Avalanche Diodes as Photon-Counting Detectors in Astronomical Photometry

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ABSTRACT

Photon-counting silicon avalanche photo-diodes (APDs) offer very high quantum efficiency, and might eventually replace photocathode detectors in high-speed photometry of astronomical objects. Laboratory studies have been performed on both passively and actively quenched APDs. Peculiarities of APDs include that the dark signal may exhibit bistability, with the count rate jumping between discrete levels. Following any photon detection, the detector itself emits some light, which might be confusing under certain conditions. Deadtimes and afterpulsing properties appear favorable, but the small physical size of APDs causes challenges in optically matching them to the entrance pupils of large telescopes.

Keywords: Avalanche diodes, photon counting, photometry, detectors, astronomy

1. HIGH-SPEED ASTROPHYSICS

High-speed astrophysics explores the possible very rapid variability in phenomena such as accretion flows onto white dwarfs, neutron stars or presumed black holes. Events may occur over scales of kilometers or less, and there is no immediate hope for their spatial imaging. Insights can instead be gained through studies of their small-scale instabilities, such as plasma oscillations, magneto-hydrodynamic flares, or stimulated synchrotron radiation. These events may be observable in the time domain, as variability on milli- and microseconds, or even shorter timescales.

For such studies of quasi-periodic oscillations, flashes, pulsars, etc., it could first appear that X-rays would be the most suitable, since they originate in high-temperature regions close to the compact object. However, optical wavelengths appear superior for the *detailed* study of the *most rapid* phenomena. The number of photons per second (and especially per millisecond!) is much greater from the optical parts of the sources (observed with large telescopes), than that from their X-ray counterparts, observed with foreseen space instruments. When observed with 8-10 m class telescopes, count rates on the order of a million optical photons per second are expected for several of these objects.[1,2]

2. DETECTORS FOR SINGLE-PHOTON COUNTING

Today, CCDs and similar silicon-based imaging detectors dominate optical astronomy, thanks to their high quantum efficiency and ease of use. However, such detectors are not really optimal for measuring rapid variability, due to their relatively long read-out times. Although devices and methods for rapid readout are being developed, there seem to be fundamental tradeoffs between speed and noise. For timing individual photons on submillisecond scales, one has hitherto been limited to photocathode detectors such as photomultipliers or microchannel plates. Such detectors, however, have a limit in their achievable quantum efficiency, and in its extension toward the infrared.

2.1. Photon-counting silicon avalanche photo-diodes (APDs)

This class of detectors has the potential for quantum efficiency approaching unity (and extending into the infrared), while counting individual photons at nanosecond resolution.[3-8] Although avalanche diodes have found uses as *technical detectors*

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in, e.g., adaptive optics, they have not yet established themselves as *scientific detectors* for photometry, although their potential has been realized[9,10], and some early attempts made.[11,12]

When used as photon-counting detectors, APDs are operated in 'Geiger mode', where each detected photon triggers an electronic avalanche as a signature of photon detection. There are different means to quench the avalanche that has been triggered, preparing the detector for a new detection. The simplest is *passive quenching* where a resistor, *R*, is placed in series with the diode. The time of recovery (dead time) of the *RC*-circuit is set by the time it takes to recharge the detector capacitance *C*. This solution is simple, but the recovery time may be as long as 1 μs.[13,14] *Active quenching* shortens the dead time through a more complicated mechanism.[15,16] Once the rise of an avalanche is detected, a certain bias voltage is immediately lowered, avoiding a complete ionization in the detector. With active quenching, dead times shorter than 50 ns can be achieved, permitting count rates up to 10 MHz or more. The quenching circuit also produces the detector output pulse, and by measuring its front slope, the photon arrival time can be accurately timed, with resolutions of 20 ps reported.[17]

2.1.1. Quantum efficiency

The wavelength sensitivity is set by the detector material, and in principle is similar to that of other silicon detectors such as CCDs. Actually, the more straight-forward electronic design may permit a marginally higher sensitivity than in detectors with elaborate charge transfers. Absolute quantum efficiencies in single-photon detection up to 76% (at λ 700 nm) have been measured.[18]

The quantum efficiency *QE* depends on the *absorption efficiency* and the *triggering probability*. The probability that a photon will be absorbed in the active area of the detector depends primarily on the material used. The triggering probability tells how likely a created photoelectron will trigger an avalanche. That depends strongly on the voltage applied, and also on the detector temperature, which therefore must be controlled to assure a constant *QE*.[19]

The type of detector structure (e.g., the thickness of different diode layers) also affects the triggering probability. A *reach-through configuration* obtains very high *QE* throughout the entire visible range. On the other hand, a *narrow depletion-layer* design may offer a better timing resolution, at the cost of a lower *QE*. The currently most promising alternative for single-photon counting appears to be the SLIK™ version[4] of the reach-through configuration, developed by EG&G (now PerkinElmer). The SLIK™ detector maintains a higher electric field throughout the entire device due to a different doping profile. This solution allows some multiplication in the entire structure instead of just within the p-n junction, resulting in a particularly high single-photon detection efficiency.

2.1.2. Sensitivity at longer wavelengths

Photon-counting avalanche diodes can be based also on germanium, gaining sensitivities into the infrared, with a cut-off at λ 1.85 μm. While the narrower band gap permits detection of less energetic photons, it also increases the dark count since it is easier to thermally excite electrons into the conduction band. Perhaps more serious is the increase of afterpulsing in these detectors, caused by the difficulty of fabricating pure germanium crystals. Afterpulsing results from carriers trapped in impurity sites, and current germanium detectors still have a high impurity density. To reduce the afterpulsing, germanium detectors are often operated with a lower reversed excess bias, which limits the *QE* by a low triggering probability on the order of 10%.[20,21]

Also InGaAsP/InP APDs are commercially available, working out to about 1.6 μm.[22] Like germanium detectors, they suffer from high dark count and strong afterpulsing. Other types of solid-state avalanche detectors extend the infrared response to 28 μm.[23]

3. LABORATORY MEASUREMENTS

3.1. Detectors used

Various detector properties were analyzed in the laboratory. Two qualitatively different silicon APD single-photon counting modules, both manufactured by EG&G (now PerkinElmer), were used: one passively quenched SPCM-100-PQ unit (serial number: 00297), and one actively quenched SLIK™ unit SPCM-161-AQ (serial. 2438).[4] Both these had been selected by the manufacturer for very low dark-count levels. The active area of the SPCM-100-PQ detector is about 200 μm across, and its peak *QE* is stated to be ≈ 43% at λ 643 nm. The SPCM-161-AQ detector has a diameter of 180 μm, while its maximum *QE* exceeds 70% at λ 630 nm.

3.2. Experimental setup

The detectors were mounted on optical benches with free ventilation in an air-conditioned laboratory environment, and illuminated by light from a stabilized halogen lamp, whose flux was adjusted by varying its supply voltage. To isolate the light source from the rest of the optical-bench setup, the light was fed to the detector through a light guide. Neutral-density and color filters were used to further modify the intensity and wavelength of the incident light. The casing temperature of the detector module was monitored to assure that it remained within the interval prescribed by the manufacturer.

3.3. Digital correlators and data handling

The output pulses from the detector modules were recorded and statistically analyzed in real time by either of two different computer-controlled digital photon correlators. One of these (Malvern Instruments K7032) was custom-built to offer particularly many modes of operation, with delay-channel resolutions down to 50 ns. Another (Malvern Instruments K7026) correlator was occasionally used, when its higher time resolution of 20 ns per channel was required.

Autocorrelations and other functions were analyzed following standard procedures.[24, 25] An ideal detector, illuminated by a stable light source (as in our setup), produces a normalized autocorrelation equal to unity for all time delays. Imperfections in the detection system will produce deviations from unity. The dead time, for example, will cause a zero value of the autocorrelation function, at delay times shorter than this dead time, followed by a rise up to unity as the detector sensitivity is restored. Afterpulsing, or some correlated secondary emission of light, will, on the other hand, contribute with an excess of correlated pulses, leading to values greater than unity.

Each measurement series, e.g., the determination of one autocorrelation function, usually lasted 600 s, and to attain sufficient statistical stability, each measurement was repeated several times, and the results averaged.

4. CHALLENGES OF AVALANCHE PHOTO-DIODES

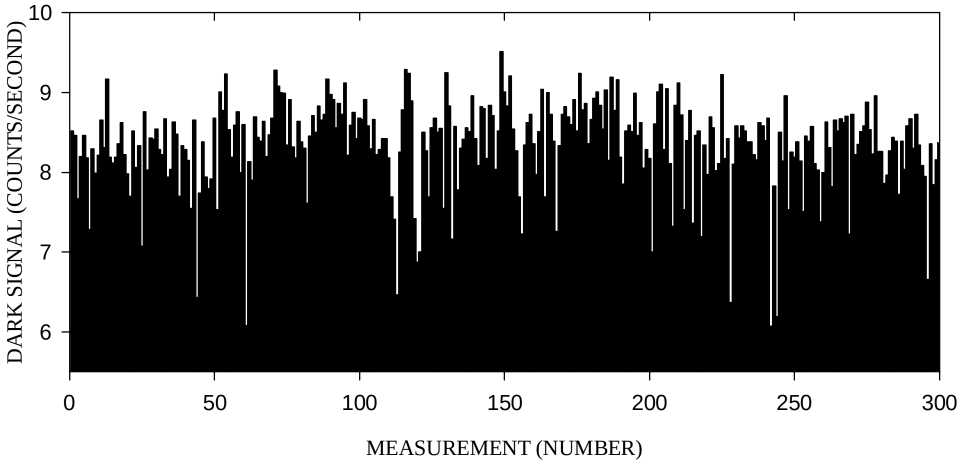
4.1. Requirements for accurate photometry

The requirements for a *scientific* detector (i.e. not just a *technical* one) are severe, in that one will be searching for possibly very small signals, to be segregated from the noise (astrophysical, atmospheric, and instrumental). Their noise properties must therefore be [very] well understood. In the past, photomultipliers have been studied in great detail, and their [non-ideal] photometric properties are well documented.[26] APDs bring a number of new, undesired, and partly not understood properties. This work is an attempt to examine some such nontrivial properties of avalanche diodes, with a view towards their ultimate application in precision photometry.

4.2. Dark-count instabilities

The mechanism producing a signal in an APD in the absence of light, is that thermal energy may excite electrons into the conduction band, triggering avalanches similar to real photon events. The main contribution comes from thermally excited bulk electrons and they follow a Poissonian distribution.[27] Since the applied voltage affects both the dark-count rate, and the quantum efficiency, an optimum can be found by minimizing the noise-equivalent power NEP.[28] At lower voltages, the NEP will increase due to a lower triggering probability (and therefore lower overall *QE*), and at higher voltages it will increase due to a higher dark count.

A more peculiar property of APDs is that the dark signal may fluctuate in a non-random manner about its average, occasionally jumping between different discrete levels. This *bistability* of the dark count may be observed as abrupt jumps between two (or perhaps more) discrete levels. This phenomenon is not well understood but may involve phenomena at semiconductor impurity sites, transiting between lower- and higher-energy states. According to the manufacturer, this effect is observed in only a certain fraction of all detectors.



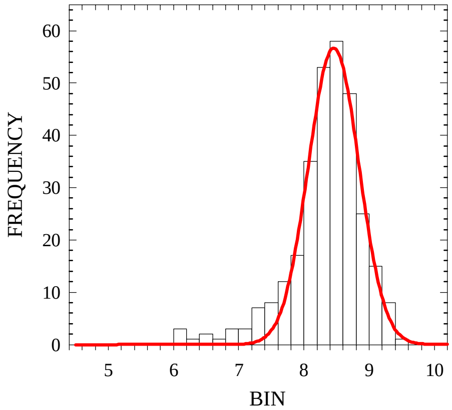


Figure 1. Dark-count measurements: A series of 300 integrations of 100 seconds each, for the actively quenched SPCM-161-AQ detector. The several points with exceptionally low dark counts appear as the shoulder outside the Gaussian fitted to the histogram (bottom). These low-count events seem to originate from a dark-count bistability, with the signal occasionally jumping to a discrete lower level.

The dark-count variation over time was studied by making many short measurements in succession. Each individual measurement lasted 100 seconds, with an interval between successive measurements (introduced by computer and correlator operations) of about 20 s.

The *actively quenched* SPCM-161-AQ shows a characteristic signature (Figure 1). This particular detector featured a very low dark-signal level: a mean of only 8.3 Hz, however varying around this average in a clearly non-Gaussian manner. The histogram in Figure 1 shows several instances with a considerably lower number of counts than the mean, resulting in the asymmetric distribution function. This is the signature of bistability, with the dark count suddenly jumping to a lower level during certain short time intervals. These statistical signatures remained quite stable at measurements during different days.

In an attempt to resolve these jumps in time, a series of 625 measurements were made of 20 seconds each, shortening the interval between measurements to 12 s. This appeared to [marginally] resolve the lower state, i.e. there is a tendency towards several successive measurements having these lower dark-count values, suggesting that the duration of the lower count-rate level may be on the order of 20 seconds. The numerical value of this lower level (assuming it is indeed *one* lower level), comes out to ≈ 4.7 Hz. A typical time separation between successive jumps seems to be around 20 minutes. According to the manufacturer, the frequency of such jumps depends on the detector temperature.

For the *passively quenched* detector, a total of 400 such measurements were made during different days. However, its data follow an essentially Gaussian distribution around the average count rate = 133 Hz, as expected for a stable dark count, with no suggestions of bistability.

4.3. Dead-time and afterpulsing

An ideal detector responds linearly to an increase in flux. However, real detectors have a finite dead time, i.e. an interval following any photon detection, when the detector has reduced or zero response. As the flux increases, a greater number of photons will arrive during the dead time and thus avoid detection, leading to a non-linear response.

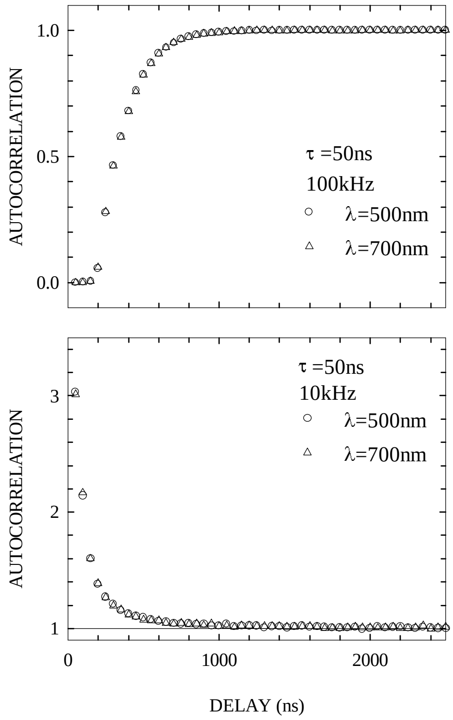


Figure 2. Dead-time and afterpulsing: The autocorrelation functions for the passively quenched detector SPCM-100-PQ (top), and the actively quenched SPCM-161-AQ (bottom). For the passive detector, the curve shows its relatively long dead time with FWHM ≈ 300 ns. For the active detector, the dead time is here unresolved, and we instead see the effects of afterpulsing as an excess number of counts in the first 15 or so channels. No difference can be seen between the curves recorded at λ 500 and λ 700 nm.

In addition to the thermally generated dark count, afterpulsing adds to the non-photon generated count rate. The phenomenon is known from photomultipliers[26], but the pulse origin is different here. Since it is almost impossible to fabricate a perfect silicon crystal, there remains a possibility that an avalanche electron will be caught in the potential well surrounding an impurity site. If that trapped electron is released by thermal excitation after a time longer than the dead-time, it can trigger a new avalanche, correlated with the real photon event. The release time depends on both the properties of the trap and the temperature of the device.[15] A higher temperature causes a faster release of trapped electrons, increasing the probability that all charges are released within the dead time (but also leading to an increase of the dark count).

Passively quenched APD: Figure 2 (top) shows the normalized autocorrelation function from the SPCM-100-PQ, at a count rate of 100 kHz. The effect of the dead time is obvious: the autocorrelation function is almost equal to zero in the first three or four 50 ns-channels. As the detector recovers, the detection probability increases gradually until reaching unity after about 1000 ns. The dead time (defined as the full-width at half-maximum, FWHM), is ≈ 300 ns for count rates up to about 100 kHz. At higher count rates (up to 1.45 MHz were measured), this autocorrelation function begins to change shape.

Actively quenched APD: The autocorrelation from the actively quenched module has a completely different appearance. The dead time is too short to be resolved in Figure 2, but was estimated to ≈ 25 ns by using the K7026 correlator with 20 ns resolution at a count rate of 100 kHz. What is instead seen in Figure 2 (bottom) is the afterpulsing, i.e. the enhanced probability of a second spurious pulse following the primary one. This is visible as the exponentially decreasing number of excess counts in the first several channels. The dependence on the count rate is shown in Figure 3.

Conceivably, the dead time or the afterpulsing could depend on the color of the incident light (since photons of different energy penetrate differently deep, and deposit different amounts of energy into the silicon). Systematic measurements were therefore made through two interference filters with peak transparencies at λ 500 nm (green) and λ 700 nm (red) but, as indicated by the points in Figure 2, no such color dependence could be identified for either detector.

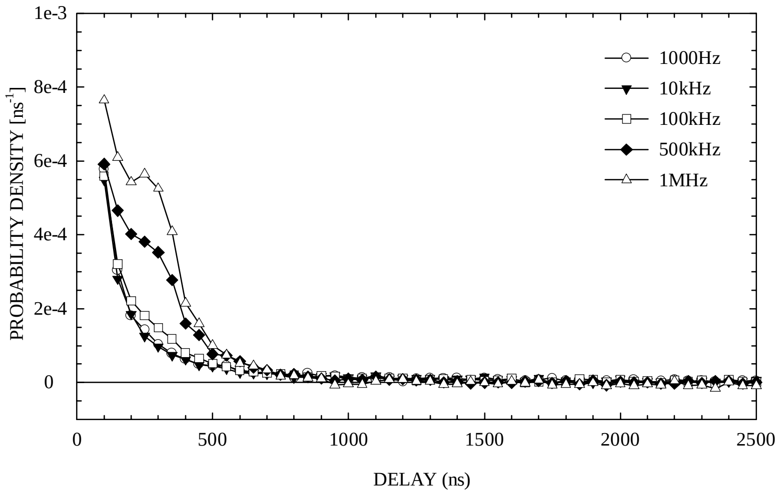


Figure 3. Afterpulsing in the actively quenched detector, as function of photon-count rate. The afterpulse probability density is shown for various count rates. Below 100 kHz, the *total* afterpulse probability for $t > 100$ ns remains constant at about 0.2%. The deformation of the function shape at higher count rates is fully reproducible.

4.4. Light emission from the detector ('*diode afterglow*')

Another 'peculiar' property of APDs operated in photon-counting mode is the emission of light from the surface of the detector. Immediately following the photon-detection avalanche, a shower of photons is *emitted from* the detector, as it recovers. For high-speed applications in large telescopes or when using long optical fibers, some such secondary light could find its way back onto the detector, causing optical 'ringing'. Such emission may also induce cross-talk between adjacent pixels when several diodes are used in a detector array. The origin of this emitted light is not well understood, but from the functional dependence of the cross-talk events in adjacent detectors, it has been concluded[28] that the emitted light does not originate from recombination of electrons and electron holes, but rather from the relaxation of single charge-carriers.

In order to detect this light emission, we used a 200 m long optical fiber-cable (consisting of two 100 m-fibers) as a delay line. The detector surface was carefully focused onto one fiber end. To generate the primary signal, the detector was illuminated from another direction. Any light subsequently emitted from the detector would then travel through the fiber and be reflected at its end, (capped by aluminum foil to enhance the reflectance). Such light would return to the detector after a delay time = $2Ln/c$, where L is the length of the fiber, n is its index of refraction and c the speed of light. For our setup, with $n \approx 1.5$, $t_{delay} \approx 2$ µs, rather longer than the detector dead-times. (Actually, the delay was experimentally determined using light from a pulsed light-emitting diode to $t_{delay} = 2.05$ µs.)

Figure 4 shows this '*diode afterglow*', as measured for the actively quenched SPCM-161-AQ unit, for count rates of 10 and 100 kHz. The peak (as expected) is seen at around 2.05 µs delay. The somewhat smaller peak at half that value corresponds to a glass-to-air reflection in the junction between the two connected fibers.

From an estimate of what fraction of the emitted light that is collected and returned to the detector, one may calculate the amount of emitted light following each avalanche. Although this estimate is quite uncertain due to, e.g., the unknown directional distribution of the emitted light, and the exact transmittance of our delay unit, it was found to be on the order of 100 emitted photons following each photon-detection avalanche.

Further tests were made to examine whether there might be any color dependences. Blue and red gelatine filters (with high transmission, and minimal effects on focusing), were placed to filter both the APD-emitted light and/or that of the primary light source. A number of measurements found no measurable dependence on any of these, thus indicating that the emitted light has a broad spectral range, and does not depend on the color of the incident light. The experimental uncertainty limits were here set by the detector having different sensitivities at different wavelengths.

Finally, we tried to measure *when* the light is emitted during the dead time of the detector. However, because of the short dead time of the SPCM-161-AQ (≈ 25 ns), and our minimum delay-time resolution of 20 ns, we were not able to resolve the emitted pulse.

Similar measurements made with the passive SPCM-100-PQ detector failed to reveal any 'afterglow' signal at all.

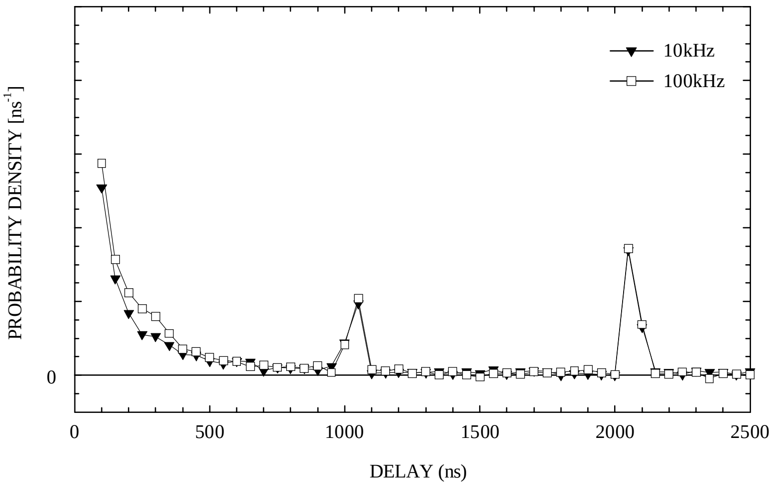


Figure 4. Diode 'afterglow' – the post-detection emission of light from an actively quenched SPCM-161-AQ detector. The relative probability density for different count rates is shown, analogous to Figure 3. By focusing the emitted light into an optical fiber and reflecting it back from the other end, the emitted light pulse was detected after a known time delay, set by the length of the fiber. The two peaks are caused by the emitted light being reflected from a fiber junction and the fiber end, respectively.

4.5. Effects on longer time-scales

Figures 2 and 3 showed the signal structure on short and very short time scales. To investigate whether any structure could be found also at longer time scales, a series of autocorrelation measurements was made, with total delay times extending up to 25 ms. The only 'peculiarity' noted was a slight positive bump at approximately 3 ms delay, for the passive detector SPCM-100-PQ. Following suspicions that this feature might perhaps originate in mechanical vibrations, several modifications were made to the experiment, exchanging mechanical, electric and electronic units, but the feature remained stable, indicating an origin from the detector module itself. However, no comparable feature was seen for the active detector module.

4.6. Junction heating

With increasing illumination, the greater number of avalanches causes the diode to heat up. Since the avalanche break-down voltage depends on the temperature, and the break-down probability depends on the voltage, an increase of the count rate will affect the *QE*. If there is not an accurate temperature control, this effect can limit the maximum count rate.[19]

During the laboratory experiments, the temperature of the external APD casings heated up already at relatively modest count rates. For the actively quenched detector, the temperature reached its allowed limit of 40°C (as specified by the manufacturer), if the count rate exceeded 100 kHz for more than about half an hour. To continuously operate this detector at higher count rates might therefore require some additional cooling.

5. VERY SMALL DETECTORS AT VERY LARGE TELESCOPES

5.1. Detector size

The highest-performance photon-counting APDs are currently available only in very small sizes (on the order of 200 μm in diameter), becoming challenging to optically interface to the entrance pupils of large telescopes. Although larger-area detectors are commercially available (up to 1 mm), this is at a price of significantly lower quantum efficiency. Also, their larger detector volume greatly increases the bulk-generated dark count. Other problems include non-uniformities in sensitivity across the detector area. Nevertheless, the development of larger-area diodes is being pursued in industry, and there is hope for significantly better performance in the foreseeable future.[29]

Optical problems arise because of the small detector area (only some percent that of a normal photomultiplier). For precision photometry, one wishes to avoid focusing the source onto the detector, where atmospheric image motion or telescope vibrations would move the focused image around, mapping the spatial inhomogeneity of detector response into a temporal flickering of the signal amplitude. Similar to other detectors, there is a need for a Fabry field lens close to the telescope focus, imaging the telescope entrance pupil onto the detector, and thus minimizing the spatial light modulation across it. However, the optical matching of the entrance pupil of a very large telescope to a very small detector may not always be practically (or even principally) possible. The challenge is further augmented by the desire to simultaneously focus "all" wavelengths (including the near infrared), in order to exploit the detector's broad spectral response.

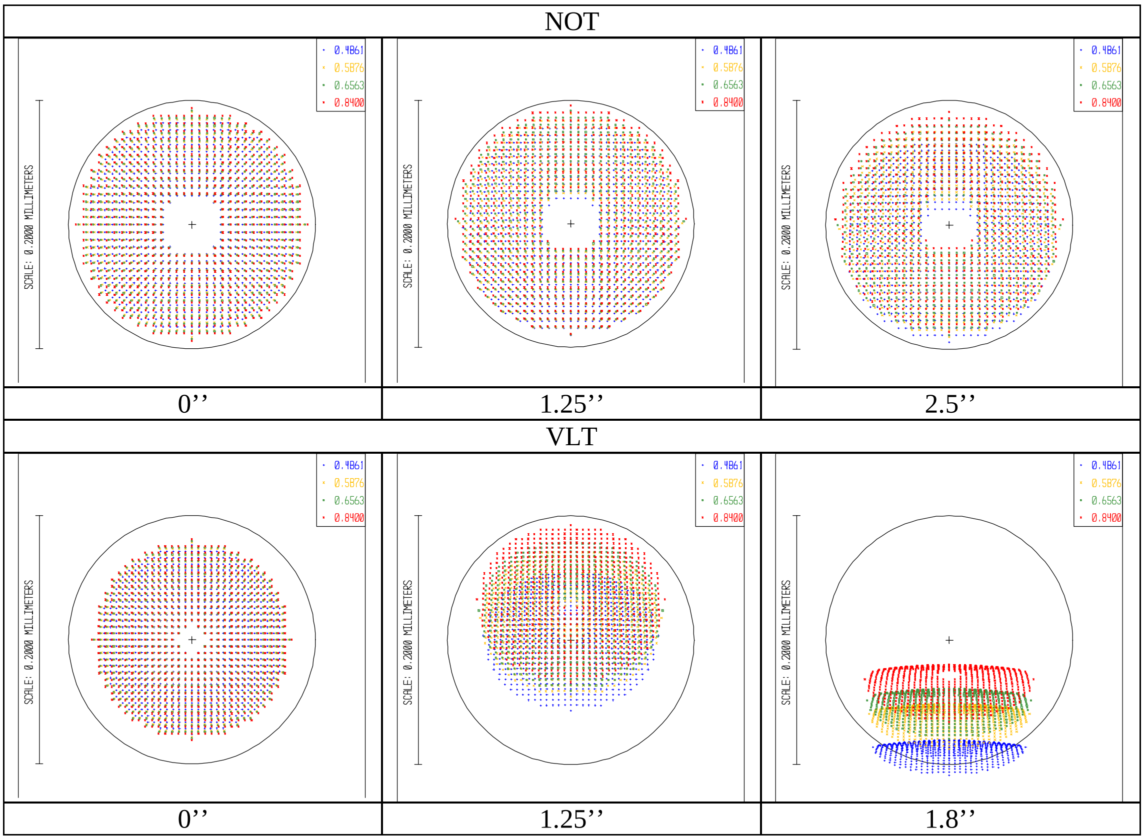


Figure 5. Example of problems in the optical interfacing of very small detectors. The image quality is shown at three field angles for a 2.56 m telescope (NOT, the Nordic Optical Telescope; top), and an 8.2 m one (VLT, ESO:s Very Large Telescope). The same type of a single plano-convex field lens was used to image the entrance pupil onto a detector of 200 μm diameter (circle). Ray-tracing in four colors (λλ 486, 588, 656, 840 nm) show the footprint for light from a star exactly in the center of the photometric aperture (left), and some arcsecond off. For large apertures, optical aberrations become severe as soon as the star becomes decentered by only one arcsecond. The field stop for VLT is limited to 1.8″ by vignetting caused by the maximum diameter of a lens with the required short focal length.

5.2. Optical design studies

To explore the possibilities and limits in the use of very small detectors, a number of optical design layouts were tested in software (*ZEMAX*), modeling telescopes in the 2.5 m class (*NOT*, Nordic Optical Telescope; ∅ 2.56 m, *f* /10.99), in the 4 m class (*WHT*, William Herschel Telescope ∅ 4.2 m, *f* /10.94)), and in the 8 m class (*VLT*, ESO:s Very Large Telescope; ∅ 8.2m, *f* /13.23). Different field-lens layouts were tested (singlets; achromatic doublets, GRADIUM™ axial gradient-index lenses, etc.), with analyses to show the sensitivity of any system to tilts, defocusing, etc.

In order to isolate the light of the target object from the sky background, a photometric aperture (field stop) in the telescope focal plane is used, of a size to match the atmospheric seeing and tracking imperfections. Probably, such an aperture cannot be much smaller than about 5 arcsec.

The conclusions from these test calculations are that it should be quite feasible to match a 200 µm APD to a 2.5 m class telescope. However, for much larger apertures, such as the *VLT,* this becomes much more difficult because of image degradation due to aberrations. Although chromatic effects can be significantly reduced by using an achromatic doublet, perhaps made of GRADIUM™ material, somewhere here appears to be a practical limit. In interfaces to large telescopes, one can clearly see how the image deforms and covers different areas of the detector as the field angle increases. Also, attention must be paid to issues such as the angle of incidence of the rays onto the detector surface, since too steep an incidence angle may cause the light to be reflected off the detector surface instead of becoming detected inside it![30]

6. CONCLUSIONS

The aim of this work has been to examine such properties of photon-counting avalanche diodes, which appear relevant for astronomical high-speed photometry. There do not appear to exist any serious obstacles that would hinder such use of APDs as photon-counting detectors. However, any user must be aware of their 'peculiarities' which are different from those of the traditional photocathode and CCD detectors. The issue of how to optically interface very small detectors to very large telescopes is not yet solved. Possibly, photometry of point sources will require adaptive image stabilization to keep the image both small in size and stable in location on a subarcsecond level. Alternatively, one could consider pupil slicing, i.e., imaging different smaller sections of the entrance pupil onto each of several detectors.

Photon-counting avalanche diodes carry exciting future prospects. Since these can be based not only on silicon, but also on, e.g., germanium, there is the prospect of high-speed photon counting also in the infrared. Efforts have been made in the industry for the development of *avalanche photodiode arrays*, apparently stimulated by needs such as detectors for *LADAR* (laser radar), recording laser-pulse illuminated scenes, where the distance to imaged objects in the field is determined by timing photon arrivals within nanoseconds. One could envision a future photon-counting photodiode array of 1024 × 1024 elements, say. If used on a large telescope to image, e.g., a globular cluster in a search for rapidly varying sources inside, photon count-rates of perhaps 10 MHz per pixel could be expected, generating a data flow of 10^7 Mb per second, or 10^{12} Mb (10^{18} bytes = 1 Eb, exabyte) during a 3-night observing run. The data handling could become rather challenging, but only with such detectors will one really begin to exploit the potential of very large telescopes for high-speed astrophysics.

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