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CMOS Sensor for RSI applications

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ABSTRACT

Three CMOS sensors were developed for remote sensing instrument (RSI) applications. First device is linear CMOS Sensor for Terrain Mapping Camera (TMC). This device has 4000 elements, 7 µm x 7 µm of pixel size. Second device is area CMOS Sensor for Hyper Spectral Imager (HySI). The device has 512 x 256 elements and 50 µm x 50 µm of pixel size. Third device is multi band sensor for Remote Sensing Instrument (RSI). This device integrates five linear CMOS sensor into a single monolithic chip to form a Multiple System On Chip (MSOC) IC. The multi band sensor consists of one panchromatic (PAN) and four multi - spectral (MS) bands. The PAN is 12000 elements, 10 µm x 10 µm with integration time of 297 µs ± 5%. Each MS band is 6000 elements, 20 µm x 20 µm with integration time of 594 us µs ± 5%.

Both linear and area CMOS sensor were designed and developed for Chandrayaan-1 project. The Chandrayaan-1 satellite was launched to the moon on October 22, 2008. The moon orbit height is 100 km and 20 km of swath size. The multi band sensor was designed for earth orbit. The earth orbit height is about 720 km and 24 km of swath. The low weight, low power consumption and high radiation tolerance camera requirement only can be done by CMOS Sensor technology. The detail device structure and performance of three CMOS sensors will present.

Keywords: CMOS Sensor, RSI, TMC, HySI, PAN, MS, Chandrayaan-1

1. INTRODUCTION

CCD image sensors have been used successfully in orbital platforms for many years. However, CCD image sensors require several high speed, high voltage clock drivers as well as analog video processors to support their operation. These support circuits must be shielded and placed in close proximity to the image sensor IC to minimize the introduction of unwanted noise. The end result is a camera that weighs more and draws more power than desired.

CMOS image sensors, on the other hand, allow for the incorporation of clock drivers, timing generators and signal processing onto the same integrated circuit as the image sensor photodiodes. This keeps noise to a minimum while providing high functionality at reasonable power levels. CMOS Sensor Inc employs its proprietary advanced CTIA structure and buffer MOS readout method to eliminate the fixed pattern. Due to performance breakthrough, CMOS Sensor Inc. had involved the following space projects for Visible and Near Infrared (VNIR) CMOS sensor.

1. C640 for 3D Terrain Mapping Camera (TMC)
   a. Moon orbit -- 100 km
   b. 20 km swath
   c. 5 meter resolution
2. C650 for Hyper Spectral Imager (HySI)
   a. Moon orbit -- 100 km
   b. 20 km swath
   c. 80 meter spatial resolution
   d. 421 nm ~ 964 nm spectral range

3. C468 for Remote Sensing Instrument (RSI)
   a. Earth orbit -- 720 km
   b. 24 km swath
   c. 2 meter resolution for Panchromatic band (PAN)
   d. 4 meter resolution for Multi-spectral band (MS)
   e. Four different MS band (B, G, R and NIR)

The C640 and C650 were designed and developed for Chandrayaan-1 project. The Chandrayaan-1 satellite was launched on October 22, 2008. The C468 will launch to the earth orbit on 2014.

Figure 1 shows the photo of the C640, C650 and C468. The C468 chip is a large monolithic silicon chip, measures at 121 mm x 24 mm. The device is housed on a 132 pins of Pin Grid Array (PGA) ceramic package with 155 mm x 60 mm dimension. The device description, performance of each CMOS Sensor product summarized as below.

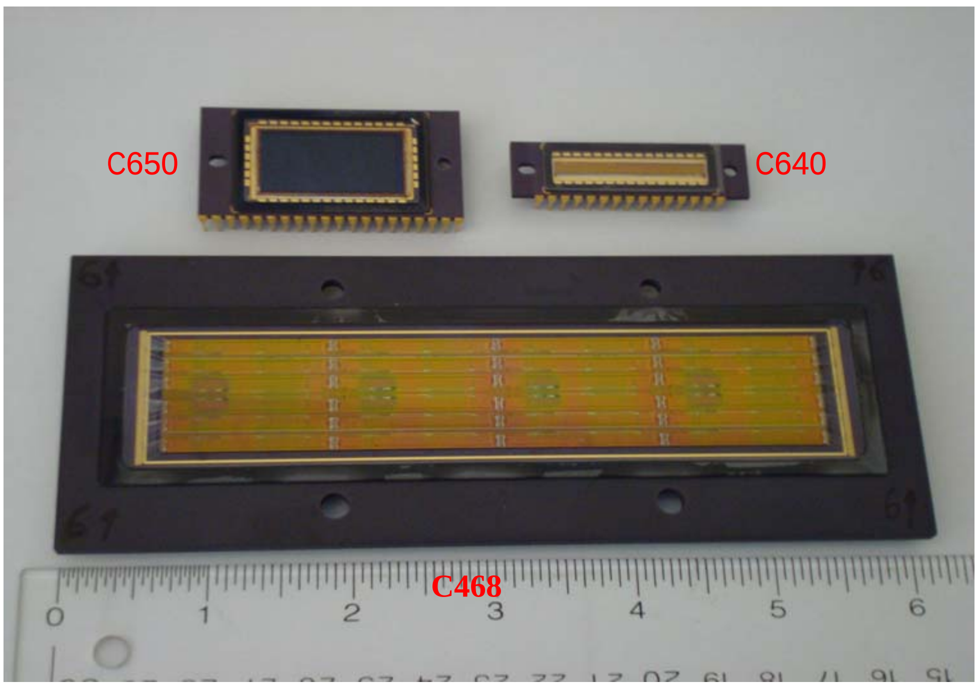

Figure 1: Photo of C640, C650 and C468.

2. C640 (4000 PIXELS LINEAR ARRAY CMOS SENSOR)

2.1 Device description

The C640, 4000 elements linear image sensor is designed to provide high resolution, low power consumption for space applications. Figure 2 shows the block diagram of C640 image sensor. The C640 is mixed mode silicon on chip (SOC) IC. It combines analog circuitry, digital circuitry and optical sensor circuitry on one chip. This chip integrates sensor array, programmable gain amplifier (PGA), 12 bit analog to digital converter (ADC), voltage regulator, low voltage differential amplifier (LVDS) and timing generator. The image processing functions include both coarse gain and fine gain control that can be latched through external latch start pulse.

The device operates in three modes; destructive readout mode, non-destructive readout mode and power down mode:

- Destructive readout mode: In this mode each pixel of the signal is readout and then reset for each frame.
- Non-destructive readout mode: In this mode, each pixel of the signal is not reset during readout, instead video signal of each pixel is accumulated during next frame. The second frame pixel charge adds to (accumulates) the charge of first frame pixel charge. The non-destructive readout mode can accumulate up to thirty-two (32) frames. Therefore, the video signal of each individual pixel can be integrated up to thirty-two (32) frames compared to the destructive readout mode in one (1) frame. This unique function enables the device to be suitable for extremely low light level application.
- Power down mode: In this mode all of the blocks except the latch block are powered down to save power.

This device uses CMOS Sensor's proprietary advanced APS technology and readout structure to reduce the fixed pattern noise, increase dynamic range and improve linearity. The device consists of 4000 photodiode elements. The pixel size is 7 µm square on an element pitch of 7 µm.

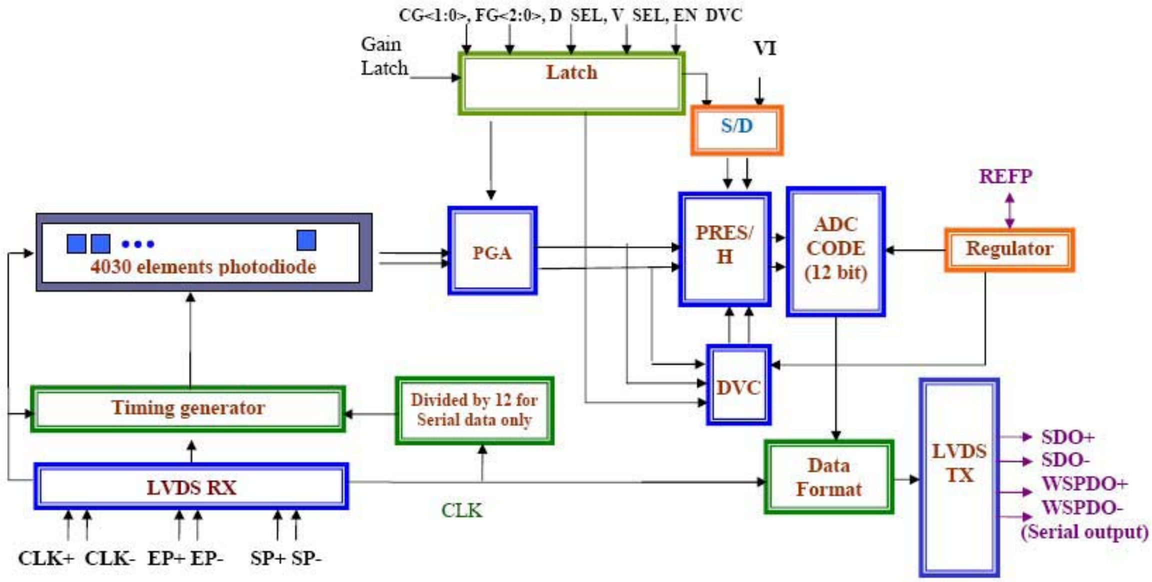

Figure 2. The block diagram of C640 image sensor.

2.2 Device performance:

2.2.1 Measured dynamic range:

The dynamic range of the sensor was carried out experimentally by illuminating the sensor at an intensity just below saturation and again at an intensity where the SNR was unity. Under full illumination, the integration time of the sensor was kept to a minimum and measurements made in destructive readout mode. With a clock period (Tp) of 750 ns and an internal gain of 1.8, the integration time was set to 42 Tp or 31.5 us. Under low light conditions, the imager's amplifier gain was turned to 8.8, the integration time increased to 132,640 Tp or 99.5 ms and operated in non-destructive readout mode.

The illumination at both extremes was measured independently using a silicon radiometer. The resultant dynamic range was calculated as 123 dB as shown below and the measured data is shown in table 1

$$\text{Dynamic Range} = 20 \times \text{Log}\,(21563 / 0.015) = 123.2\text{dB} \qquad \text{--------------------} \qquad (1)$$

Operating Mode	Illumination (Candela/m^2)	Output (DN)	Sensor Noise (DN)	SNR

Destructive Read	21653	4010	6.78	591.4
Non Destructive Read	0.015	15.7	15.2	1

Table 1. Measured data used to calculate Dynamic range

2.2.2 Dark signal non-uniformity:

The dark output voltage is measured when light source is turned off for one integration time. The dark offset mean is calculated by the mean value for all of the pixels.

$$\overline{Vd} = \frac{1}{S}\sum_{i=1}^{S} Vd_{si} = \frac{Vd_{s1} + Vd_{s2} + ... + Vd_{sS}}{S} \quad \text{------------------------------------} \quad (2)$$

where S is the number of sample taking, which is 256 frames.

$$Vd = \frac{1}{N}\sum_{i=1}^{N} \overline{Vd_i} = \frac{\overline{Vd_1} + \overline{Vd_2} + ... + \overline{Vd_N}}{N} \quad \text{---------------------------------} \quad (3)$$

where i is a pixel number, i from pixel # 1 to 4000 and N is a total of 4000 pixels. The dark offset non-uniformity (Ud) is calculated by the standard deviation for all 4000 pixels when light source is turned off.

$$Ud = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N} \overline{Vd_i} - Vd\right)^2} \quad \text{--} \quad (4)$$

Figure 3 displayed the dark signal for 4000 pixels. The dark signal non-uniformity is very small.

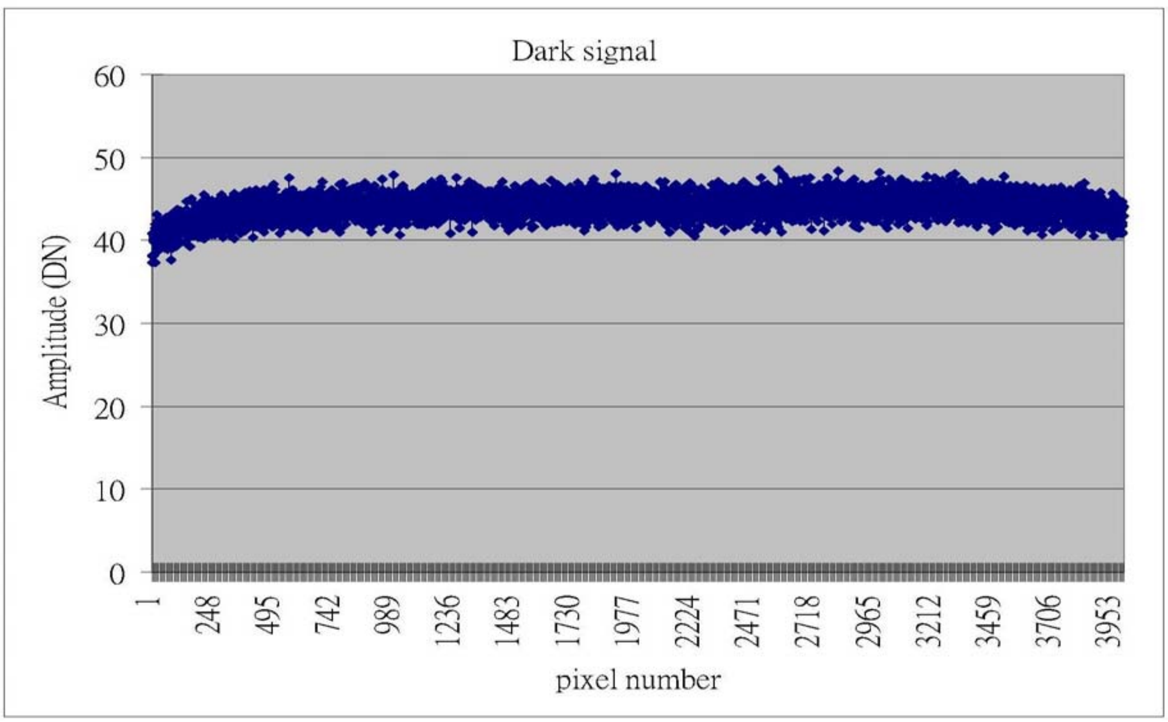

Figure 3. The dark signal of the 4000 pixels

2.2.3 Photon transfer curve:

Photon transfer curve is used to measure the device performance. For each pixel, the noise equals to the square root of the noise floor and shot noise, which is shown as the following equation.

$$N_t = \sqrt{Ns^2 + N_{noise\ floor}{}^2} \quad \text{---} \quad (5)$$

where N_t is a total noise; N_s is shot noise; $N_{noisefloor}$ is noise floor. The signal and noise is proportional to the light intensity and exposure time for each pixel. By increase the light source and the exposure time, the output signal increase. Figure 4 shows a plot logarithmically the rms noise against mean value of the C640 sensor, known as Photon transfer curve (PTC). The measured noise floor is 350 electron; the full well capacity is 400 ke and the conversion rate is 100 e / DN.

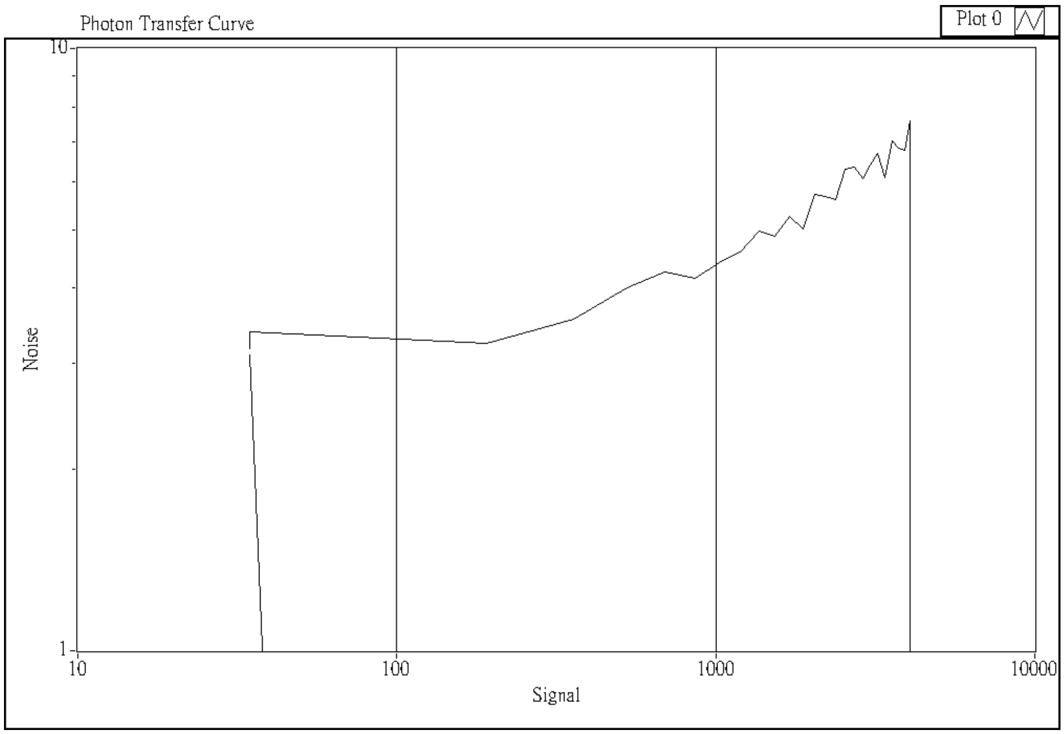

Figure 4. Photon transfer curve (PTC).

2.2.4 Non-linearity:

The output signal versus intensity (integration time) was measured and plotted. The slope of the plot is the linearity of the image sensor. The non-linearity is the percentage error of the measured data with ideal curve. The measured device non-linearity is less than 0.5% between 10 to 90% of full well capacity.

2.2.5 Modulation Transfer Function (MTF)

Due to project an optical MTF pattern to the image sensor is difficult and might be tolerated from lens, a special MTF pattern metal mask is used for MTF measurement. By using an uniform light source to illuminate the device, the MTF data can be measured and calculated. The output signal is a dark signal (D) if the pixel covered by metal mask. It is a light signal (L) if the pixel is not covered by metal. The metal mask arrangement is shown as below.

First 100 pixels:	All dark
Second 100 pixels:	D, L, D, L, …
Third 100 pixels:	D, D, L, D, D, L, …
Fourth 100 pixels:	D, L, L, D, L, L, ….
:	
:	

The MTF value for each spatial frequency is calculated from the equation as below.

MTF (%) = $[(V_L - V_D) / (V_L - V_D)] \times 100\%$ --------------------------------------- (6)

where V_L is the light signal output at each spatial frequency; V_D is dark output signal at each spatial frequency. Table 2 shows the measured MTF value for different wavelength at Nyquist spatial frequency.

	Wavelength	MTF @ Nyquist spatial frequency
Blue light source	470 nm	78%
Green light source	560 nm	68%
Red light source	640 nm	50%
Near Infrared light	940 nm	25%
White light (CCFL)		70%

Table 2. Measured MTF value for C650.

2.3 Image performance:

The TMC in the visible spectrum band from 500 nm to 750 nm utilizing three separate C640, linear images sensors facing fore, nadir and aft to the lunar surface. Being used in push-broom mode to provide along track stereo viewing, the TMC covers a swath of 20 km with the fore and aft imagers being placed at +/- 25 degrees from nadir. The end result is a ground resolution of 5 meters at an altitude of 100 k. Figure 5 presented the earth image taken from nadir of TMC that made by C640 sensor on about 70,000 km of earth orbit before the satellite reach to moon.

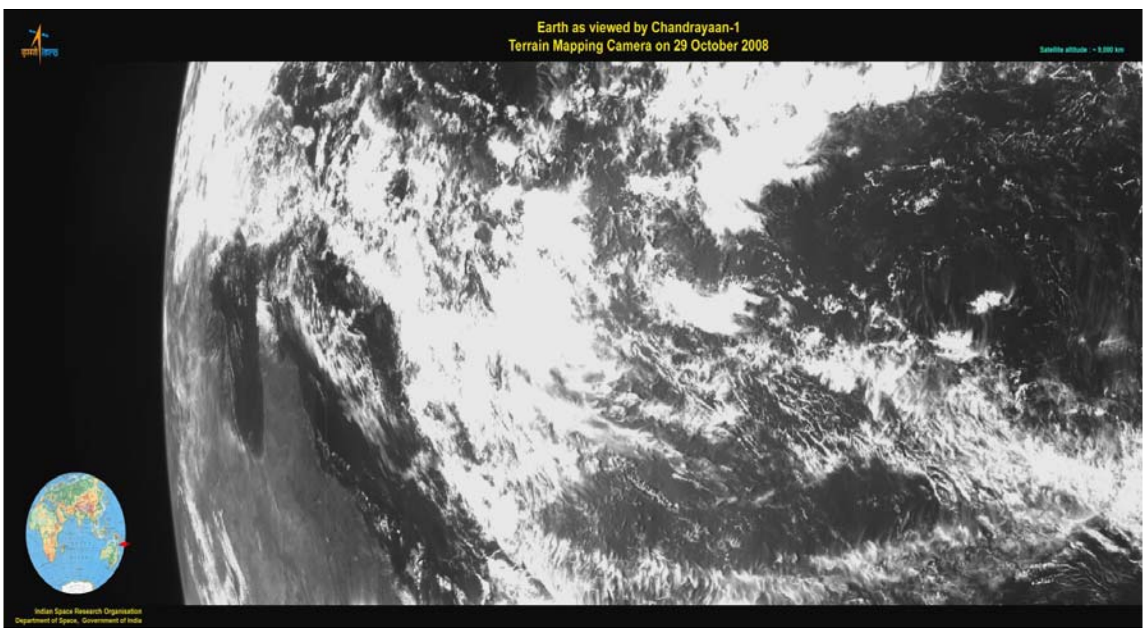

Figure 5. Earth image from TMC (70,000 km high)

Image data from TMC was used to create 3D image of the lunar surface. These digital elevation models (DEM) were generated from combinations of images produced by three CMOS image sensors. The process is to obtain the same image from two or three of the CMOS sensors taken at different angles due to the orientation of the image sensors within the satellite. These stereoscope views are then processed to identify matching points between the two images. Having identified as many matching points as possible, these points are fit to a triangular mesh from which the 3D coordinates are interpolated for all data points [1]. Draping the imaging features over this 3D coordinate surface results in very effective image as shown below. A measure of the effectiveness of this procedure is the number of pixels or data points that can be matched up between two or three viewing angles. As one might expect, the worst correlation (27%) occurs using images from the fore and aft camera (largest angle between images) while the best correlation (100% point matching) is obtained from using all three images: aft, nadir and fore. Figure 6 displayed the 3D view of mountain on moon surface. The 3D crater view was presented in figure 7.

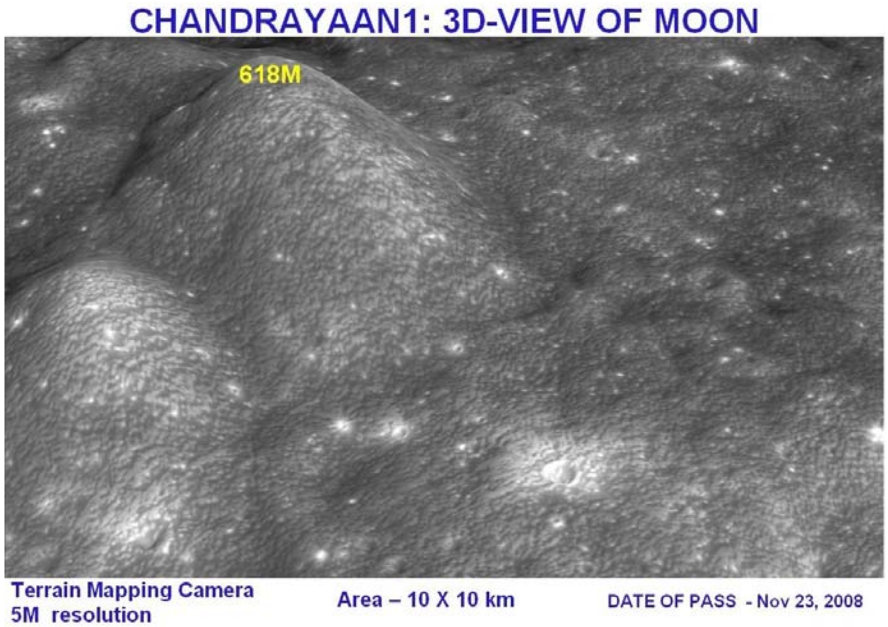

Figure 6. 3D mountain view on moon surface.

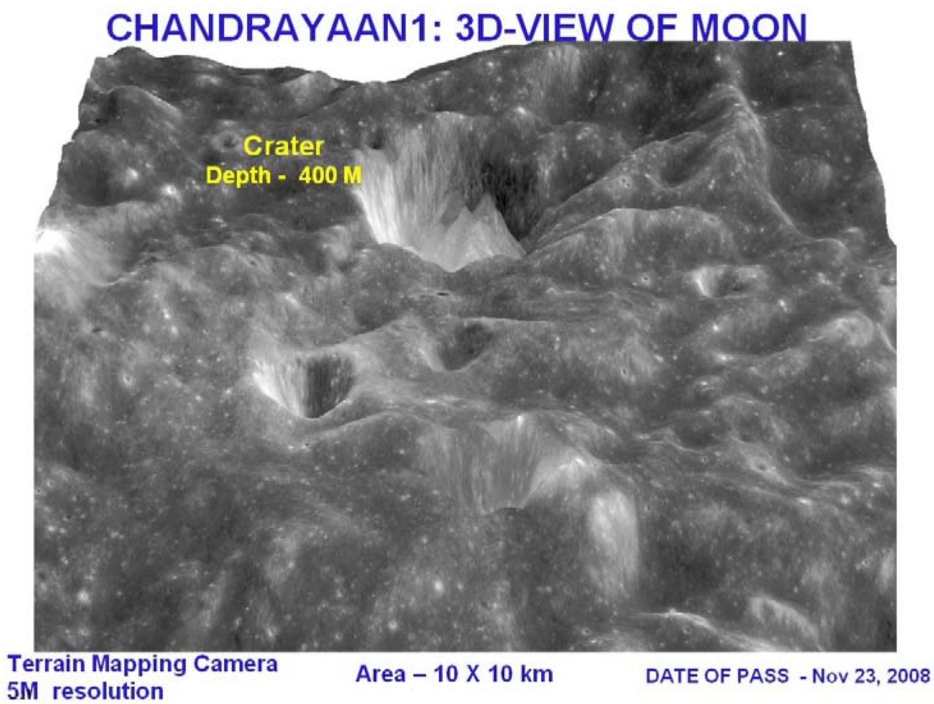

Figure 7. 3D crater view on moon surface.

2.4 Comparison:

The advantages afforded CMOS image sensors can be summarized by the following comparison. Table 3 lists the characteristics of four recent lunar projects. The Kaguya launched by Japan, the Chang'e-1 launched by China and the Lunar Reconnaissance Orbiter launched by the US used CCD imagers. While the Chandrayaan-1 launched by India used CMOS imagers.

	Japan	*China*	*India*	*USA*
Satellite	Kaguya	Chang'e-1	Chandrayaan-1	Lunar Reconnaissance Orbiter (LRO)
Overall Weight	3.0 tons	2.3 tons	1.4 tons	
Launch Date	September 2007	October 2007	October 2008	June 2009
Camera Type	Terrain Camera & Multi Band	3D Terrain Mapping	3D Terrain Mapping	3D Terrain Mapping
Camera Sensor	CCD	CCD	CMOS	CCD
Camera Weight	9.4 kg[2]	> 30 kg	6.3 kg	9.8 kg
Camera Power consumption		> 10 watts	1.8 watts[3]	20 watts[4]

Table 3. Comparison of four recent lunar terrain mapping cameras.

As seen from table 3, the LRO and Chang'e-1 both weigh more and consume more power than the CMOS imagers aboard Chandrayaan-1 while the Kaguya imager weighs at least as much as that found aboard Chandrayaan-1.

3. C650 (256 x 512 AREAR ARRAY CMOS SENSOR)

3.1 Device description

The C650, 256 x 512 pixel area array active pixel sensor (APS) has a large pixel size, slow scan and low power consumption needed for space based, scientific and medical applications. The device block diagram is displayed in figure 3. The C650 chip integrates a 256x512 active pixel sensor array; a PGA for row wise gain setting; I^2C interface; SRAM, 12 bit analog to digital (ADC); voltage regulator; low voltage differential signal (LVDS) and timing generator. The device can be operated in normal imaging capture mode or row wise gain readout mode or power down mode. Device settings, including coarse gain, row-wise PGA gain, ADC input selection, data output type selection and operating modes can be readable through the I^2C interface. Furthermore, the row wise PGA gain can be set with this interface and the coarse gain can be latched through external latch start pulse.

- In normal imaging capture mode, all of the photo detector gain is equal to one.
- In row wise gain readout mode, one can set a different gain (from gain = 1 to 5 for 7 bit increment) on each row of the photo detector by stored the gain setting data on the SRAM thru I^2C. For example, user can set gain = 2 on 10th row and gain = 3 on 11th row on each frame for this device. This unique row wise gain setting can compensate the silicon spectral response non-uniformity problem. Since this unique function, the device is suitable for hyper-spectral imager application.
- In power down mode, all of the blocks are power down to save power.

The default setting of the operation for this device is normal imaging capture mode. The photo detector has very low dark leakage. The device is operated in snap shot operation. All of the pixels are start and stop integration simultaneously. The device also provides global exposure control function (no integration will take place till exposure control is active). The detector's high sensitivity is suitable for the very low light imager application, such as space, scientific or telescope application.

This device uses CMOS Sensor's proprietary advanced APS technology and readout structure to reduce the fixed pattern noise, increase dynamic range and improve linearity. The pixel size is 50 µm by 50 µm have a full well capacity of 700,000 electrons. The photo diode area is 41 µm x 22 µm results in a 36% of fill factor as shown in figure 10. The device is sensitive over the spectral wavelength of 421 to 964 nm.

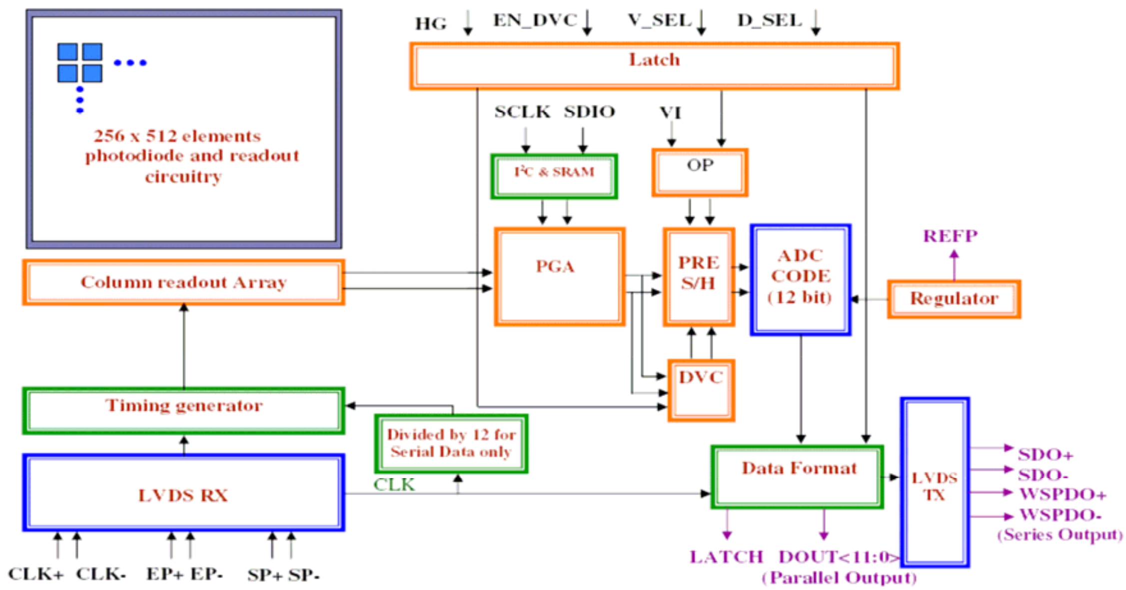

Figure 8. Block diagram of C450 image sensor.

The sensor has an active image array size of 256 columns x 512 rows. However, the full array contains 286 columns and 516 rows, with the extra 30 Optical Block (OB) pixels in each column and the extra 4 OB rows. The optical block pixels are designed to provide a dark reference voltage and eliminate edge effect. For each column, they are arranged for 20 pixels on the beginning of the 1st active pixel and 10 pixels after the 256th pixels. The optical block rows are arranged for 2 rows on the beginning of the 1st active row and 2 rows after the 512th active row. Figure 9 shows the pixel arrangement of the sensor array and the APS unit. The optical block pixels are same as active image sensor except a light shielding opaque element covers them.

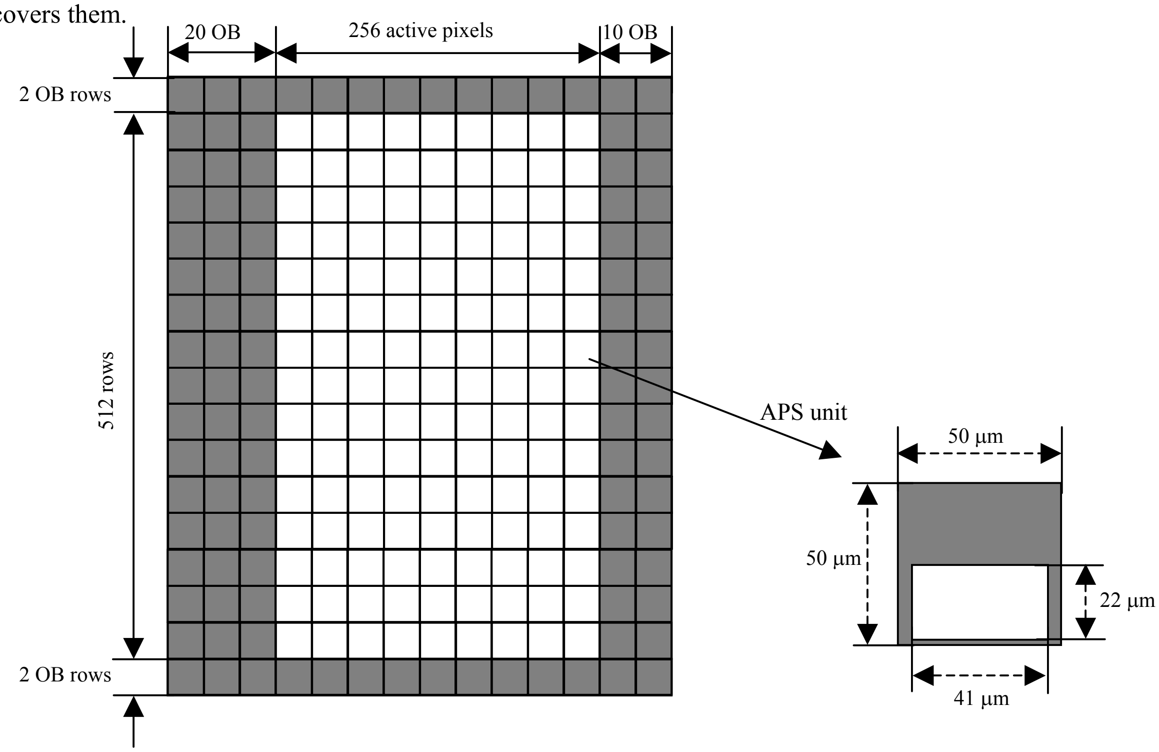

Figure 9. Sensor array and each pixel geometry.

3.2 Device specification:

The C650 device was designed for hyper spectral imager in a space borne application. Table 3 summarizes the C650 device specification.

Item	Specification	
Readout mode	Read while integrate: Start and stop integration of all pixels simultaneous (snap shot)	
Maximum Frame rate	50 frames per second	
Minimum Frame rate	5 frames per second	
Dark Current	≤ 9500 electrons / s / pixel for all pixels of the array	
Noise floor in dark	≤ 8 LSB	
SNR:90% of Full well	≥ 501	
SNR: 50% of Full well	≥ 243	
SNR: 1% of Full well	≥ 5	
PSRR of the device	≥ 60 dB on all the supply lines at maximum readout frequency	
Power consumption	≤ 350 mW at maximum readout frequency	
Full well capacity	~ 700Ke	
Dark offset mean	≤ 3 LSB at integration time Ti	
Dark offset non-uniformity	≤ 2 LSB RMS including FPN at integration time 250 ms	
Along track MTF (512 row direction)	Wavelength	MTF @ Nyquist frequency
	470 nm	99%
	560 nm	99%
	640 nm	99%
	940 nm	98%
Across track MTF (256 column direction)	470 nm	96%
	560 nm	96%
	640 nm	95%
	940 nm	92%
Residue (Line to Line)	≤ 1% when alternate Lines are illuminated up to 90% of Full Well	
Non-linearity at digital output	≤ 1% in 10% to 90% of Full Well for any pixel	
Maximum non-uniformity	≤ 2% RMS	
Anti-blooming	Built in lateral anti-blooming structure	

Table 3. Device specification.

3.3 Image performance:

The 256 x 512 element image sensor area array was designed for HySI in a space borne application. As part of the Chandrayaan-1 mission to map the lunar surface, it is critical to gaining an understanding of the mineralogical makeup of the moon. The camera was designed such that one row of 256 elements would image a spatial swath of 20 km on the lunar surface and each of the 512 rows would image a different spectral band. Spectral separation is achieved through the use of wedge filter. The choice to use a wedge filter instead of a prism or grating was made for a reason of simplicity and compactness. The spectral band is cover from 421 nm to 964 nm with 512 rows result in a spectral resolution slightly greater than 1.0 nm per row. However, several rows are combined to produce 64 contiguous bands with a spectral resolution between bands of better than 15 nm. The spatial resolution of HySI camera in the cross track direction is 80 meters [5]. By operating the camera in push broom mode, each of the 512 rows would get an opportunity to image the same 20 km spatial swath collecting 512 different spectral images of the same surface geometry. The wedge filter is oriented such that the cross track dimensions of the wedge filter are uniform and the along track dimensions are those of the varying thickness produced by the wedge filter. Hence, the spectral bands appear in the along track direction.

The HySI camera has produced impressive imagers as shown in figure 10. This series of images was taken from a 40 km by 20 km section of the moon near the equatorial region from an altitude of 100 km. The majority of the imagers only show subtle variation in the shades of gray because the lunar surface is devoid of many of the color producing features we are accustomed to. However, by subtracting and / or taking the ratio of one image to another these subtleties become evident. This slight variation across the 64 bands will produce the chemical signatures of the lunar surface.

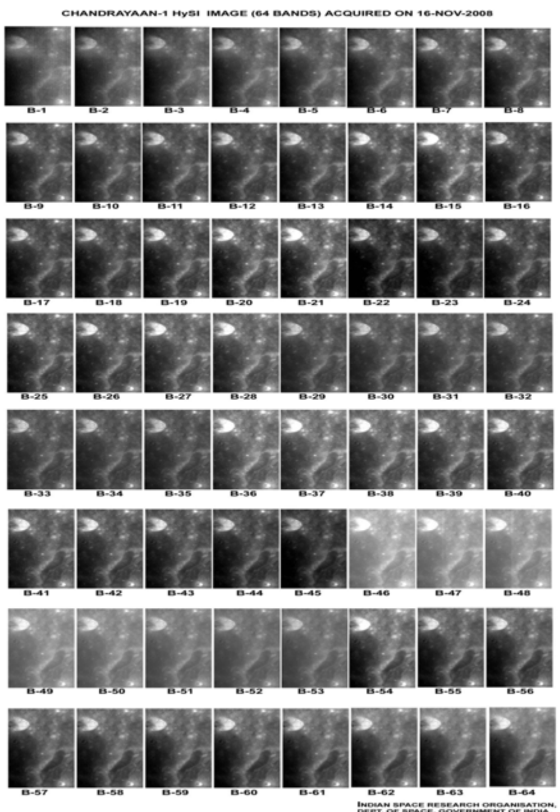

Figure 10 (a). 64 bands of image taken near lunar equatorial region.

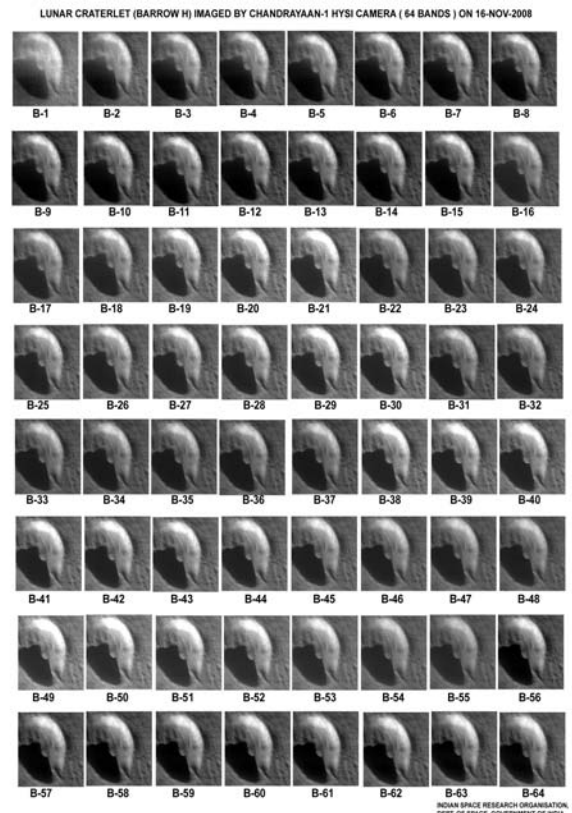

Figure 10 (b). 64 bands of images of craterlet barrow H.

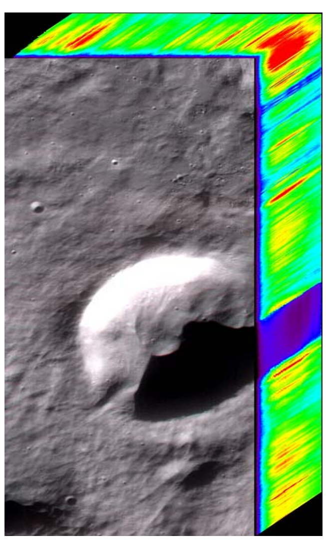

Figure 11. Hyper cube of a isolated crater

Figure 11 is a hyper cube of a single crater. A hyper cube is obtained by stacked all 64 images (one from each band) of the same surface topography. In this case, the information has been color coded to make it easier to detect changes in the chemical makeup of the surface.

4. C468 (FIVE BANDS CMOS SENSOR)

The C468, five bands image sensor array consists of five independent sensor lines: one PAN band and four MS band which designates as MS1, MS2, MS3 and MS4, packaged in a ceramic substrate. The PAN band has a total of 12,000 pixels, the pixel size is 10 μm square on a pixel pitch of 10 μm. The multi-spectral (MS) bands, (MS1 ~ MS4), each band has 6000 pixels, the pixel size is 20 μm square on a pixel pitch of 20 μm. Five bands arranged on MS1, MS2, PAN, MS3 and MS4 sequence. The spacing between each band to neighbor band (MS1 to MS2, MS2 to PAN, PAN to MS3, and MS3 to MS4) is 4 mm. Thus, the focal plane (image sensor area) is 120 mm x 16.02 mm. A 132 pin of Pin Grid Array (PGA) ceramic package is used to house the silicon chip. The space qualified radiation hardness glass window with double side AR coating is used to seal the silicon sensor. The device after package is 155 mm x 60 mm x 8.77 mm.

The device uses our proprietary technologies (e.g., wafer butting, multi chip butting, and multiple readout) to achieve the requirement of gapless image pixel line and very short integration time. The array is designed to provide a high resolution, low power consumption for high attitude (~ 720 km) earth orbit RSI application. The C468 is mixed mode MSOC IC that integrates active pixel sensor (APS), programmable gain amplifier (PGA), 12 bit analog to digital (ADC), voltage regulator, low voltage differential amplifier (LVDS) and timing generator together. The C468 is also built with power down mode that will consume a very small of power while the focal plane array (FPA) is not active. The device is response over the spectral wavelength of 450 to 900 nm with five different bands. With external multi mode filter, it is defined as: PAN (450 ~ 700 nm), MS1 (455 ~ 515 nm), MS2 (525 ~ 595 nm), MS3 (630 ~ 690 nm), and MS4 (762 ~ 897 nm). A scribe line is designed between each band to band. Therefore, all five bands are total isolation and an independent chip. All of five sensor bands are electrically isolated. The user can power on any band of the sensor array independently. This functionality allows the user to read different colors from the imager.

4.1 Device description:

The C468 utilized our proprietary technologies to achieve gapless image pixel line with five sensor arrays: four MS (MS1 ~ MS4) bands and one PAN band. Each band consists of four identical sub-chips so there are a total of 20 sub-chips. Figure 12 shows the principle to produce a long image sensor packaged in a ceramic substrate. The sequence of band to band is MS1, MS2, PAN, MS3 and MS4 (see figure 13).

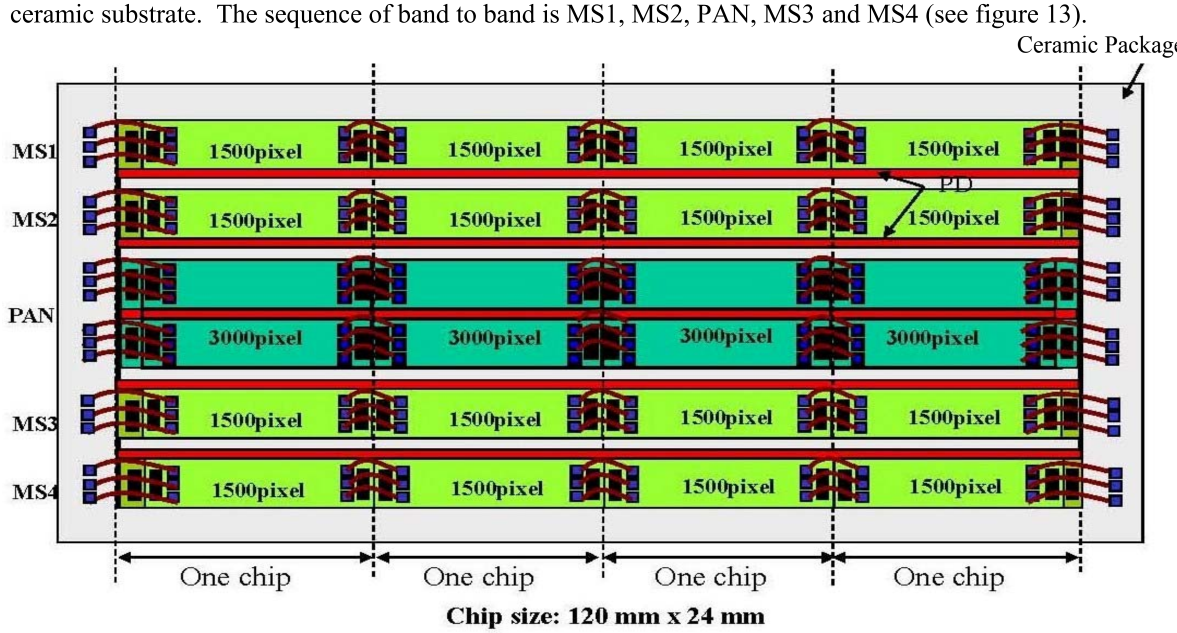

Figure 12. Demonstrate C468 sub-chip diagram in a ceramic package

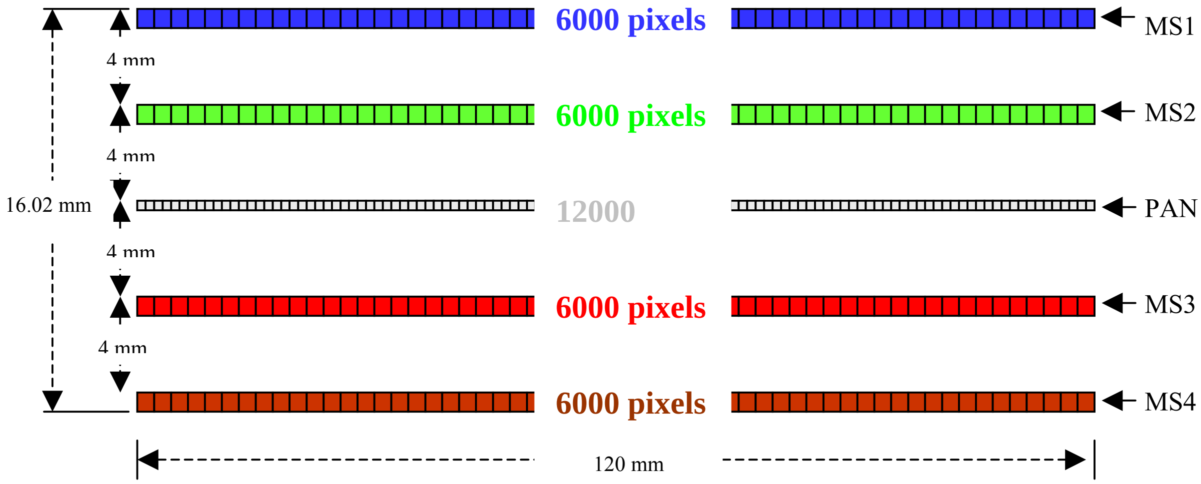

Figure 13. Band to band sequence.

Since the sensors are manufactured on the same wafer, the registration errors between bands to band cannot occur. All of the pixels are in same elevation. The color image produced with this approach is superior to conventional CCD method of assembling several individual CCD array onto a FPA.

4.2 Device specification:

The specification of C468 device is displayed in table 5.

Item	Specification	
Readout mode	Snap shot operation; Start and stop integration of all pixels simultaneous	
Integration time	PAN	297 us ± 5%
	MS (MS1 ~ MS4)	594 us ± 5%
Dark Current	≤ 1000 electrons / s /pixel for all pixels of the array	
PSRR of the device	≥ 60dB on all the supply lines at readout frequency	
Power consumption	PAN	1.6 W
	MS1	0.8 W
	MS2	0.8 W
	MS3	0.8 W
	MS4	0.8 W
	Total	4.8 W
Full well capacity	PAN	32,000 electrons
	MS1	95,360 electrons
	MS2	138,000 electrons
	MS3	132,000 electrons
	MS4	123,000 electrons
Dark offset non-uniformity	Dark signal variation is less than 5 times its noise level at mean radiance.	
Residue (Line to Line)	< 1% when alternate Lines are illuminated up to 90% of Full Well	
Non-linearity	< 1% in 10% to 90% of Full Well for any pixel	
Maximum non-uniformity	< 1% RMS including FPN	
Anti-blooming	On chip lateral anti-blooming structure	

Band	Band definition (nm)	Mean irradiance (W/m2)	Saturation irradiance (W/m2)	SNR @ mean irradiance
PAN	450 ~ 700	0.1820	0.5460	> 93
MS1	455 ~ 515	0.0397	0.1193	> 100
MS2	525 ~ 595	0.0467	0.1402	> 100
MS3	630 ~ 690	0.0413	0.1239	> 100

MS4	762 ~ 897	0.0815		0.2445		> 100
PAN @ 50 lp / mm						
	450	500	550	600	650	700
Min MTF	0.723	0.694	0.664	0.604	0.538	0.507
MS @ 25 lp / mm						
	MS1	MS2	MS3	MS4		MS1
Min MTF	0.78	0.766	0.716	0.655	Min MTF	0.78

Table 7. C468 specification

5. SUMMARY

Three CMOS image sensor was design for space application. Both C640 and C650 were launched to moon orbit and the moon surface were taken and sent back to earth for analysis. The image quality and device performance can compete with CCD camera. Since CMOS Sensor can integrate not only sensor array but also analog circuitry, digital circuitry into a tiny silicon chip, the support circuitry to operate the CMOS is very simple. The result is whole camera design is very simple, light weight and low power consumption which is superior than CCD device. The third CMOS Senor, C468, will launch to the earth orbit soon. This work provides an evidence for CMOS Sensor as an alternate solution other than CCD device for RSI applications.

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