Future directions in focal-plane signal processing for space-borne scientific imagers

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ABSTRACT

The potential of focal-plane signal processing for space-borne scientific imagers is discussed. Significant improvement in image quality and consequent scientific return may be enabled through the utilization of focal-plane signal processing techniques. The possible application of focal-plane signal processing to readout noise reduction, cosmic ray circumvention, non-uniformity correction, and throughput enhancement is described. On-focal-plane analog-to-digital (A/D) conversion and micromotion stabilization are also discussed. It is the intention of this paper to stimulate further thought and efforts in this field.

1. INTRODUCTION

Scientific imaging using focal-plane arrays lies at the heart of many of NASA's present and future missions. The orbiting great observatories such as the Hubble Space Telescope (HST), the Space Infrared Telescope Facility (SIRTF), and the Advanced X-Ray Astronomical Facility (AXAF) are critically dependent on the performance of their imaging detector arrays. In the Earth Observing System (EOS), many of the planned instruments are similarly dependent on the quality of their scientific imaging. Future planetary missions will also contain instruments for scientific imaging in the visible and infrared spectral regimes. As is generally the case in scientific imaging, each application has its own set of unique requirements that push performance needs beyond the state-of-the-art. Focal-plane signal processing refers to the integration of image acquisition and signal processing on the focal-plane [1-3]. In the extreme, this involves the physical integration of circuitry on the same chip. More loosely, it implies that the signal processing circuitry is in close proximity or hybridized to the imaging detector array (e.g. in the same cryogenic dewar).

By its nature, scientific imaging is not congruent with extensive signal processing. Users nearly universally require only an accurate count of the number of photons incident on each pixel. Unlike many DoD and autonomous vehicle imaging applications, space-borne scientific imaging does not require feature recognition or other image-based processing. Furthermore, there appears to be a reluctance in the user community to subject the imagery to lossless compression processing, and there is great concern over lossy compression processing. Thus, the object of focal-plane signal processing in a space-borne scientific imaging system is limited to improving the accuracy or throughput of the photon flux measurement, provided such processing does not significantly add to the power budget of the instrument.

The focal-plane is a logical place to improve the accuracy of the photon flux measurement since this is where the photons are transduced into electrons (and holes). The readout of the focal-plane often introduces the majority of noise into a low-background imaging system. Throughput in imaging systems is often limited by the serial readout of the imaging detector array and therefore becomes increasingly important in large array formats. Corruption of the signal by cosmic rays also occurs on the focal-plane. Parallel signal processing on the focal-plane, while constrained by available integrated circuit (IC) area, is inherently compatible with the spatially parallel nature of the imaging process. The IC area associated with each pixel can be extended though the use of 3D microelectronics [e.g. 4,5]. Furthermore, it is also important to observe that pixel size, determined by imaging optics, has generally been reduced to the 15-30 micron regime and stopped, whereas microelectronics technology continues on its exponential density curve. Thus, there is an increasing window of opportunity to apply parallel and massively parallel electronic circuitry on the focal-plane to enhance scientific performance.

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NASA missions have long technology development lead times. The technology employed in a typical mission is often frozen five or more years before the instrument is launched into space. Thus, today we must consider applications for focal-plane signal processing that are targeted to fly sometime after the turn of the millenium. These instruments are just being defined, and it is an opportune time to explore the potential of focal-plane signal processing to scientific imaging.

This paper discusses seven areas in which focal-plane signal processing might play a role in spaceborne scientific imaging systems. These areas are (1) readout electronics noise reduction, (2) cosmic ray circumvention, (3) non-uniformity correction, (4) analog-to-digital conversion, (5) photon-counting, (6) event-driven readout, and (7) micro-motion stabilization.

2. POSSIBLE ROLES FOR FOCAL-PLANE SIGNAL PROCESSING

2.1 Readout electronics noise reduction.

In images with high average intensity (or background), the predominant source of noise in the image is from fundamental photon shot noise, whose mean is proportional to the square root of the number of photons collected. For low intensity images, the signal is typically dominated by readout noise from the focal-plane electronics. Fundamental noise sources in semiconductor electronics have been under study for decades and are generally dictated by material quality. Steady progress has been made in improving material quality and thus reducing intrinsic device noise. However, many future imaging detector arrays will require readout noise in the sub-electron range so some form of advanced circuit design coupled with on-focal-plane signal processing will be required to achieve these ultra-low noise levels. Possible approaches include:

Multiple read and averaging to reduce white noise.

It is well-known that non-destructive reading and averaging of the signal from a pixel can reduce noise roughly as the square root of the number of read cycles. Perhaps the first focal-plane integration of this concept was reported by Wen in 1975 [6] to improve the low light level performance of CCD imagers. More recently, a simplified CCD structure for multiple non-destructive reads was reported by Chandler, et al. [7] in which very low read noise levels were obtained. X-Y readout-type image sensors are more amenable to multiple non-destructive read cycles. For example, Fowler and Gatley [8] have shown significant improvement in read noise by applying this technique to astronomical IR focal-plane arrays with X-Y readout.

One of the major trade-offs in utilizing this averaging approach is that the readout time of the focal-plane array is increased. In most instruments, imaging and readout "lock up" the instrument so an optimal exposure and readout period must be determined. Thus, one trades integration time (signal) for readout cycles (noise reduction). For example, consider an image that is integrated for time T_{int} and then readout (once) in time T_{read}. Assume P photoelectrons are generated within a given pixel such that the photon shot noise has an expected value of $P^{1/2}$ and that the average read noise for the imager is $<n_r^2>^{1/2}$. The signal-to-noise ratio (SNR) for the pixel is simply $P/(<n_r^2>+P)^{1/2}$. We can consider changing the imaging operation such that some of the previous integration time is reassigned to mulitple-read and averaging. The total instrument time (previously $T_{int}+T_{read}$) is $T_{total}=T_{int}'+mT_{read}$, where T_{int}' is the new integration time (less than T_{int}) and m is the number of read cycles. The new number of photoelectrons is $P'=P{\cdot}T_{int}'/T_{int}$ and the new photon shot noise is $(P')^{1/2}$. The read noise is reduced by $m^{1/2}$ and thus the new signal-to-noise ratio is $SNR'=P'/((<n_r^2>/m)+P')^{1/2}$. The optimum value of m to maximize the SNR can be readily computed by machine. For example, consider a 1024x1024 imager read out at 50,000 pixels/sec. The readout time, T_{read}, is 21 seconds. Assume the imager has a 5 electron read noise floor and that 5 photoelectrons are generated in a 100 minute instrument time consisting of exposure and single readout. Optimizing SNR suggests integration and 33 read cycles maintaining a 100 minute total instrument time and improving the SNR from unity to 1.95, nearly double the original value. However, for a 4096x4096 imager with the same readout rate (a 16x longer readout time), same number of photoelectrons, and same read noise, the optimal conditions are just 5 multiple read cycles yielding a maximum SNR of 1.29. This illustrates the impact of large array readout time and suggests that parallel, multiple readout of large arrays will be desirable.

Other approaches, suitable for X-Y readout can also be considered. For example, it is possible to non-destructively read the signal while integrating and calculate the integration slope by least-squares fit [9]. If only a portion of the image is of critical interest, that portion can be read multiple times to reduce its read noise leaving the remainder of the image at a higher read noise level. The CCD imager described above [7] also has the capability to vary the number of multiple read cycles in portions of the image. The practical utility of such an approach has yet to be demonstrated since it requires apriori knowledge of the image and thus precludes discovery.

Rebirth of frequency up-conversion.

Low frequency noise has been a major difficulty in imaging with long integration periods and buffered input circuits. This problem is particularly acute in cryogenic LWIR focal-plane arrays. One approach to reduce the noise is to convert the low frequency detector input signal into a high frequency by mixing it with a higher frequency reference signal [10] and thus get above the MOS 1/f noise knee. The drawback of the approach is that the reference signal and mixer operation may inadvertently add noise to the array through circuit coupling. However, it may be time for a reexamination of this approach in view of the advances in CMOS microelectronics and analog circuit design.

Optical readout techniques.

Advances in material engineering and optoelectronics has yielded intriguing opportunities to consider using optical techniques to read out focal-plane arrays. Optical modulators require little power to operate and free-space optical interconnects (or fiber-based interconnects) represent a low thermal load on cryogenic systems [11]. This area is ripe for exploration with application to focal-plane array readout.

Digitization within unit cell.

The increased density in microelectronics circuitry will yield an opportunity to perform analog-to-digital conversion within each unit cell of an imager. Hybrid technology will be the first to take advantage of this opportunity that can (potentially) significantly reduce read noise. Using either photon-counting techniques or more sophisticated converter circuitry, the readout of the array will be digital rather than analog, thus eliminating read noise (by folding it into the A/D conversion process). Photon-counting involves digitally integrating the photon flux by incrementing a digital counter within the unit cell each time a photon is detected. Although presently in the concept stage, it will require a low noise high gain amplifier in each unit cell to count individual photoelectrons as they are collected and a small digital counter circuit. Alternative means to achieve gain, such as amplification in a microchannel plate array, might also be utilized. A/D conversion circuitry in the unit cell might also be employed to convert an integrated charge packet into digital form. This approach would have the advantage of permitting short, high flux bursts to be accomodated that would otherwise swamp a photon-counting circuit. Using 3-D packaging techniques, such unit cell A/D conversion has already undergone initial investigation [12]. Monolithic imagers using stacked layers will also be able to have "digital pixels" without loss in fill-factor.

2.2 Cosmic Ray Circumvention

Space-borne imaging in all wavelengths without photon-energy resolution is vulnerable to high energy photon and particle-induced spurious charge signals similar to those causing single-event upsets in digital circuits. Such events degrade an image by flooding small neighborhoods of pixels with charge. Long exposures are particularly susceptible to such image "salting". This problem closely parallels the gamma radiation circumvention problem in many DoD imaging applications, and is amenable to similar solutions. Two basic approaches can be pursued:

High read rate with post-discrimination integration.

In this approach the image sensor is read out at a high rate. Each pixel is compared to its value in the previous frame. If the deviation is significant, the pixel value is changed, typically to the previous frame's value. Such non-linear filtering removes spurious high values corresponding to a cosmic ray event. Successive frames are integrated following this discrimination process. This approach increases the focal-plane power consumption due to the increased readout rate. Furthermore, read noise is significantly increased due both to the high read rate and the use of multiple frames to form one image. On-focal plane implementation of the discrimination and integration functions may ameliorate these disadvantages. Parallel readout techniques can reduce the readout rate requirements.

Gated Photon-Counting

Photon-counting might also be used to perform the circumvention function. In this mode, charge pulses from the detector (typically single electrons) are used to increment the photon count by one. A charge pulse consisting of many charges, rather than a single electron, would still be counted as one photon, thus discriminating against high energy photons and particles. A monolithic photon counting imager has not yet been demonstrated, though microchannel plate technology has achieved the sensitivity necessary for photon-counting and is amenable for integration with IC-type readout.

2.3 Non-Uniformity Correction

Infrared detector arrays, unlike their visible, silicon counterparts, are notorious for material inhomogeneities that result in detector-to-detector variations in spectral response and dark current. The readout multiplexers used with these detector arrays also introduce gain and dc offset errors into the pixel output. Thus, the output of an IR imager must typically be corrected before it becomes useful even to the human eye. Unlike DoD applications though, scientific imaging requires exact knowledge of any corrective transformation of the image since radiometric information in the image must be preserved, contraindicating emerging adaptive techniques [13]. To date, infrared images are typically uncorrected when transmitted from space and instead are corrected on ground. The imagers are calibrated periodically using on-board calibration targets. The utility for on-board non-uniformity correction presents itself when it is desirable to reduce the communications bandwidth from space. Because the uncorrected image has a large amount of high spatial frequency content, an uncorrected image is generally not amenable to compression techniques and requires a higher transmission bandwidth. For instruments such as planetary orbiting spectrometers, this represents a serious concern due to the large volume of data generated by such an instrument. On-board, off-focal plane non-uniformity correction using post-A/D DSP ICs is the most straight-forward way of achieving the desired correction, but requires significant power. On-focal plane correction using time-dependent A/D converter gain and offset is a simpler approach.

2.4 On-Focal-Plane A/D Conversion

Performing analog-to-digital conversion on the focal-plane circumvents the corruption of the signal between the focal-plane and an off-focal-plane (and outside the dewar) A/D converter. Anecdotal evidence from several sources indicates that one or two digital bits are often "lost" due to such corruptive noise. On-focal-plane A/D conversion also opens the door to on-focal-plane digital signal processing and enables digital optical readout of the focal-plane. On the other hand, on-focal-plane A/D increases focal-plane power consumption and increases focal-plane complexity. Technical approaches to integrating A/D converters on the focal-plane include using conventional CMOS-type successive approximation circuits. A second technique that allows parallel implementation with low power is to compare the pixel output value with the output from a D/A converter that is digitally ramped. The digital value input to the D/A converter is latched when the comparator switches states. Such an approach was utilized by Smetana [12]. Sigma-delta converters that utilize oversampling have been recently suggested for focal-plane integration. These converters trade circuit speed for intrinsic circuit accuracy to obtain overall accuracy. Finally, as was discussed above, photon-counting within the unit cell is an alternative way of performing digital readout to eliminate readout noise. A unit cell A/D converter might also be utilized but the lack of circuit area places severe constraints on the design approaches for the converter.

2.5 Photon-Counting

As was discussed in section 2.1 above, photon-counting involves digitally counting each photon detected in the array. Photon-counting need not be implemented within the unit cell to be useful. For example, in high energy photon detection (UV, x-ray, gamma-ray) each photon often generates many photoelectrons, in proportion to the photon energy. Determination of both the spatial location of the incident photon and its energy is critical to operation of several future instruments. This event must be read out before the next photon is incident within the pixel in order to avoid ambiguities in the photon energy. Semi-parallel approaches to improving detector array throughput could significantly enhance system throughput and performance.

2.6 Event-driven readout

In the case of sparse illumination in a large array, readout of the entire array at a high rate can result in unnecessary power dissipation and consequent shortening of mission life or reduction in payload. For example, in x-ray astrophysics, only small neighborhoods of pixels may be active in a large array. Because the enegy of each incident photon must also be determined, the effective readout rate of the array must be very high. An alternative approach is event-driven readout. In this case, a pixel is not read out unless there are photoelectrons present in the pixel. The pixel must flag a readout controller that it has collected photoelectrons and needs to be read out. In this way, only active pixels are addressed. This represents a significant departure from the way imaging systems are presently utilized, but parallels work presently under way in other high energy particle detector systems. [14]

2.7 Micro-motion stabilization

In almost all scientific imaging systems, there is a pointing stability requirement on the guidance system to insure that any residual motion is fully compensated. In planetary instruments, particularly in fly-by missions, the camera must be slightly panned to compensate for relative motion of the spacecraft. In a pushbroom-type TDI scanning array, the array must be perpendicular to the direction of motion to insure that MTF is not degraded due to residual skew angle between the array integration direction and the motion track. In all cases, it may be possible to correct residual micromotion and/or alignment accuracy electronically. For example, in a CCD array, the charge may be physically shifted to track the image motion. This would require both horizontal and vertical degrees of freedom in charge transfer. Some degree of electronic compensation may also be possible in X-Y readout arrays at the expense of read noise. In all cases, some sort of integrated fine guidance sensor would be required to track residual image motion on the focal-plane and then electronically control the relative position of the image integration.

3. SUMMARY

Approaches for applying focal-plane signal processing techniques to space-borne scientific imaging have been discussed. The major motivation for investigating these approaches is the improvement in image quality obtainable by reducing noise, corruption from cosmic rays, detector response non-uniformity, and motion smear, with a consequent positive impact on scientific return. System throughput performance might also be enhanced, particularly in the case of sparsely illuminated arrays for high energy particles if event-driven readout techniques are adopted. There appears to be much room for innovation in this area, though the user community is not presently well-informed about the potential of the technology.

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