# Active Pixel Sensors For Autonomous Spacecraft Applications

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## INTRODUCTION

Over the foreseeable future, the size and scope of spacecraft missions will change. dramatically. No longer will we see the large, expensive, and complex spacecraft that characterized the past decades. Successful as they were, they represent a technology and approach which is not supportable in today's economic environment.

The New Millennium will require smaller spacecraft with a more focused set of mission goals and flying on-board sensors having greatly reduced size and weight and a greater range of capabilities. The need for additional autonomy will be created by the greater number of small spacecraft operating and the need to reduce the expenses of mission operations.

Thus the emphasis on newly developed instruments for guidance and target image processing will stress enhancing instrument capabilities, minimizing size and power requirements, and maintaining the reliability that has been achieved over the past years. Toward these goals, we believe the, new APS-based generation of sensors will provide the basis for achieving these goals.

### Autonomous Pointing and Tracking

Autonomous spacecraft missions will encounter three key mission phases that will drive pointing and tracking requirements as shown in Figure 1. The first phase. is encountered immediately after launch and requires the tracker help stabilize the spacecraft, point it toward the destination target, and verify that the orbital release and trajectory toward the target are executed correctly. During the next phase. the tracker must help navigate the spacecraft using references along the way, Finally, the encounter phase begins and the tracker must help point science instruments at targets of interest and then repoint the communication link for data transfer. These tasks can be accomplished with intelligent image sensors that can, using APS technology, operate with reduced power and increased on-focal-plane capability compared to conventional CCD-based sensors.

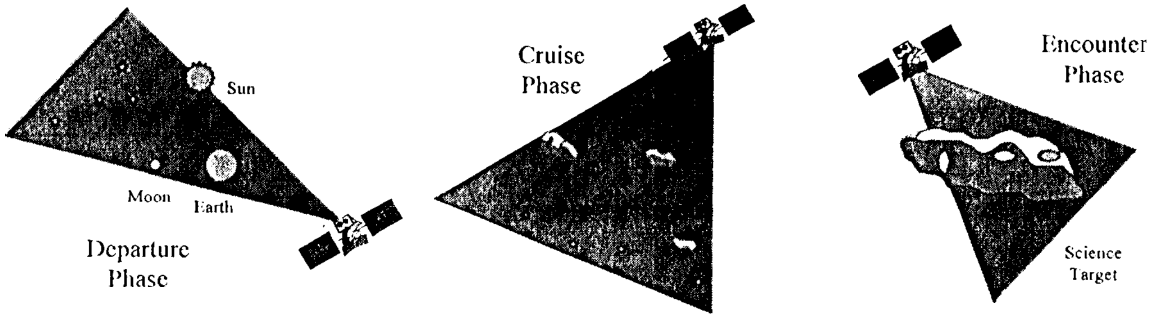


**Figure 1. Autonomous missions will typically require star and feature trackers to support three mission phases – Departure, cruise and encounter phases.**

In each phase it is anticipated that conventional star field identification and tracking will be carried out. This implies then that a reasonable number of sufficiently bright stars will be available for tracking. Traditionally, this is accomplished with moderate field of view (FOV) star trackers that image a 10 to 20 degree FOV that sees a small set of stars. More recently, however, there has been a trend towards much wider FOV optics and the centroiding of many stars. In some newly-designed trackers it is planned to observe as many as a hundred or more stars with a FOV greater than 25 degrees. It now appears that these trackers may provide accuracy as high as 5 arcsec.

However, during the second phase, cruise to the target, it may be necessary to observe the parallax of asteroids to generate data useful to spacecraft navigation. It may be the case that a combination of the wide FOV tracker along with a narrow FOV science camera may be required to locate and image asteroids. While it appears that the wide FOV trackers may provide sufficient accuracy, they lack the light gathering power to see asteroids at the magnitude 9 to 12 range needed. The science cameras, on the other hand, tend to have a large aperture and so are better suited to making the navigation parallax measurements.

One important aspect of achieving a high degree of instrument autonomy has to do with the amount and type of circuit integration that may be achieved on the sensor silicon. Since the APS utilizes rather conventional CMOS fabrication technologies, ultimately, the same level of integration may be achieved as is currently seen in the newer generations of microprocessors.

Apart from the basic APS light sensing circuitry, we are now seeing the additional integration of an A/D converter on chip and plans are being formulated to add RAM and ROM areas to the chip architecture. Thus, the required elements for a high level of autonomy will be present on the APS chip.

The addition of the A/D converter will provide a digital value of each active pixel site's light response, and on-chip RAM will buffer that digital data. Processing algorithms will be stored in ROM areas to provide on-chip processing of the image data and create the required detection information. Operating in this fashion will allow a high level of autonomy in that the sensor will be able to gather specific target information, process that information in a variety of ways, and output the end result to the user systems. All of these tasks will be performed without external intervention or interaction.

### Development of APS Devices As An Alternative To CCD Sensors

Charge-coupled devices have achieved extraordinarily excellent performance with respect to read noise, quantum efficiency, large pixel count, and uniformity during the past 26 years of development. Active pixel sensor (APS) technology, on the other hand, has emerged only in the past few years (the first device was demonstrated in 1993) and has not yet achieved the same levels of performance as the CCD. However, the APS has achieved read noise that is acceptable for many scientific applications (less than 15e-r.m.s.), quantum efficiency exceeding 60% for photodiode-type APS sensors, 1024 x 1024 element array sizes, and less than 1.5% overall gain uniformity). The APS requires only TTL or 3.3V logic input signals to operate, and can run from a single 5V supply. The APS has built-in anti-blooming protection at the pixel and is immune to smear during readout. Furthermore, the APS has significant advantages in power, functionality, size, radiation hardness, and reliability that make it very attractive for optical tracker applications.

APS-based tracker focal planes will dissipate less than 20 mW of power on-chip, and perhaps as low as 5 mW. This includes timing and control electronics and signal chain. For example, JPL has demonstrated a 256 x 256 element sensor with on-chip timing and control circuits and signal chain, including correlated double sampling (CDS), that dissipates 3 mW at 100 kpixel/sec data rates.[1] This is a significant advantage over a CCD system with the same functionality, with at least a 100x power reduction savings.

With most of the required circuits implemented on-chip, the electronics size and weight of the tracker is greatly reduced. Radiation shielding mass is also reduced due to the. smaller electronics volume. The low power require ments of the APS and reduced wiring count can reduce thermal loads, reducing cooler requirements and further reducing spacecraft mass.

The potential for radiation hardness of the. APS is significantly enhanced over that of the CCD. CCDs are inherently susceptible to proton damage to their requirements for charge transfer in the readout process. Since the APS is read out with out multiple charg e transfers, bulk damage to the silicon has minimal effect on AI'S performance. Radiation damage induced dark current is of concern for both CCDs and AI'S devices. Surface-pi nned CCDs are somewhat less susceptible to dark current effects than the AI'S, though recent developments in pinned-photodiode APS devices may also result in superior dark current immunity in the APS.[4] Dark current is readily quenched in both CCDs and APS devices by lowering their operating temperature. Unlike a CCD that experiences charge transfer performance degradation lower temperatures, the AI'S works well to temperatures below 77K.

## Active Pixel Sensor Development Progress

To accommodate the needs of an autonomous mission and to be consistent with the increasing demand for lower mass and power instrumentation, APS developments are under way that are directly applicable to autonomous spacecraft applications. Currently, there are several areas of instrument development areas that are driving, A1'S designs. Common to each is the desire to reduce overall sensor complexity and part count, and to reduce sensor power demand. CCDs require a sizable set of control electronics and a range of support power supply Voltages. The net result is a relatively large component count, over and above the image sensor itself, that require several different supply voltage.s, populating a circuit board with components. A much more desirable solution, offered by the AI'S, is to place the majority of army control circuitry on to the image sensor itself. This reduces the number of components needed in the camera, while reducing the overall power demands through reduced chip count and red uced chip-to-chip interface drive requirements. Further, placing low-noise. sampling circuits on-chip also reduces the susceptibility to external noise sources Often countered in camera circuit boards having many compone nts. Figure 2 shows a typi cal APS tracker.

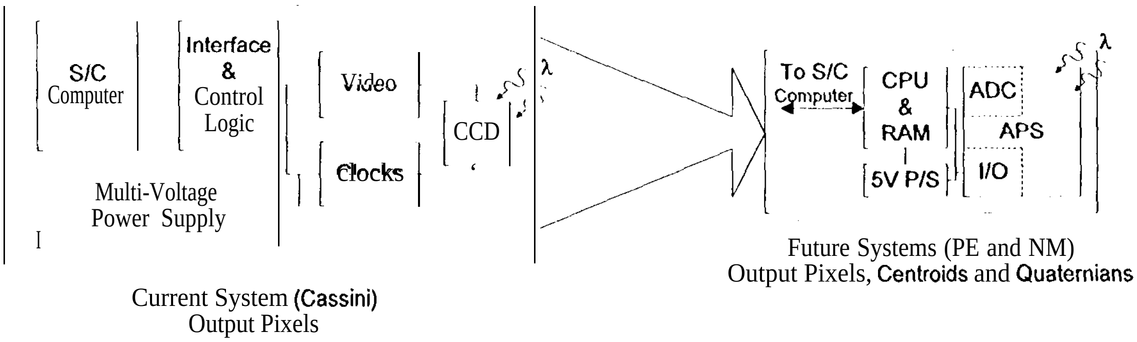


**Figure 2. AI'S technology provides a path towards a reduced mass and power star camera in a minimized volume and profile. Electronics are simplified and part counts are reduced.**

There are several challenges in the. development of the APS technology. These include reduction of read noise, improving quantum efficiency and fill factor, demonstration of large format devices, increased radiation hardness, and on-chip ADC development.

Read noise (single read) has been reduced to below 15 e-rms. In test devices, read noise as low as 5 e-rms has been demonstrated. One way to combat read noise is to red uce the capacitance of the read out floating diffusion neck. This increases conversion gain (uV/e-) but reduces "well capacity". Fortunate.ly, 15 e-rms noise is adequate for most scientific applications.

The AI'S has a fundamental disadvantage in design fill factor compared to full-frame CCDs. The fill factor of the APS pixel is comparable to that of interline transfer CCDs, or about 25%. Increasing the fill factor is important to improving

MTF and centroiding accuracy. However, it has been discovered that the "dead" area of the APS pixel that includes the readout circuitry is in fact reasonably responsive, and makes a significant contribution to the overall QE of the sensor, as well as improves centroiding accuracy. The use of microoptics, such as microlenses presently used in CCDs, can be used to improve effective fill factor of the APS. Space qualified microlenses may be more difficult to develop. Back side illuminated APS arrays have been suggested, but the development of this technology is expected to be costly.

Improved radiation hardness through the use of radiation-hard CMOS foundries is an attractive development approach. Use of these foundries is also relatively expensive and progress here is expected to be slow. More clever designs that improve radiation hardness in conventional CMOS should also be explored.

On-chip ADC has been under investigation at JPL for one or two years. Recent progress has been encouraging and on-chip ADC for 8 bit and 10 bit applications is imminent. More resolution, such as that required for many scientific applications, is more difficult to achieve on-chip with minimal chip area and power, and will lag behind lower resolution approaches.

Larger format APS detectors with small pixel size are desired for many applications. The use of more advanced CMOS processes (e.g. 0.5 micron technology) enables realization of 10 micron pixel pitches and less, and enables the practical realization of megapixel APS formats. More advanced CMOS processes are less mature and more expensive to utilize than somewhat older processes, and for now, large format array development is budget-limited. In a few years (e.g. 2-3), 0.5 micron CMOS technology will be mature and more readily accessible, and the realization of large format arrays with small pixel sizes readily demonstrated.

### APS Test Camera

Our initial entry into the design and test of an APS-based sensor utilized an APS array having a pixel format of 128 x 128. A camera system was designed which was intended to provide verification of the performance of the APS as a star sensor for spacecraft guidance applications. The APS was mounted on a two-stage thermoelectric cooler and housed in a vacuum cavity. Operating the APS at reduced temperatures allowed us to evaluate the spectral sensitivity of the detector for a wide range of target stars. Additionally, the point spread functions for stellar images was to be evaluated in an effort to determine how well centroiding algorithms would work with the APS sensor. Figure 3 shows a star field imaged by the 128 x 128 APS array.

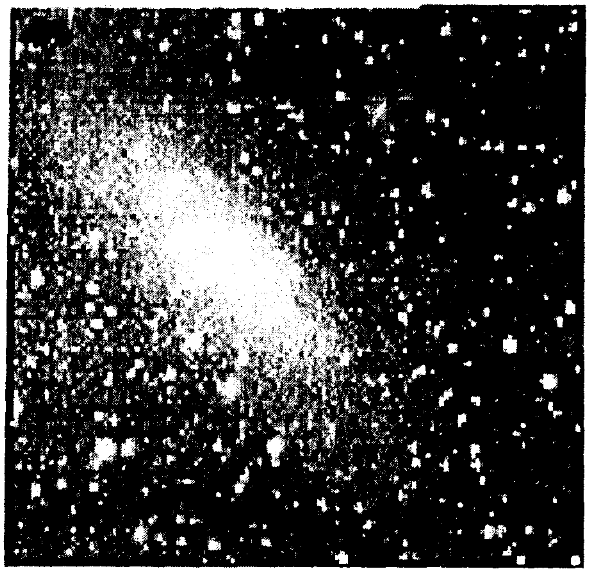


**Figure 3. The Andromeda Galaxy. First-light image with a CC128 APS array on the night sky. The camera is described in the text.**

The APS was operated at a clock rate of 125 KHz and each pixel was digitized to 12 bits using a 1.0 MHz conversion clock. Since the APS divides the input clock by four to derive the pixel rate, each pixel was 32 usec in duration. Of that time, 13 usec was used by the A/D for each conversion, leaving 19 sec to transfer each digitized pixel to the host data acquisition computer. A 12-bit parallel data transfer was used to the host computer.

Analog processing of the APS output signal is quite straightforward. Since the analog pixel output of the APS is fairly high level, about 1.3 volts, a relatively small amount of analog gain is required. Referring to Figure 4, we employed a balanced differential unity gain amplifier to provide a difference signal from the two APS outputs, SIGNOUT and RSTOUT. The following stage provided additional gain and allowed any DC offsets from the APS to be nulled out. A fast sample and hold circuit operating at unity gain then sampled the analog video using the timing signal, PIXEL, as a sample strobe, and presented the held value to the A/D converter. One shot multivibrators were used to optimally time the sample and hold amplifier to the analog video output

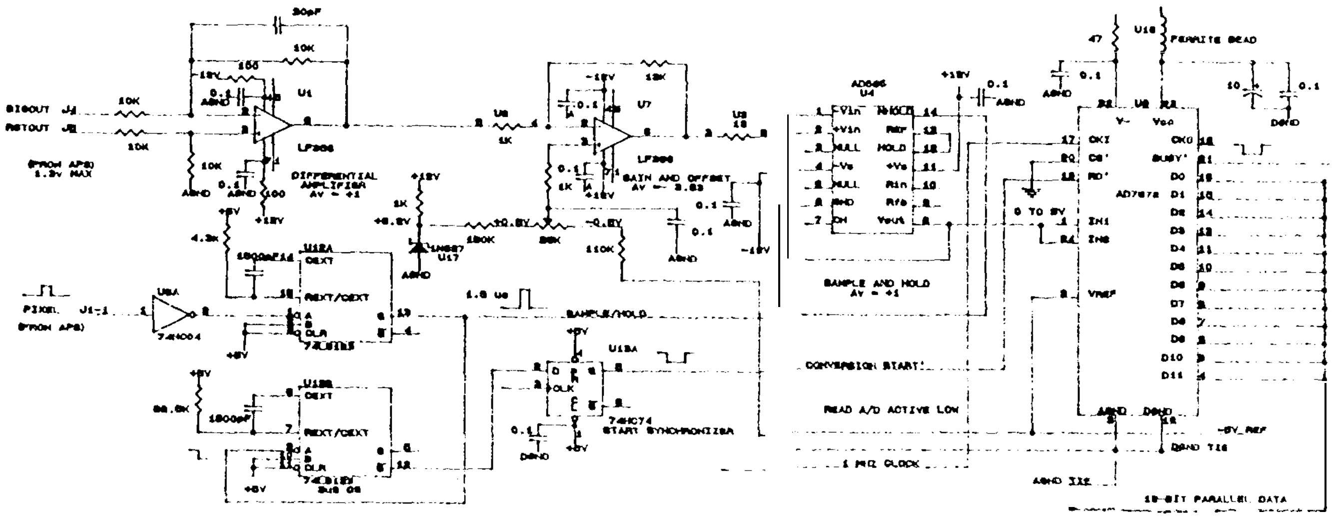


Figure 4. APS Signal Processing Circuitry.

The host computer provided the means of defining the pixel window in terms of Column Start and Column Width, Row Start and Row Width. Light integration time was also programmable having a range of 1 usec to over a half of an hour in 1 usec selection increments. Figure 5 shows the point spread function as sampled by the 128 x 128 APS array. Our next upgrade consisted of retrofitting the APS device with a newer device having a 256 x 256 pixel format. Operation of this device is essentially the same as the earlier 128 x 128 device in terms of host computer commands and readout. The APS chip connections are shown in Figure 6.

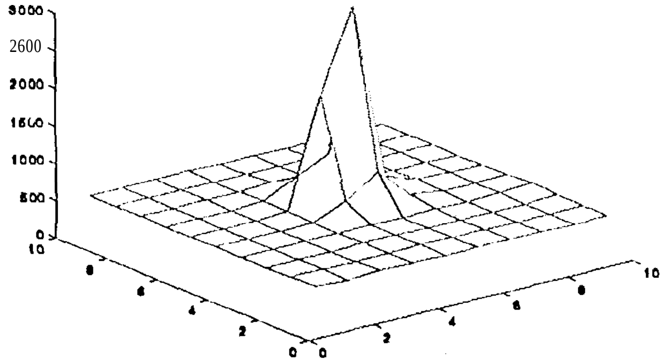


Figure 5. Point spread function as sampled by the CC128 APS array.

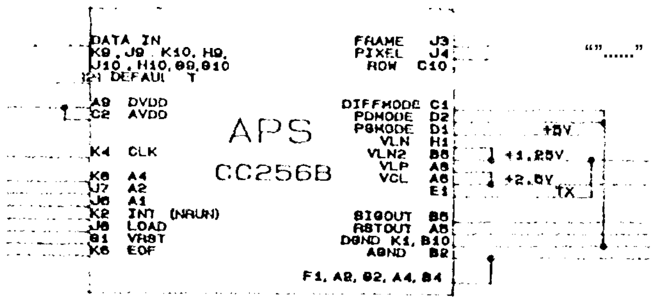


Figure 6. APS Chip Pinouts.

## Support Electronics

The support electronics needed to effectively operate an AI'S may be divided into two groups: Video Processing and Digital Control. The required features of with circuit group are discussed below.

*Video Processing* - The video signal from each active pixel is available as a high-level differential AI'S chip output. The processing electronics consists of a differential amplifier which eliminates common mode signals and a following gain stage allowing video offset adjustment (nulling). A Sample and Hold amplifier is synchronized to sample the video signal during each pixel and present the held sample to a 12-bit A/D converter which digitizes each pixel sample. The digitized pixel signals are then utilized by a processor to extract guidance or scene intelligence information.

The synchronizing signals necessary to perform the A/D conversion are created within the AI'S chip and further simplify the task of digitizing the video data stream. Our APS chip provides pixel, row, and frame sync to allow synchronization to the video data.

*Digital Control* - The internal configuration of the AI'S chip is determined by the data loaded into the eight internal registers of the device. Each register is accessible by means of a 3-bit address and an 8-bit data load. Parameters loaded consist of Column starting location and width, Row starting location and width, and optical integration time interval. Thus an array of pixels to be read out is defined by a loaded register data as is the effective exposure time of the array. A loading strobe, LOAD, is active during the time that the. register data is input, In the event that no register data is loaded, default values allow the entire APS array to be readout with a nominal 256 count integration interval. Default values are loaded by activating the DEFAULT input signal.

Read control is provided by the INT signal assuming an active low state. The APS will continue to read successive frames as long as the INT signal is in the logic () state. If the INT signal becomes inactive during the reading of a frame, the current frame will finish its readout and then the. APS will enter the standby state.

While in the. standby state, internal configuration register parameters should be loaded. If register parameters are loaded during the time when the INT signal is active (logic 0), the AI'S will respond to the changes during the frame readout,

The ability to program the APS device with scan window information allows a great deal of versatility in scanning imagery, especially in star or target tracking applications. Full array scanning can locate features of interest and then smaller scan windows can be placed on those features of interest to optimize the extraction of information. Differential sampling can be employed where selected features are scanned at a different frame rate from the remaining features. Differential integration times can also be employed to balance the signal obtained from targets of differing brightness such as might be encountered in the tracking of a star field.

## APS Performance

In a photo detector, such as an AI'S sensor, the. number of signal photo-electrons is numerically equal to a fraction (quantum efficiency) of the number of photons that constitute a measurement. This photo-electric process is inherently lineal. As a result, two fundamental relationships can be used to describe an ideal photometer: 1) the temporal variance of the measured signal is proportional to the. mean measured signal and 2) the output data numbers will be proportional to the light exposure.

A number of factors can disturb these relationships. The signal chain may have non-linearities, limited dynamic range, inadequate bandwidth, or other imperfections. The system may have sources of extraneous noise from amplifiers or external sources. There will always be a thermal source of photo-electrons (dark current) although at lower temperatures this dark current contribution is generally very small.

Star and extended source trackers are often more sensitive to signal chain imperfections than science imaging cameras or spectra photometers because defects cannot always be removed during real-time processing. Trackers must often use low light level source.s and image position measurements can be distorted by small data imperfections.

Laboratory tests of an image sensor like the AI'S are intended to verify that the system dots not introduce distortions or noise that could degrade the measurement results. Slatting with the photon to photo-electron transition any component in the system can be a source of measurement degradation. The standard laboratory tests include. uniformity of gain and pixel bias measurements. Quantum efficiency and dark current data are also important. Subjective analysis of the image is also an important tool for finding defect and image processing patterns. Linearity can be measured by determining the relationship between exposure and signal output. Most laboratory grade mechanical shutters are suitable for obtaining ibis data.

The mean/variance data can be. obtained by making a series of measurements from a single pixel. This approach has the disadvantage that it is difficult to hold all of the measurement parameters very constant during the measurements period. Measuring the RMS variation of a uniformly exposed area of the sensor has the disadvantage that spatial variations of sensitivity, individual pixel bias, the dark current add to the data variations. One method calculates the difference between two successive frames on a pixel by pixel basis. The RMS value. of these differences divided by the square root of two gives a very accurate measurement of the temporal noise. The light source must be reasonably stable and uniform to get good results.

The mean/variance data gives the sensitivity (electrons/data number) from the variable ratio and the system noise offset (noise for no exposure) from the zero exposure intercept. By far the most valuable data from Ibis measurement is the evidence of any departures of linearity of the mean/variance data. For most sensor systems the system noise is small and the photon induced noise is dominant. Therefore, any departure from linearity in this data is a sensitive measure of system problems.

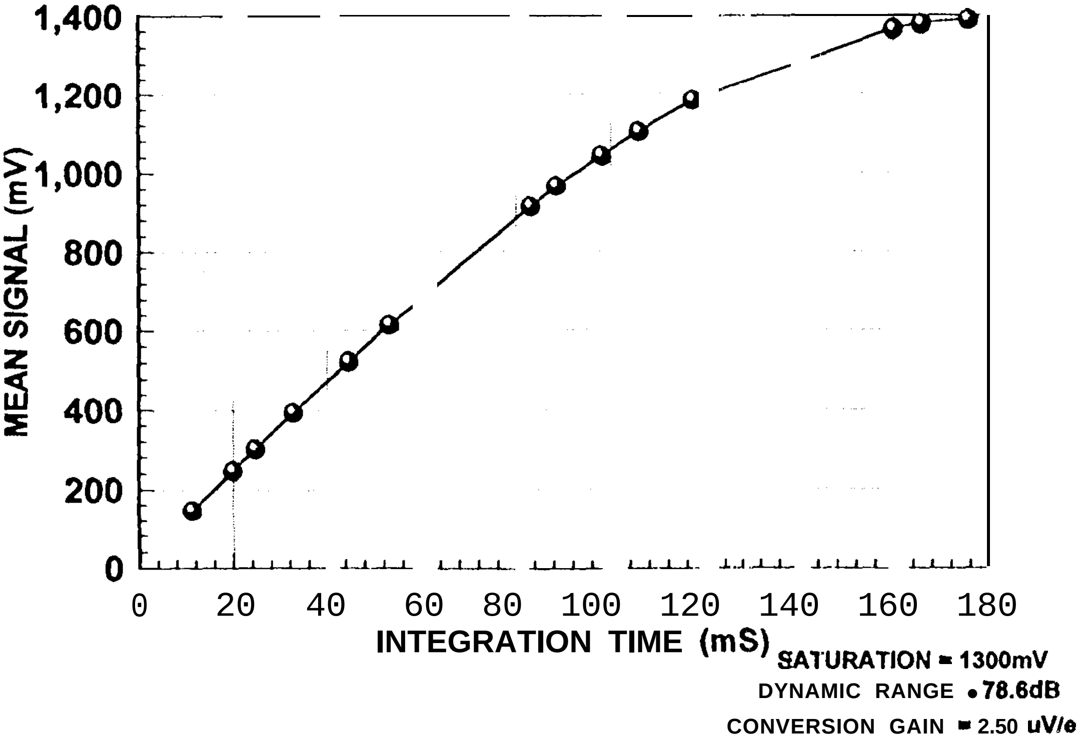
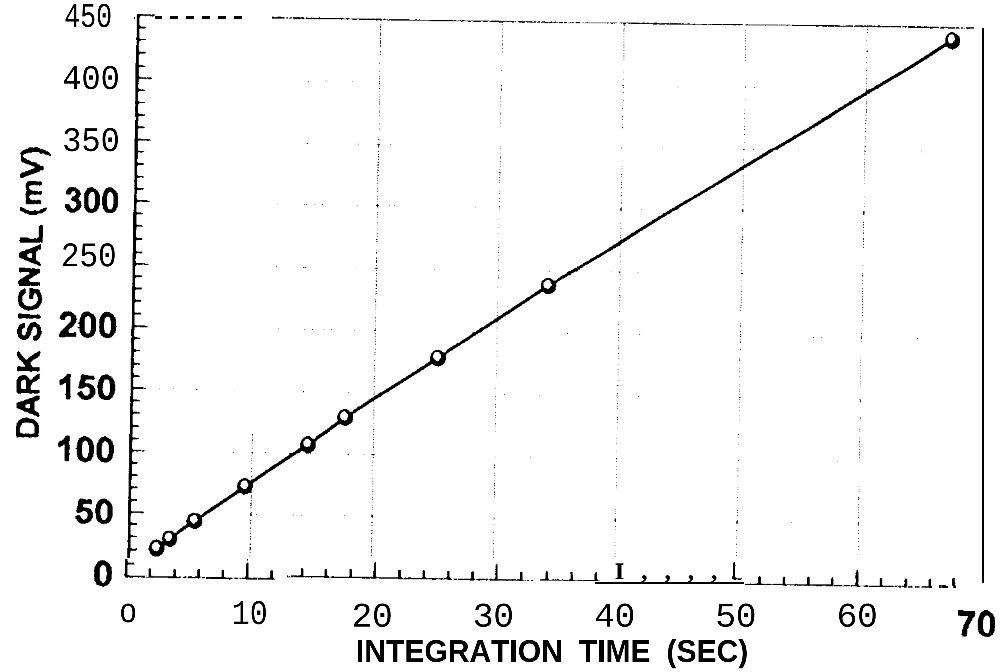


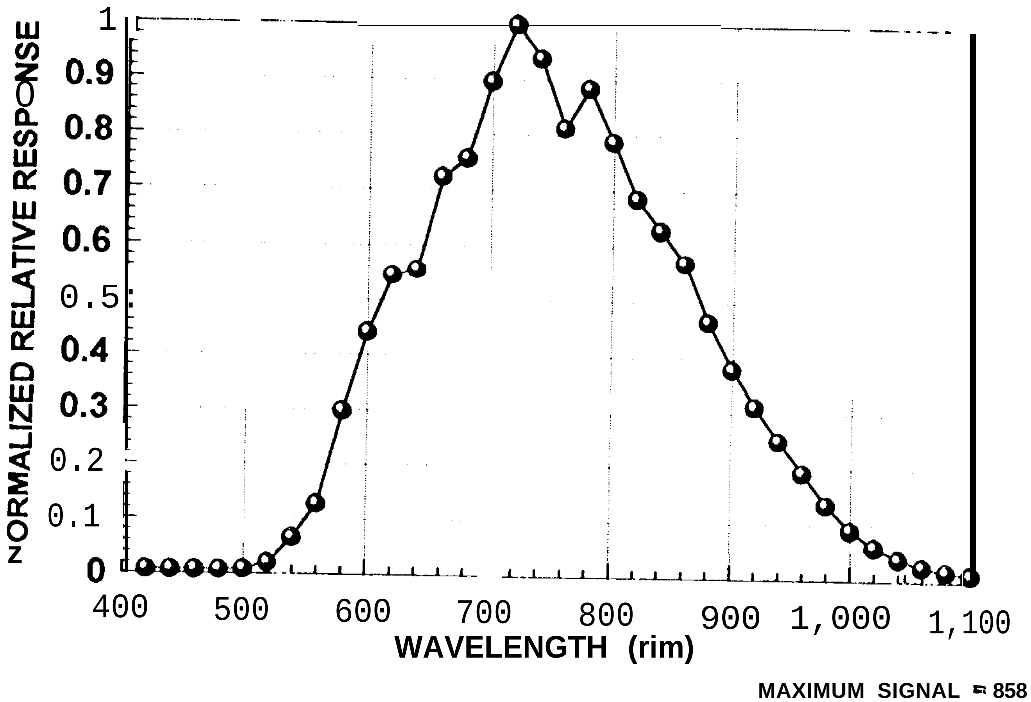
Figure 7. APS Type CC256D Signal Response Linearity.

Figure 7 shows the signal response linearity for an 256 x 256 AI'S device. The device shows a dynamic range of 78.6 dB and a saturation signal level of 1300 mV. The conversion gain constant is 2.50 uv/e. The rate of dark current buildup is shown in Figure 8. The rate is found to be 6.5 mV/sec (2600” e/sec) over integration times approaching 70 sec. This is room temperature data. For the measurements shown, the RMS noise level was determined to be 151.8 µV (60.7e). The dynamic range was calculated as saturation) voltage (1 300” mV) divided by RMS noise level (15 1.8 µV). The normalized relative response is shown in Figure 9.



CONVERSION GAIN = 2.50uV/e

Figure 8. AI’S Type CC256D Dark Signal vs Integration Time.



MAXIMUM SIGNAL ≈ 858 mV

Figure 9. AI’S Type CC256D Normalized Relative Response.

## APS optical Trackers

Star tracking with AI'S arrays will be done in the same manner as with CCD arrays. Therefore the same algorithms may be applied. An additional step may be required, however, to achieve the same results as the CCD. Because AI'S technology places an amplifier circuit within each pixel, the fill factor or light collecting area of the pixel is reduced. This reduced fill factor will introduce an error term in centroid calculation related to pixel geometry induced aliasing. This may be overcome through one or more steps. First, for trackers with lower accuracy requirements it may be sufficient to defocus star images and calibrate the error terms. Proper choice in pixel layout geometry will aid this solution. Another option is to place microlens structures oa the sal-face. of the array with the intent of optically directing incoming light into the J>l]oto-sensitive region of the pixels. As the Oersted tracker has demonstrated using a commercial interline transfer CCD with microlens structures, accuracy better than 5 arcseconds can be achieved.

For feature tracking applications it may be desirable to image both a large, bright and extended object, while retaining the ability to track background stars in the same FOV. Again a physically small, very wide FOV tracker may be well suited to this role from the optical point of view. Conventional CCDs, however, suffer from saturation limits under these conditions. A recent development in APS design, a regional electronic shutter, will help this situation. Here the AI'S provides a means of making very short integration and readout sequences oa the bright extended body, while making a longer integration on background stars. The short integration of the extended body can be used for feature tracking operations, while the back ground star images arc used in more conventional tracking algorithms. Figure 10 strews an expected future AI'S design configuration.

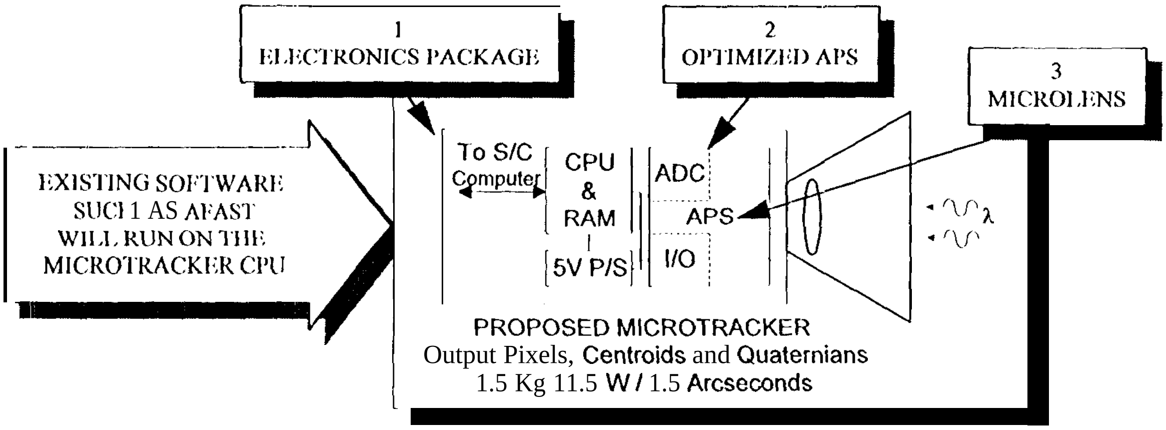


**Figure 10. Future trackers designed around APS arrays may look like this.**

## Summary and Conclusions

We have presented the results of our recent work with Active Pixel Sensors ia terms of optical instrument design, label-story and field tests, and sensor development concepts. The work continues at JPL as the improved AJ'S devices are designed and become available.

The Active. Pixel Sensor holds great promise for future optical sensors capable of achieving a high degree of circuit integration on a single chip. The possibility of incorporating optical sensing, signal processing, and control algorithms in a single integrated circuit will allow a level of instrument autonomy not previously attained, The "Sensor On A Chip" concept appears to be closer than ever before.

Our early work with AI'S devices has demonstrated their capabilities and potential for a variety of optical sensors. We are impressed with the. ease of usage and the rather minimal support electronics necessary for operation. The rate at which the AJ'S devices are being upgraded and their capabilities enhanced is truly remarkable. In the very near future, we will see pixel densities comparable with the best CCDs with the added features of on-chip A/J) conversion and versatile readout logic.

## Acknowledgments

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