Operational and performance comparisons between conventional and foveating large format infrared focal plane arrays

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ABSTRACT

We present a detailed comparison between the operational performance of "conventional" and "foveating" large format infrared focal plane arrays (FPAs). Foveating FPAs provide its users with a substantial advantage when compared with imaging sensors currently in use. This paper details the differences between foveating and traditional FPAs and provides objective comparisons to aid systems designers select the appropriate imaging device for their applications.

A variety of on-FPA operations are performed with foveating sensors; some of these operations require the use of a companion processor to spatially reprogram the foveal sensor. We will compare several critical sensor performance parameters including: frame rate, data bandwidth, spatial and temporal noise. In addition, operational comparisons will be made to contrast the various applications that may be best suited for the two respective imaging sensor types.

Keywords:
Variable acuity, superpixels, FPA, programmable, visible, infrared

1. INTRODUCTION

Nova Sensors has developed a novel two-dimensional imaging chip whose design is based on properties exhibited by biological retinas[1]. The VASI™ imager permits the user to program a unique spatial arrangement of "superpixels" that may be updated in real time and at the operational frame rate. In effect, any spatial configuration of pixels in the imager may be realized by programming the device to permit pixels to share their individually-collected photocharge with any or all of their neighbors. Single and multiple "foveal" configurations are possible, and these high spatial resolution regions may be "flown" around the FPA controlled by an embedded FPGA based processor. The controller processor board is also available from Nova Sensors.

A "foveal FPA" as discussed here has the property of higher spatial frequency of pixel channels near the "center of attention" (COA), with a radially-symmetric spatial frequency diminishing radially out from the COA. The device as described permits the user, through a programmed controller-processor, to define any desired spatial distribution (size and location) of pixels, and may change this distribution at the frame rate, if desired. Hence, COA focused on a potential target may be directed to move within the total field of view of the FPA in order to track the target of interest with high angular precision, without sacrificing the ability to detect other potential targets which may enter into the sensor's lower resolution periphery.

This general methodology could also be applied to the use of multispectral detector arrays. These capabilities are now possible through the use of "READIN" commands to the FPA, used to program the characteristics of

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[1] McCarley, P., M. Massie, J. Curzan, "Large format variable spatial acuity superpixel imaging: visible and infrared systems applications", SPIE Aerosense Infrared Technology and Applications XXX, Orlando, FL., 2004.

individual pixels in the array. Figure 1 demonstrates the concept of "FPA READIN Programmability", resulting in a user-defined effective distribution of pixels. Also indicated in the figure is that the readout state for each pixel may be programmed individually through the use of the READIN command.

The use of such a focal plane imager has an impact on a variety of system-level parameters such as (a) frame rate, (b) field-of-view and (c) sensor noise. This paper will discuss quantitative comparisons between two fundamental FPA types, conventional and foveating, with respect to these parameters.

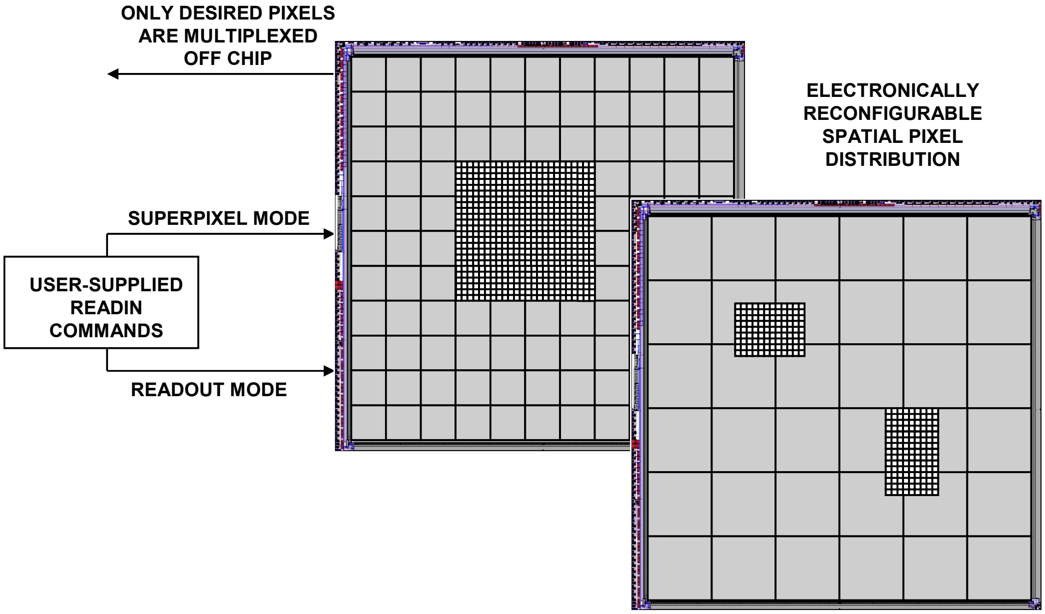


Figure 1 - User-supplied commands are "read in" to each pixel, resulting in unique superpixel and readout state attributes. Notice that ANY spatial configuration for the VASI™ is possible

2. CONVENTIONAL VS. FOVEATING FPAS

VASI™ Device Versus N:1 Pixel Dilution and Conventional Windowing

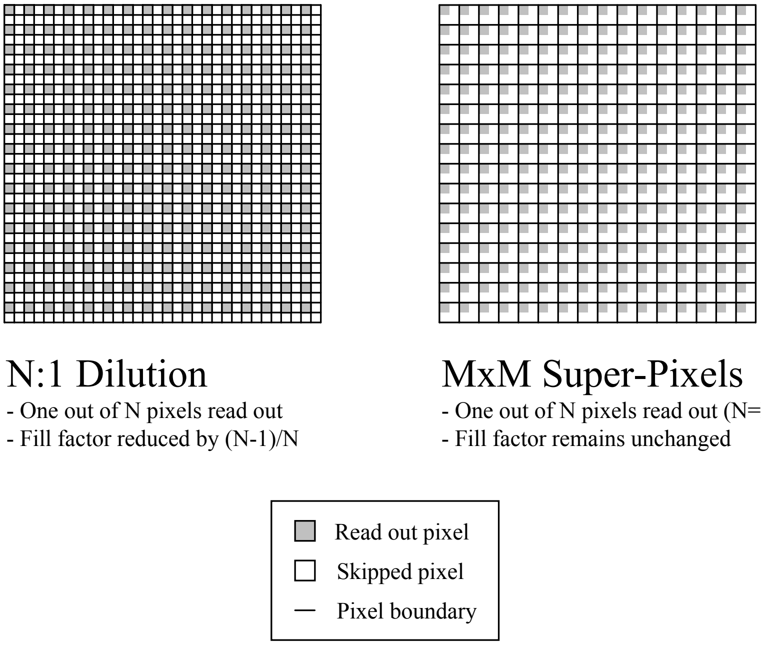
Figure 2 and Figure **3** illustrate the differences between the VASI™ readout design and conventional on-chip data reduction techniques of pixel dilution and region-of-interest (ROI) windowing. With superpixels, only one output channel is required to obtain significant improvements in frame rate while maintaining surrounding scene information. Having one analog output video channel rather than two, four, or sometimes up to 32 greatly simplifies off-chip ADC and re-vectoring electronics. Further, most windowing readouts are modal, meaning the device is set into a window mode with a fixed X,Y window location and size, which cannot be relocated or resized on a frame-to-frame basis.

The left panel of Figure 2 shows a conventional imager operating in dilution mode in which every N^{th} pixel is read out, thus reducing the total number of pixels per frame and increasing the effective frame rate. However, this technique ignores the skipped pixels, so small potential image targets may be overlooked and rendered undetectable.

In comparison, VASI™ foveating FPA uses photocurrent produced by every "native" pixel in the array and reports single values from individual superpixels. As described by the right panel of Figure 2, a similar reduction in the total number of output pixel values, when compared with conventional FPAs, may be obtained. However, essential information of the surrounding (outside the fovea) regions is produced by the foveating FPA, not so with a conventional windowing FPA.

Figure 3 illustrates the differences between how conventional and a VASI™ foveal FPAs can produce "windows" of specific regions within the total image area, thereby reducing the total number of pixel values per frame. This leads to an increase in the frame rate of the sensor. In summary, the major differences between the conventional and VASI™ foveal FPAs are:

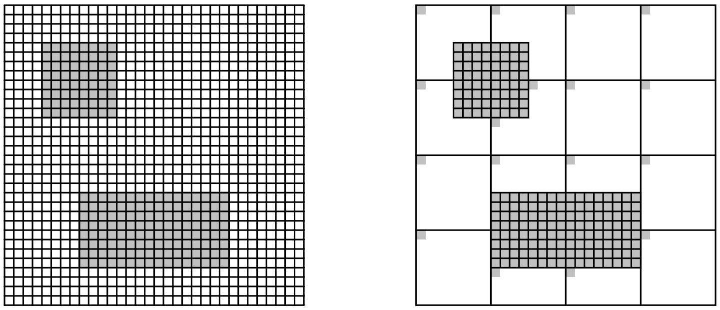
1) Scene information outside the windowed region(s). While the conventional FPAs essentially ignore the pixel values outside of the specified window regions, the foveal FPA continues to monitor the "out of window" regions using spatially larger superpixels. Hence, foveal sensors continue to observe the Total Field of View (TFOV) and trade lower spatial resolution in background regions with a corresponding increase in the sensors effective frame rate.
2) Foveal regions can be defined for any shape/size and location at the frame rate. Secondly, Nova's foveal FPAs have the capability of multiple foveas (windows) of arbitrary shape and size located anywhere in the FOV and changing at the frame rate. In contrast a conventional windowing FPA is modal and the windows are typically specified at a specific location and size within the FOV.



N:1 Dilution
- One out of N pixels read out
- Fill factor reduced by (N-1)/N

MxM Super-Pixels
- One out of N pixels read out ($N=M^2$)
- Fill factor remains unchanged

Figure 2 – Dilution modes throw away pixel data in exchange for higher frame rates to maintain total FOV (left), while a comparable superpixel configuration maintains both FOV and fill factor since all skipped pixels share photocharge with read out neighbors.



Windowing

- Sub-frame regions read out successively
- IFOV reduced to increase frame rate
- Size and position usually limited by the number of address bits
- Rectangular only

Super-Pixels

- High acuity and low acuity regions read out
- IFOV remains unchanged with increased frame rate
- Any shape and location permitted

▨	Read out pixel
☐	Skipped pixel
—	Pixel boundary

Figure 3 – Windowing modes reduce instantaneous FOV (IFOV) while increasing frame rate (left), while a comparable superpixel configuration can read out both the high-resolution ROI as well as the low resolution peripheral pixel regions with little additional clocking overhead.

Figure 4 illustrates the mechanism for summing (superpixellating) of charge between unit cells based on the switch Lxx and Uyy positions. These switches may be user-commanded every frame and hence the entire array configuration, foveal region location and size and the superpixel area and location, may vary from frame to frame. Via the configuration bits associated with each unit cell connection, new superpixel regions can be read within a frame period, allowing moving foveae, object tracking and dynamic center-of-attention (COA) control. A nearly infinite number of configurations are possible.

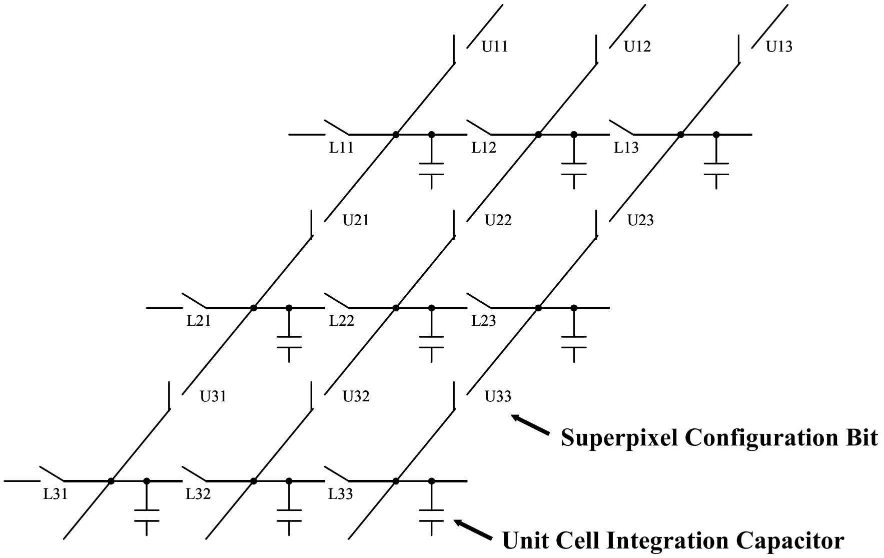


Figure 4 – VASI™readout array interpixel charge summing capability. Various unit cell switches are controlled on a frame by frame basis.

3. PERFORMANCE COMPARISONS

For the purpose of a comparative analysis of conventional large-format FPA devices with their foveal FPA counterparts, this study has considered the operation of a 1024 x 1024 pixel size device. The operational frame rates, fields of view and sensor noise properties of these devices will be compared.

Frame Rate Comparisons - 1024 x 1024 Pixel Format

Figure 5 quantifies the VASI™ read-time as a function of the number of aggregated pixels that form a super-pixel, with parameterized full-resolution foveal regions. An example is given to illustrate the point:

• Aggregated background pixels:	9x9 pixel area
• Foveal Region:	128x128 pixel area
• Resulting Frame Period:	6.33 msec; assuming a 5MHz readout master clock; 0.5msec integration.

The sensor frame period is given as follows:

Tframe = Tread + Tint + Tprogram
where: Tread = frame read time
Tint = sensor integration time (0.5msec)
Tprogram = Overhead required to move foveal region within the FOV (6.6msec)

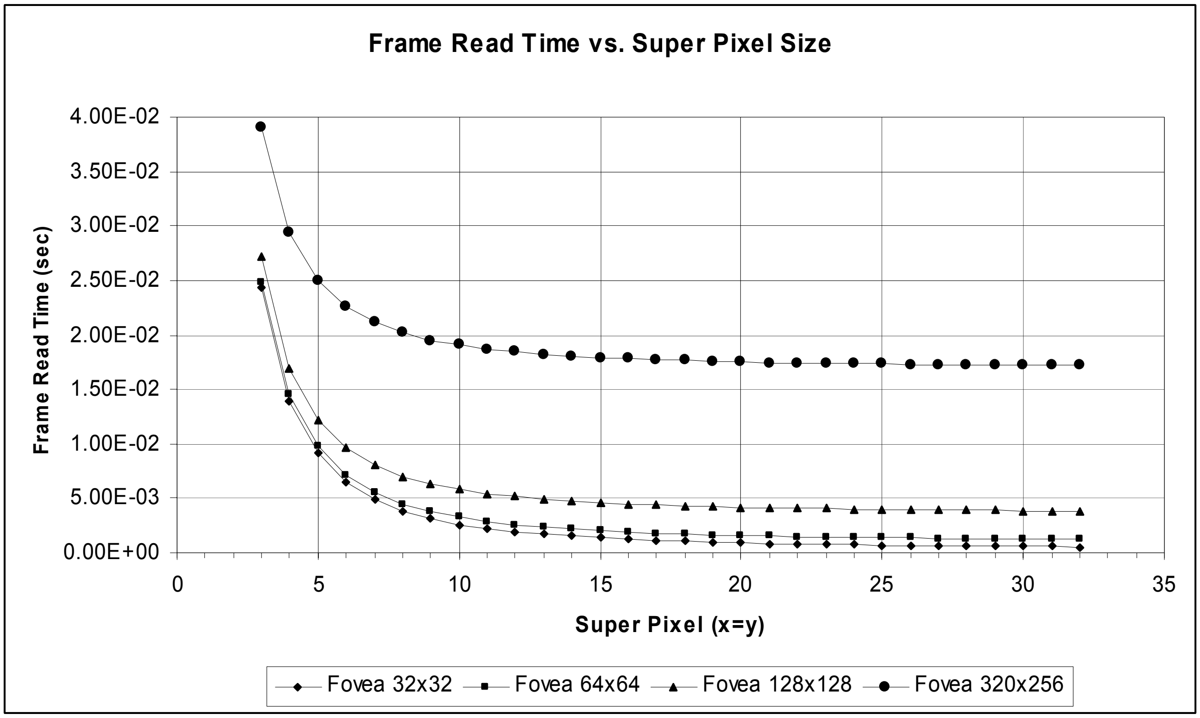


Figure 5 VASI™ trade of array read-time to number of aggregated pixels (superpixels).
Note: Not shown is the full array resolution (1024x1024) read time: 214 msec.

Figure 6 illustrates the frame rate as a function of aggregated pixels and parameterized for four (4) different foveal regions with full array resolution. Continuing with the above example, the resulting frame rate is 74.42Hz as compared with a full resolution maximum frame rate of 4.7Hz (not shown). Therefore for this example with:

- Read clock: 5MHz
- FOV or array size: 1024x1024

Resulting frame rate with a VASI™ sensor
- Super resolution pixel: 9x9
- Foveal region: 128x128

- Maximum frame rate: 74.4Hz
- Compared with full resolution transmission: 4.7Hz
- Minimum acceptable frame rate: 30 Hz for most displays

This comparison has been made with the assumption that a single output channel has been used to provide the entire 1024 x 1024 pixel values per frame. Most applications, though, require frame rates in excess of 30 Hz; this forces conventional FPAs of this large size to have multiple parallel output channels. As an example, commercially available 1024 x 1024 FPA may require as many as 16 output channels. While effective at producing large quantities of image data, these devices dissipate up to 150 mw of power, as compared to a VASI device that dissipates approximately 50 mw of power. In addition, in many cases these commercial large format FPAs are operated in a variety of windowing modes to maintain high frame rates while having data bandwidths within reasonable limits.

A comparably-sized VASI™ FPA achieves similar frame rates with a single output channel because bandwidth is traded for spatial resolution in background regions of its field of view.

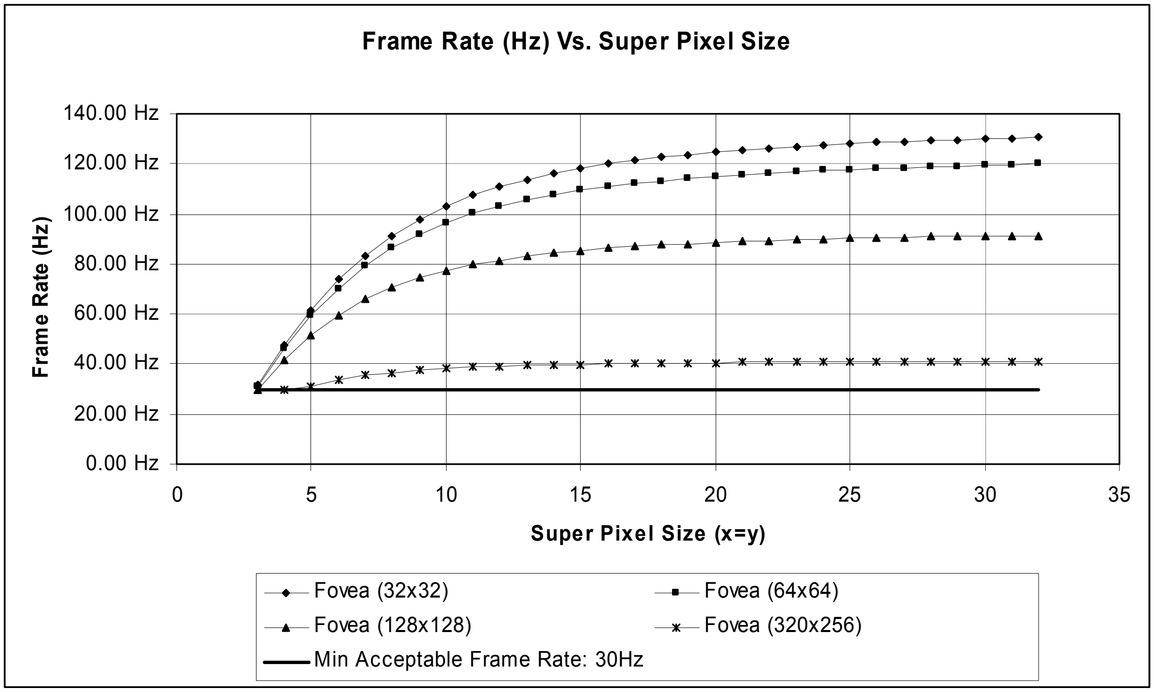


Figure 6 VASI™ trade of Frame Rate to number of aggregated pixels (Super-Pixels).

320 x 256 Pixel Format

Another means for comparison between foveal and conventional imagers is found by considering the frame rate comparisons given for an existing 320 x 256 pixel MWIR VASI™ FPA as shown in Figure 7.

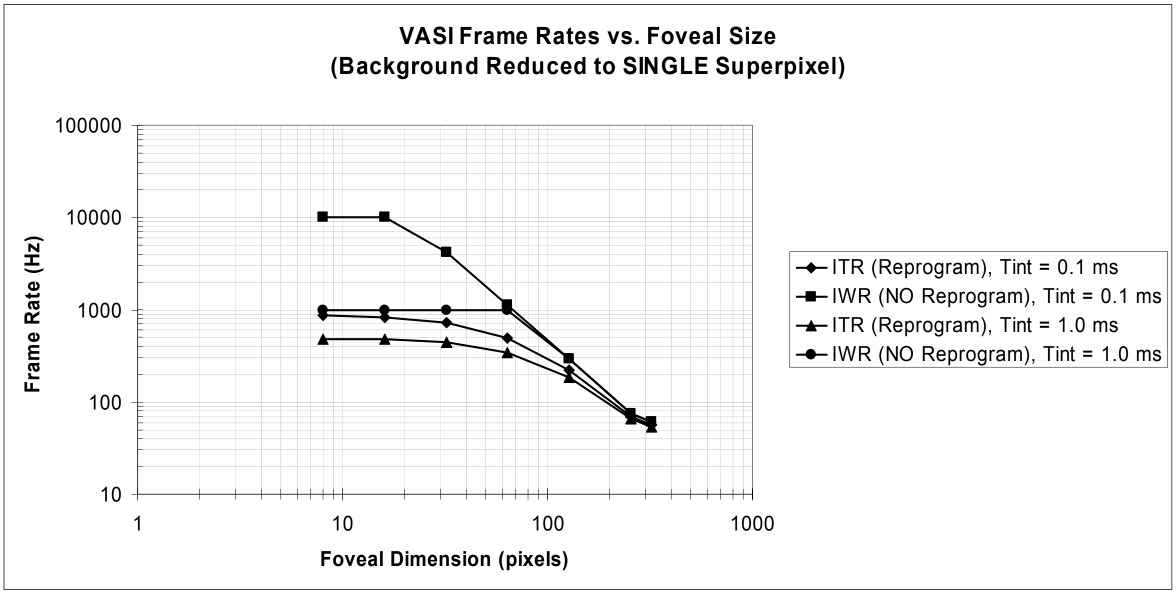


Figure 7 320 x 256 midwave IR VASI(TM) frame rates.

This chart shows that, if the foveal FPA were operated much like that of a conventional windowing FPA, the frame rates increase as the high-resolution foveal region is reduced in size. An added concept reflected in this chart is that of “Integrate Then Read” (ITR) and “Integrate While Read” (IWR) modes of operation.

In the context of a spatially-reconfigurable imager such at the VASI™, the ITR mode implies that the device’s spatial configuration is reprogrammed with each frame at the frame rate. The additional overhead timing required to perform such reprogramming eventually limits the frame rate of the device. As can be seen from this figure, a frame rate of approximately 1000 Hz is achievable with such a foveal device as long as a single high resolution region of 16 x 16 pixels or less is used, and the integration time does not limit the frame rate. In this example, the integration time is 0.1 ms and all background pixels are reduced to a single superpixel (which effectively computes the entire frame average on-chip).

Many applications will not require real-time spatial reconfiguration of the foveal array. In this case, the effective frame speed for a 16 x 16 pixel region (or smaller) can be in excess of 10,000 Hz through a *single* output channel. And, as before, since the remainder of the entire field of view is captured in a single background superpixel, the frame average is contained in this single superpixel’s value. This averaging is performed directly on the FPA at no additional computational cost to the user.

VASI™ Imager Throughput Advantage

Whether the image processor is on a UAV or ground based, VASI™ provides a clear advantage in terms of processing throughput.
The following example illustrates the VASI™ pixel rate advantage as it relates to processor data throughput load.

- Array size: 1024x1024
- Pixel quantization: 8 bits/pixel
- Number of processing steps/pixel: 100 ops/pixel. This represents a very light processing requirement. The higher the number of processing steps per pixel, the greater the VASI™ advantage becomes apparent. Therefore, this example represents a conservative case.
- Frame rate: minimum 30 Hz (minimum acceptable)
- Window size: 128x128 (conventional windowing focal planes are modal, i.e. the user selects either the window or full image mode. In addition, the window size and location are predetermined and cannot be varied during operation)

- VASI™ Foveal size: 128x128 (Although the foveal region(s) is variable in size, shape and location and is user selectable on a frame by frame basis, for this illustration and comparison, 128x128 is assumed)
- SuperPixel Size: 9x9

Figure 8 illustrates the processor throughput advantage afforded by a VASI™ sensor. For the example given, the required processor throughput in Millions of Operations per Second (MOPS) is:

VASI™ with 9x9 superpixel and 128x128 fovea:	202 MOPS
Conventional 128x128 windowing array:	65 MOPS (no background pixels)
Conventional full resolution (1024x1024) array:	3,317 MOPS (3.2GOPS)

When compared with the processing requirement of the full FOV image of 1024x1024, VASI provides a substantial (factor of 16.4) reduction in the processor throughput requirement, while maintaining full field of view coverage.

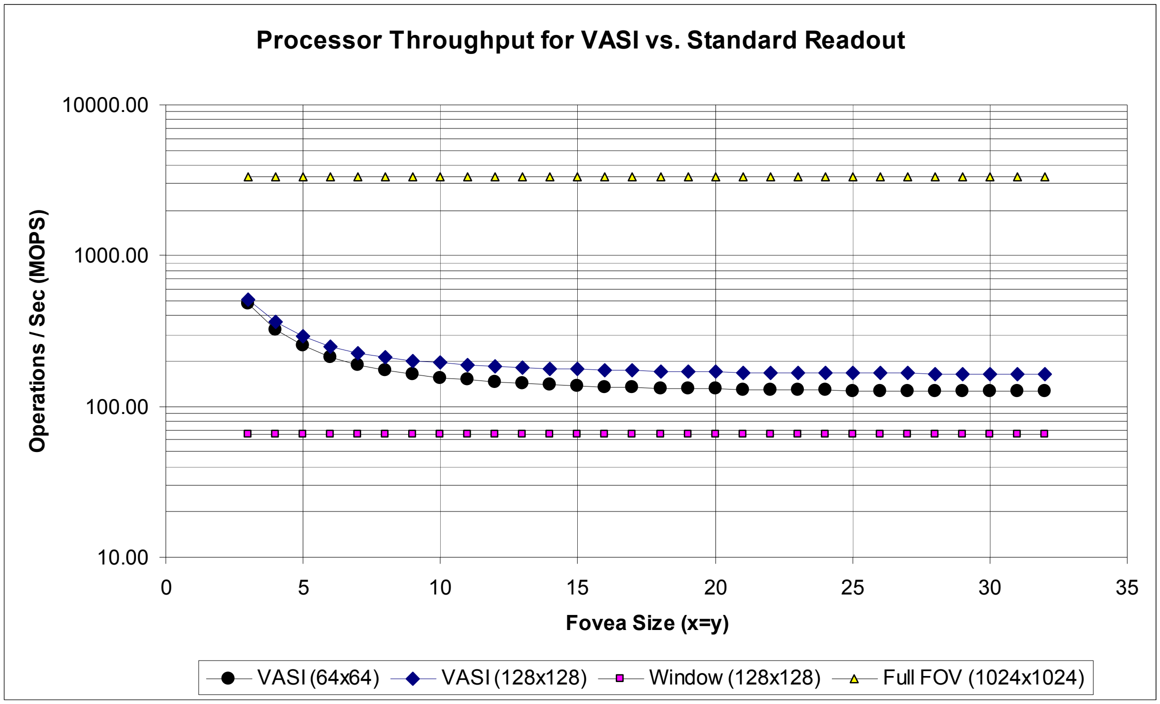


Figure 8 Processor throughput trade between VASI based focal planes and conventional windowing.

VASI™ Transmission Bandwidth Advantage

Certain system operating parameters are a priori defined and cannot be changed during sensor operation. For example, the maximum transmission bandwidth is limited by the selected data link. The minimum sensor frame is also set based on the requirement of the mission, display systems and target motion characteristics.

Typically the frame rate is at least 30Hz. Therefore, for a given transmission link bandwidth, allocation of bandwidth may be made to increase the window size (FOV), increase spatial resolution or increase frame rate (temporal resolution). For illustration, we examine the possibility of using a “Commercial Off-the-Shelf” (COTS) 802.11g (54MHz theoretical) link. Utilizing a COTS link has two advantages. First, it provides a realistic basis for the illustration and second, it may be a cost effective means to demonstrate the system concept.

As evident in Figure 9, the full resolution, full frame (1024x1024) transmission bandwidth of 257Mbps exceeds this example's allocated COTS bandwidth of 54Mpbs by a factor of nearly 5. Whereas all other VASI™ configurations, even with a nominal 3x3 superpixel aggregation are within the bandwidth allocation of the COTS 802.11g link bandwidth. The implication is that full field-of-view, effective 1024 x 1024 pixel 30 Hz image data, capable of being transmitted across a wireless data link is possible using a foveal sensor and would not be possible using a conventional imaging sensor of the same size.

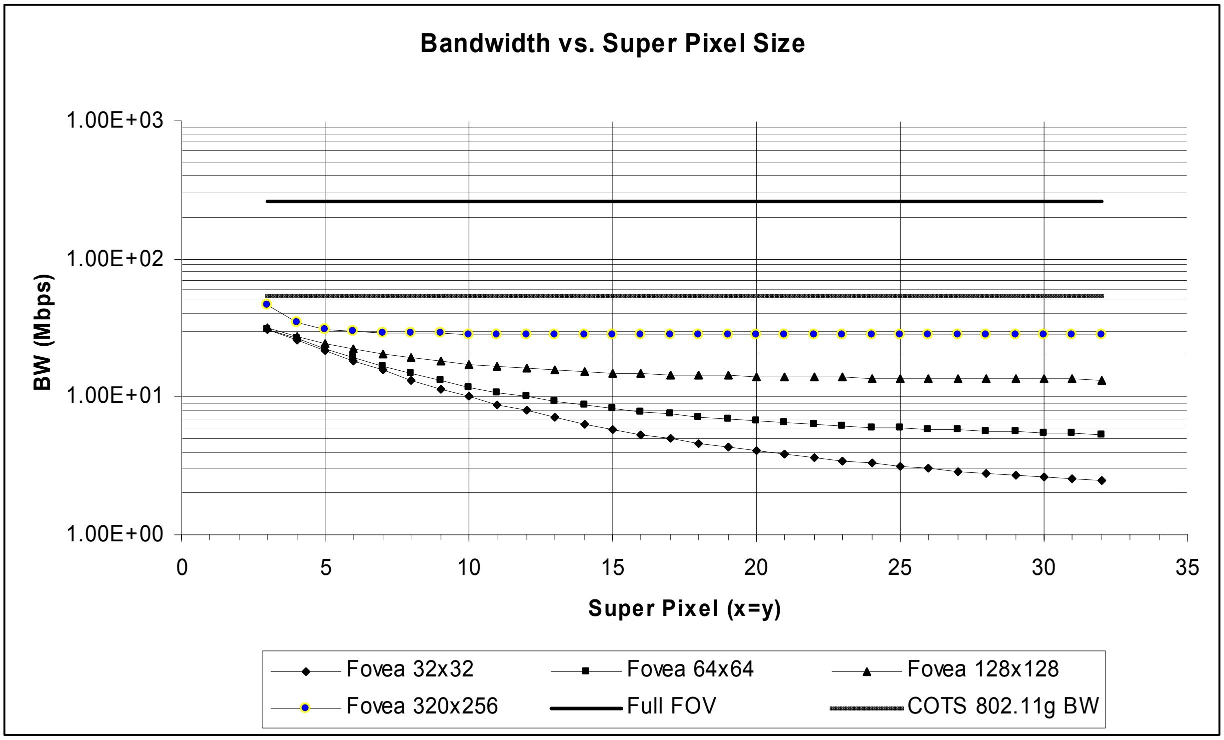


Figure 9 Data transmission bandwidth (Mbps) for various foveal sizes and full resolution 1024x1024 array. The full resolution bandwidth (1024x1024) array at 8bits/pix at minimum of 30Hz is 257Mbps, exceeding a COTS bandwidth (802.11g: 54Mbps) by a factor of nearly 5, but this bandwidth limit is not exceeded when using VASI™ technology.

Field of View Comparisons

A windowing FPA essentially trades total field of view (TFOV) for effective frame rate. In order to achieve very high frame rates, either the window size must be small or the FPA must be designed to utilize multiple parallel output channels. For these devices, the remainder of the TFOV is simply ignored. An example would be that of a human looking through a drinking straw, thereby limiting TFOV; in the human case, though, we do not have the ability to increase our frame rate as would a windowing FPA.

If an important target were to enter into the TFOV while the FPA were operating in this windowing mode, the target would remain undetected. An important difference between conventional windowing FPAs and those of foveating FPAs is that, even though the foveating FPA operates at high frame rate, it continues to permit monitoring of the TFOV, albeit at somewhat lower spatial resolution.

Sensor Noise Comparisons

A conventional cryogenically-cooled FPA has numerous inherent noise sources which are functions of :

- Photon noise
- Readout noise due to 1/f, thermally-generated sources and capacitor reset (kt/c) sources
- Spatial fixed offsets due to nonuniformities of the CMOS silicon process.

Since the foveating FPAs that have been discussed in this paper also utilize CMOS readout structures, many of the same noise sources that apply to conventional FPAs also apply to these reprogrammable spatially-configurable foveal FPAs as well. An important distinction, though, is that the VASI™ device, by virtue of its photocharge sharing characteristic, essentially averages out spatial fixed patterns on-chip. The resulting superpixel output values display lower levels of spatial fixed patterns than those of their conventional-pixel counterparts. An analytic treatment of VASI™ noise sources is beyond the scope of this paper but will be documented in future publications.

Temporal noise may be reduced in some FPAs[2] by implementing an on-chip subframe averaging filter into each unit cell site. In this case, temporal noise is improved at the expense of frame rate because numerous samples are taken and internally time-averaged before reporting a given resulting frame having the characteristic of lower temporal noise. Nova Sensors is currently working on future FPA designs that combine the best properties of spatially-reprogrammable variable acuity sensors and those which also reduce temporal noise by similar temporal noise-averaging techniques.

4. APPLICATIONS COMPARISONS

It is expected that large format arrays (>1024x1024) will be needed to meet the mission requirements of large field of view (FOV) coverage and sufficient resolution on targets with the pixel's instantaneous field of view (IFOV). For comparison purposes in this paper, a large format 1024x1024 array is being evaluated. The large format array combined with fast frame rates puts a high throughput demand on image processors. With limited data transmission bandwidth, unmanned air vehicle (UAV) -based digital image processors will have to perform real-time target detection and tracking and transmit only detected target information to the command base. However, a UAV-based surveillance system, including the image processors, will have to be a small package, light weight and low power. In order to accommodate the pixel data rate produced by large format arrays, the required on-board image and data processors may be incompatible with the limitations placed on UAV installation. Most likely the raw imagery will need be transmitted to either a ship-board processor to perform automatic target detection and tracking or a human-in-loop evaluation of the imagery, which likely represents the near term solution. The advent of spatially-reconfigurable foveal imaging sensors will ease the processing burden currently imposed by high volume, "low relevancy" data output products of today's imaging devices.

Figure 10 shows recent image data taken from Nova's 320 x 256 pixel MWIR VASI™ FPA system. This device uses an indium antimonide detector array to provide spectral sensitivity in the 3 to 5 micron spectral region.

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[2] Caulfield, J. T., P.L. McCarley, C.R. Baxter and M.A. Massie, "AIRS FPA applied to the MIRIADS: Powerful infrared systems applications", SPIE Aerosense 2001, Orlando, FL.

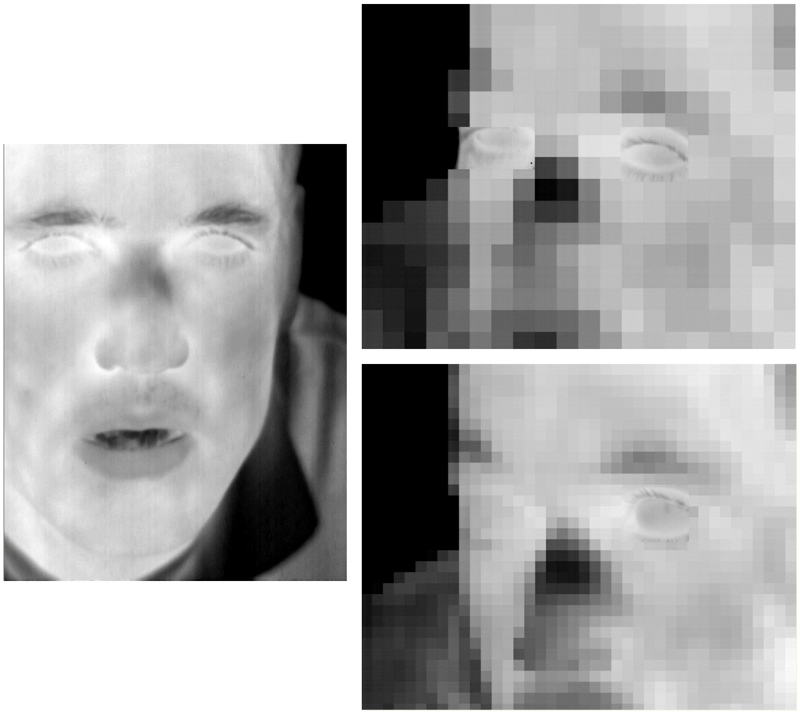

Figure 10 320 x 256 MWIR imagery from VASI™ FPA.

The left panel shows output in "full resolution" mode that is identical to that for a conventional imager; the right panel shows foveal regions on one and two eyes, shown in different background resolution conditions. A conventional imager operating in windowing mode would only have the capability of collecting high-speed image data on one of the high resolution regions, not two or more as indicated with the VASI™ device.

Superpixel-mode operation is useful in applications requiring high effective frame rate without sacrificing total field-of-view or the spatial resolution on objects of interest within the scene. Reducing the total number of pixels per frame which must be read off of the imaging device will reduce the effective frame period, thus increasing effective frame rate.

Possible high frame rate applications would include high speed image motion capture/freezing, remote sensing of object closing velocities, passive depth measurement at high speed, and particle fragment trajectory measurements. While conventional windowing FPAs could be used in these applications, the foveal devices also capture the rest of the background imagery at lower spatial resolution.

Tracking Systems

Motion sensing techniques may be used to direct the VASI™ device to "track" moving objects by placing high-resolution pixels over the moving target, leaving the rest of the image area in a low-resolution spatial condition. By comparing the center location of the "foveal" region to the center of the total field-of-view, a tracking error signal is produced that may be used to servo the sensor platform so as to reduce the pointing error. While covering a very wide total field-of-view, high resolution target imagery is maintained while keeping the target near the center of the image. Significant processing resources, if applied to the high-resolution center of the field of view, would thereby retain a high degree of relevance on the target.

Vibration/Platform Stabilization

External sensors (vibrometers, accelerometers, etc.) attached to a sensor platform may be utilized to produce two-dimensional error signals which may be used to generate the requisite foveal position control to the VASI imager. Image data contained in the foveal region of the sensor, having "tracked" platform motion, would approach a "pixel stabilized" condition useful in improving a system's ability to identify objects of interest.

A range of "Unmanned Air Vehicle" (UAV) applications exist for such a sensor configuration[3]. In addition, recent work with VASI sensors has developed a spatial configuration that permits the on-chip collection of imagery for angle-rate computation as well as the production of high-speed two-dimensional image data.

Template Matching Operations

Pre-determined object shapes may be used to program one or more "foveal" regions of the VASI imager. When the desired-shape object is imaged onto the sensor and becomes spatially aligned with these spatially-formed foveal regions, a high degree of signal correlation will exist in the output of these foveal regions. A following image processing system could evaluate this correlation condition so as to produce a "probability of match". Since the spatial configuration of the fovea may be re-programmed at the frame rate of the sensor, this would provide a convenient means for producing such two-dimensional correlations in real time.

5. SUMMARY AND FUTURE WORK

The various analyses presented in this paper clearly identify the advantage of using spatially-reconfigurable foveal imaging sensors over conventional focal planes in many application areas. Use of such devices will allow the system user/designer to allocate limited resources to best address the mission objectives. By reducing the overall frame read time, VASI™ technology enables the user to increase the frame rate, reduce the signal processing requirement or reduce data transmission bandwidth or some combination of the above. In the near term, it is likely that a man-in-the-loop is required to identify and track hostile targets. This implies a shipboard processor and display system. Conventional full FOV sensors with 1024x1024 format arrays will require in excess of 255Mbps, without compression or encryption. In comparison, a VASI™ device requires only 30Mbps, or nearly half of a COTS 802.11g link of 54Mbps.

Nova Sensors would like to refine the analyses of this paper to better reflect a true or likely scenario with realistic link bandwidth, operations per pixel and processor data throughput. In addition, if compression and/or encryption techniques are likely to be used, assessment of their impact should also be analyzed.

Nova's VASI™ technology has already been developed for monolithic visible arrays and a 320x256 format MWIR (InSb) VASI™ sensor and we are currently on track to complete the development of a 1024x1024 format MWIR (InSb) and Near IR (InGaAs) array in 2005.

6. ACKNOWLEDGEMENTS

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[3] Massie, M., C. Baxter, J. P. Curzan, R. Etienne-Cummings, and P. McCarley, "Vision Chip for Navigating and Controlling Micro Unmanned Aerial Vehicles", IEEE ISCAS03, Bangkok ,Thailand, May 2003.