientific Instruments Development Project of China (2013YQ030595); National High Technology Research and Development Program of China (2013AA122902).