Flexible High Performance IR Camera Systems

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ABSTRACT

Indigo Systems Corporation has developed a family of standard readout integrated circuits (ROIC) for use in infrared focal plane array (IR FPA) imaging systems. These standard ROIC's are designed to provide a complete set of operating features for camera level FPA control, while also providing high performance capability with any of several detector materials. By creating a uniform electrical interface for FPA's, these standard ROIC's simplify the task of FPA integration with imaging electronics and physical packages. This paper begins with a brief description of the features of four Indigo standard ROIC's and continues with a description of the features, design, and measured performance of indium antimonide (InSb), quantum well infrared photo-detectors (QWIPs) and indium gallium arsenide (InGaAs) imaging systems built using the described standard ROIC's. F

Keywords: Infrared, Camera, ROIC, InSb, QWIP, InGaAs, HCT

1. INTRODUCTION

Many of the first FPA's integrated into commercial IR camera systems had their origins in defense funded projects . At best, these FPA's were intended to be dual use; to demonstrate or advance some particular technology and be usable later in a more widely available IR camera system. Even ROIC's intended specifically for use in commercial IR cameras tend to be designed with greatest emphasis on improved capabilities, at the expense of the impact a new ROIC design has on support electronics and associated software. Consequently, each new ROIC design typically requires an entirely new support electronics design to perform FPA control, supply necessary clocks and biases, and to accept and process FPA video output. This redesign effort is undesirable. Design, fabrication, and testing of new camera electronics increases the cost of camera development. In addition, each new design adds risk to a camera development schedule.

With the market for commercial IR cameras firmly established, and an understanding of the ROIC features most users require, Indigo Systems has designed a family of ROIC devices that share a common electronic interface. Specifically, the bias voltages, and input clocks, and FPA control interface are all the same, with larger format FPA's requiring more clock periods per frame. FPA operating control for features such as windowing, on-chip-gain, charge skimming, detector bias voltage, readout order, number of outputs (1, 2 or 4), and FPA current draw adjustment is handled by a single serial data input line. These FPA's can be used with multiple detector materials, giving flexibility across the IR spectrum from the short wave to the long wave IR.

There are a number of benefits to this bottom-up approach to camera design. First, FPA support electronics need only be designed once. While different cameras may be given different feature sets to attract different groups of end users, the overhead in developing electronics is greatly reduced. Since the same camera may contain an FPA with InSb detectors for MWIR imaging, a QWIP FPA for LWIR imaging, or an InGaAs FPA to see in the SWIR, the extra effort involved with designing a camera for a new detector material/wavelength is minimized. End users also benefit from this approach. IR cameras for different wavelengths will have common user interfaces, as will cameras with different format devices.

Indigo Systems has taken the next step along this path of flexible camera development by demonstrating FPA's with different detector materials operating on the same ROIC design, the ISC9705. The first FPA's made on the ISC9705 were with InSb, QWIP, and InGaAs detectors. These devices all perform excellently. At the same time that FPA fabrication and evaluation was taking place, Indigo was designing its first camera, Merlin. The Merlin camera is the first in a family of cameras that will be designed around Indigo's standard ROIC's. Merlin cameras will be available with InSb, QWIP, InGaAs, and HgCdTe detectors all operating on ISC9705 ROIC's.

2. INDIGO COMMERCIAL ROIC DESIGNS

Indigo's family of commercial ROIC's for IR imaging are the ISC9801 and ISC9806 which have 128 x 128 pixels, the ISC9705 which has 320 x 256 pixels, the ISC9803 which has 640 x 512 pixels and the ISC9809, a 320 x 256 pixel device for low backgrounds. An ROIC for linear arrays has also been designed as a product for non-imaging IR detection applications. These ROIC's have a standardized interface and share a common set of features.. Each ROIC also has a number of unique attributes that make it optimal for certain applications.

2.1 Common features

Indigo ROIC's share the following common features:

- P-on-N InSb, HgCdTe, QWIP, or InGaAs photovoltaic or photoconductive detectors
- Snapshot signal integration
- 1, 2, or 4 outputs, up to 10Mhz per output (at 80 Kelvin)
- Windowing with invert/revert capability
- High detector bias voltage capability
- On-chip detector bias adjustment
- Charge skimming and on-chip adjustable gain
- Device power control
- Default or command mode operation

The detector materials listed are those that Indigo has either used or considers using with these ROIC's. However, other detector materials are possible. Snapshot integration of the IR scene has become an important feature for cameras systems, because it provides a method for stopping the action of fast moving events when individual frames of output are examined. Multiple output capability allows trades to be easily made between down-stream electronics complexity and frame rates. Single output mode multiplexes all pixels out through one FPA output. This is the slowest method to read out the FPA, but it requires only one A/D converter in the external camera electronics. Windowing with invert and revert are also very useful. Windowing allows users to select the area of the FPA to be read out. Selecting a window allows the user to include in the readout cycle only those pixels of interest, eliminating the output of unnecessary data. This may be done to reduce the load on data recording devices or alternately to increase the frame rate of the FPA. Invert and revert capability allow control over the order that pixels are readout. Pixel readout can begin in any corner of the device, so that compensation can be made for different FPA orientations or optical configurations. The capability for detector bias voltages to be set from external sources allows QWIP detectors and other detectors requiring high bias voltage to be biased optimally. The on-chip detector bias adjustment (disabled for external biasing) allows remote control of detector bias optimization. This feature is useful when a camera may be used for both high and low background imaging applications. Charge skimming and on-chip adjustable gain are two complimentary approaches to optimizing camera signal to noise ratio. For IR scenes that result in low signal levels on the integration capacitor, increased on-chip gain can provide immunity from down stream noise sources, resulting in an enhanced signal to noise ratio. For IR scenes with relatively high signal on the integration capacitor but little contrast (little signal variation) from pixel to pixel, charge skimming allows the removal of a DC pedestal from the signal before down-stream signal processing. Once the DC pedestal is removed, more on-chip gain can be applied to the signal, resulting in performance enhancements similar to the low signal case. Control of device power dissipation allows the RIIC power dissipation to be tailored for the specific application. In a camera that makes use of low frame rates and a single output, ROIC power consumption can be minimized; a useful feature for portable cameras. Four outputs running at the FPA maximum frame rate require more drive current and will have higher power dissipation requirements. The default mode allows the ROIC to operate with a minimum number of control inputs for applications where simplicity of the electrical interface is more important than control of all the ROIC features. Command mode allows all the operating and windowing capability to be controlled through input on a single clock line.

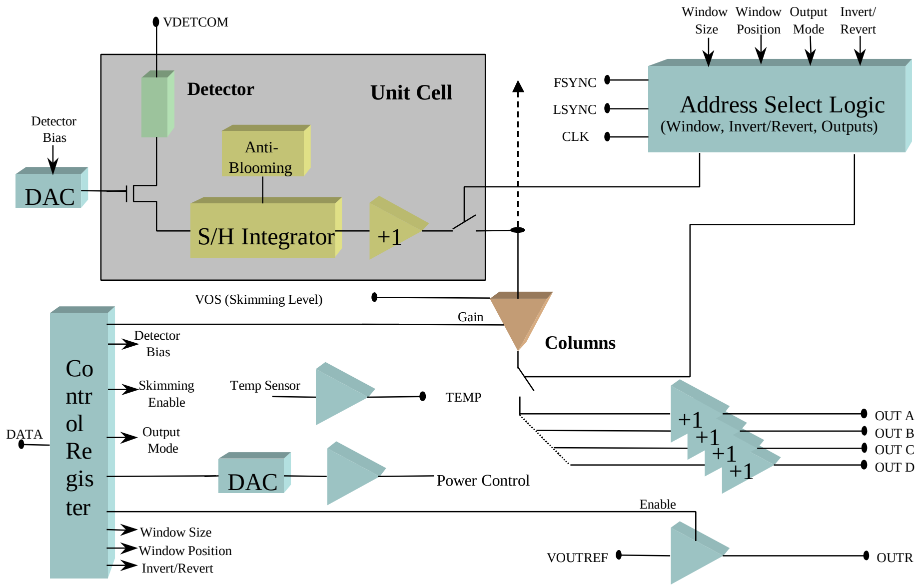

Figure 1. Typical block diagram of unit cell

2.2. 128 x 128 ROIC's : ISC9801 and ISC9806

The design is functionally the same for the ISC9801 and the ISC9806. However, the ISC9801 requires detectors with 30-micron pitch while the ISC9806 requires 38-micron detectors. In addition to the set of features that is common to all the Indigo ROIC designs, these two ROIC's have a number of unique attributes. Both designs come in two versions with either a 6.2 million electron charge capacity or an 18 million electron charge capacity. Each has a maximum full frame output rate of 1200 frames per second. Applications for these ROIC's include FPA process development and low cost imaging systems. Figure 2 lists the specifications for the ISC9801. The ISC9806 has the same specifications except for pixel pitch.

Parameter	Value
Format	128 (H) x 128 (V)
Pixel Pitch	30µm x 30µm
Storage Capacity	6.2e^{6} electrons (.2pF C_{int}) 18e^{6} electrons (.6pF C_{int})
Operability	≥ 99.99%
Dynamic Range	> 72 dB
Readout Noise	< 400 electrons
Non-Linearity	< 0.5%
Cross Talk	< 0.1%
Input Polarity:	p on n
Integration Time	> 5µsec, adjustable
Number of Outputs	1, 2 or 4 selectable
Output Signal Swing	3 volts
Power Dissipation	< 24mW at 280 Hz single output <95mW at 1200 Hz, 4 outputs
Max Frame Rates (full frame)	1 output, 480 Hz 2 outputs, 800 Hz 4 outputs, 1200 Hz

Figure 2. Specification for the ISC9801

2.3. 320 x 256 ROIC's : ISC9705 and ISC9809

The ISC9705 was the first commercial ROIC designed by Indigo and has become the most popular of the presently available ROIC's. This device has an 18 million electron charge storage capacity and a maximum full frame output rate of 346 frames per second. Applications for this ROIC are extensive and include general purpose imaging cameras, high speed IR data acquisition systems, vehicle mounted FLIR's, thermographic cameras, non-destructive testing, and laser imaging. The specification for the ISC9705 is contained in Figure 3.

Parameter	Value
Format	320 (H) x 256 (V)
Pixel Pitch	30µm x 30µm
Storage Capacity	$18e^6$ electrons
Operability	≥ 99.99%
Dynamic Range	> 72 dB
Readout Noise	700 electrons
Non-Linearity	< 0.5%
Cross Talk	< 0.1%
Input Polarity	p on n
Integration Time	> 5µsec, adjustable
Number of Outputs	1, 2 or 4 selectable
Output Signal Swing	3 volts
Power Dissipation	< 30mW at 60 Hz, 1 output <120mW at 346 Hz, 4 outputs
Max Frame Rates (full frame)	1 output, 110 Hz, 2 outputs, 202 Hz 4 outputs, 346 Hz

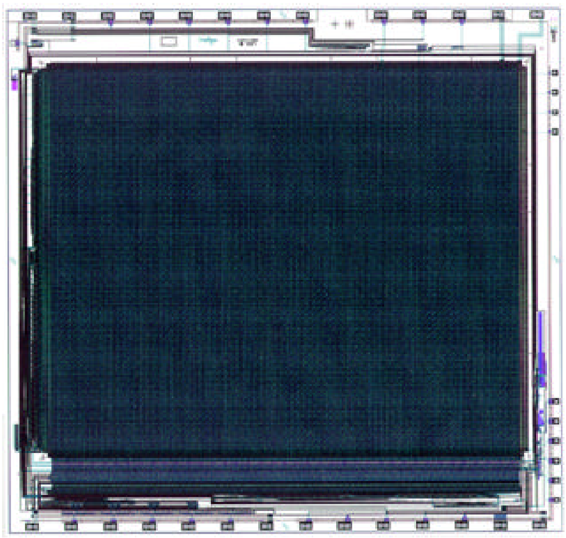

Figure 3. Specification and picture of the ISC9705

The ISC9809 is designed for low background applications. This readout has much smaller charge handling capacity and has the unique capability to switch between a 3.5 million electron integration capacitor and one with a 175 thousand electron capacity. Multiple reads of the integration capacitor between reset are possible and can take place during integration. This ROIC can use both n-on-p detectors and p-on-n detectors. This design also features on-chip selectable bandwidth limiting. Figure 4 shows expected performance for the ISC9809.

Parameter	Value
Array Configuration	320 (H) by 256 (V)
Pixel Pitch	30µm x 30µm
Storage Capacity	175K carriers or 3.5M carriers (selectable)
Operating Temperature	Room Temperature to < 80 Kelvin
Total Readout Noise	~ 50 electrons (Room Temperature) ~ 25 electrons (80Kelvin)
Number of Outputs	Selectable 1, 2, or 4
Maximum Output Data Rate	10MHz at Room Temperature
Maximum Frame Rates (Full Frame)	110 FPS (One Output) 200 FPS (Two Outputs) 350 FPS (Four Outputs)
Power Dissipation	< 15mW (Minimum, One Output) < 75mW (Nominal,(One Output, 10Mpix/sec) < 150mW (Maximum, Four Outputs, 10Mpix/sec)
Output Voltage Swing	> 2.5 Volts
Non-Linearity	< 0.1%
Integration Time	0.5µsec (0.25µsec at 80 Kelvin) to ~ Frame Period

Figure 4. Specification for the ISC9809

2.4. 640 X 512 ROIC: ISC9803

The ISC9803 includes the addition of an optional clock line to allow readout order in interlaced format for applications that can use this readout option to simplify off-chip display electronics. This ROIC features 25 micron pixels and can operate in full frame output mode at frame rates up to 108 Hz. Applications for the ISC9803 include high resolution imaging cameras, military FLIR systems, and long range surveillance cameras.

3. FPA'S MADE WITH STANDARD ROIC'S

Presently eight different manufacturers have used or are currently using Indigo standard ROIC designs to fabricate IR FPA's. Consequently, Indigo has access to multiple detector materials and fabricated FPA's for evaluation and resale using InSb, LWIR QWIP and InGaAs detectors with the ISC9705 ROIC. All FPA's were fabricated from ROIC's that passed a complete set of functional and performance tests, as is the norm for all Indigo commercial ROIC testing. These FPA's have excellent performance and have allowed full verification of the ISC9705's predicted performance. Typical performance tests include measurement of noise equivalent delta temperature (NEDT), quantum efficiency (QE), uncorrected uniformity, and operability.

3.1. InSb FPA performance

The InSb FPA's that have been tested are anti-reflection (AR) coated for optimized performance in the 3 to 5 micron spectral range. Testing is performed at 80 Kelvin in liquid nitrogen cooled test dewars. Thus far, over 25 FPA's have been tested, demonstrating both the capability of the InSb manufacturers and the suitability of these FPA's for use in camera systems. Typical performance numbers are listed in figure 5.

Parameter	Value
NEDT (@ 25° C and f/3.6)	< 0.020° C
QE	> 75%
Uncorrected non-uniformity	< 5% (σ/mean)
Operability	> 99.9%

Figure 5. Typical InSb FPA performance

3.2. LWIR QWIP FPA performance

QWIP FPA testing also measures NEDT, QE, uncorrected uniformity, and operability. Typically these FPA's are not AR coated and the QE is low compared to InSb. However, the higher background in the LWIR band, partially compensates for the lower QE. Only a few LWIR QWIP FPA's have been fabricated so far. The performance and corrected uniformity have been excellent for the devices that have been tested and used to generate an image. Figure 6 is a table that lists average performance values for the two FPA's that have been tested.

Parameter	Value
NEDT (@ 25° C and f/1.9)	0.0016° C
QE	0.5%
Uncorrected non-uniformity	5.1% (σ/mean)
Operability	99.96%

Figure 6. Average QWIP FPA performance

3.3. InGaAs FPA performance

At the time of publication, only one InGaAs FPA had been fabricated using the ISC9705. Other FPA's will be made in the future using the ISC9809 ROIC which is better matched to the low signal levels generated by these detectors for many applications. Because InGaAs material responds to SWIR, noise equivalent irradiance (NEI) and not NEDT is a more relevant performance parameter. Figure 7 is a table showing performance for the one FPA tested. The operability is lower than expected and the uncorrected uniformity higher than expected due to undetected defects in the material chosen for the first FPA. Future operability is expected to exceed 99%, with uncorrected non-uniformity approaching 2%.

Parameter	Value
NEI	3.88E+10 ph/cm^{2}s
QE	95%
Uncorrected non-uniformity	17.5% (σ/mean)
Operability	98.1%

Figure 7. Performance for the first InGaAS ISC9705 FPA

4. MERLIN CAMERA FAMILY

The Merlin camera family will incorporate ISC9705 and ISC9809 FPA's with InSb, QWIP and InGaAs detectors. These cameras will be distinguished from each other as Merlin M (mid-wavelength, InSb), Merlin S (short-wavelength, InGaAs) and Merlin L (long wavelength, QWIP). The Merlin camera design is intended to meet the needs of price sensitive users who are looking for high performance, medium format IR cameras. The Merlin electronics package does not make full use of the ISC9705 capabilities for windowing or high-speed operation, in an effort to be a lower cost, entry-level product. Figure 8 shows a rendering of the Merlin camera.

Figure 8. Perspective view of Merlin camera, showing top mounted button panel/remotecontrol

4.1. Merlin camera features

4.1.1. Display features

The Merlin camera display features include S-video and RS-170 video output formats (available simultaneously) and 12-bit digital image data. The video outputs are updated at the standard 30 Hz rate, while the FPA's frame rate and the camera's digital output operate at 60 frames per second. PAL video output is also available as a factory configurable option in place of RS-170. Camera symbology generation allows cross hairs and menus to be displayed on the video output. Display control allows selection of color or grayscale video lookup tables. Adjustment of brightness and contrast can be performed manually or by the camera's automatic gain control (AGC).

4.1.2. Camera control

The Merlin camera may be operated through the button panel/remote control or via personal computer, using supplied camera control software to send control commands over the serial port. The button panel/remote control is designed to fit into a recessed section of the upper camera housing for storage or use as a camera control keypad. Alternately, the button panel/remote can be removed and used as a wireless remote control. The buttons on the remote allow instant adjustment of brightness and contrast, selection of the AGC on/off, and selection of stored non-uniformity corrections with their associated camera settings. Other buttons are designed for easy navigation and selection of the on-screen menus. Camera control using a computer gives access to all the on-screen control and allows more advanced camera features to be accessed including the upload of new camera firmware.

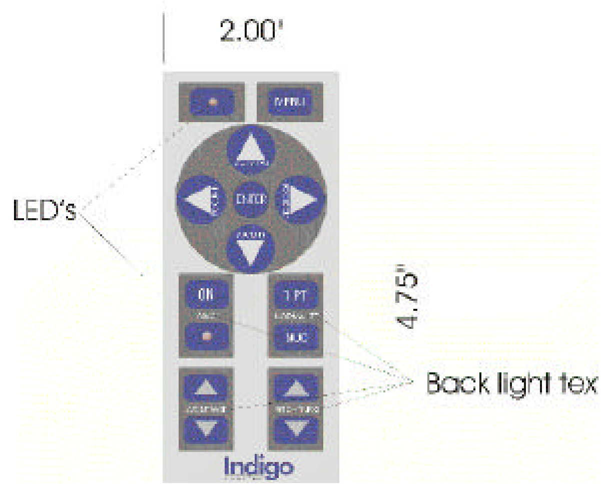

Figure 8. Merlin camera button panel layout

4.1.3. Non-uniformity correction

The Merlin camera allows two point (gain and offset) and one point (offset) non-uniformity corrections (NUC) to be performed using the camera's internal calibration flag or user supplied external sources. The calibration flag temperature can range from 15° C below the ambient temperature to at least 20° C above the ambient temperature. Two point NUC results in the formation of an inoperable pixel map, allowing the inoperable pixels to be replaced by the output of an operable nearest neighbor, both in the video and digital outputs. One point NUC provides an update to each pixel's NUC offset value without changing the existing gain value. The one point NUC process will leave the bad pixel map unchanged.

4.2. Mechanical

The Merlin mechanical design has several points of focus. First, while accommodating previously designed electronics and an existing cryo-cooler, minimization of the size and weight of the camera was identified as an important design criteria. In addition, the design had to accommodate splitting the sensor head from most of the electronics for certain OEM applications. These requirements led to a design that mounts the cryo-cooler and electronics to an internal frame and allows a lightweight external case to be "wrapped" around the frame. The OEM user with specific packaging requirements will be able to easily split the camera, using the internal frame to keep the split components in place. Camera end users will benefit from a design that results in a sleek lightweight enclosure, while maintaining rigid mounting points for lenses and a tripod. One design aspect that received specific consideration was the optical interface. Indigo sought to create a design that would be manufacturable, while maintaining mounting tolerances for the FPA and lens positions. Another mechanical design consideration was camera cooling. After careful consideration of the trades, a convective cooling approach was chosen over a sealed conductive design. This decision was based on projected types of end use, Indigo's own experience with both convective and conductive cooling designs, and input from prospective customers.

4.3. Electronics

The Merlin electronic functions are handled by four primary electronics boards: a camera controller printed circuit board (PCB), an FPA support PCB, an FPA close proximity (proxy) PCB, and a DC to DC power supply PCB. Other peripheral connections from these boards are made to the button panel/remote control, the cryo-cooler temperature controller (built into the cryo-cooler), the calibration flag motor, thermal electric cooler (TEC) and a motorized lens controller (if applicable). A top level block diagram of the Merlin electronics can be seen in figure 9.

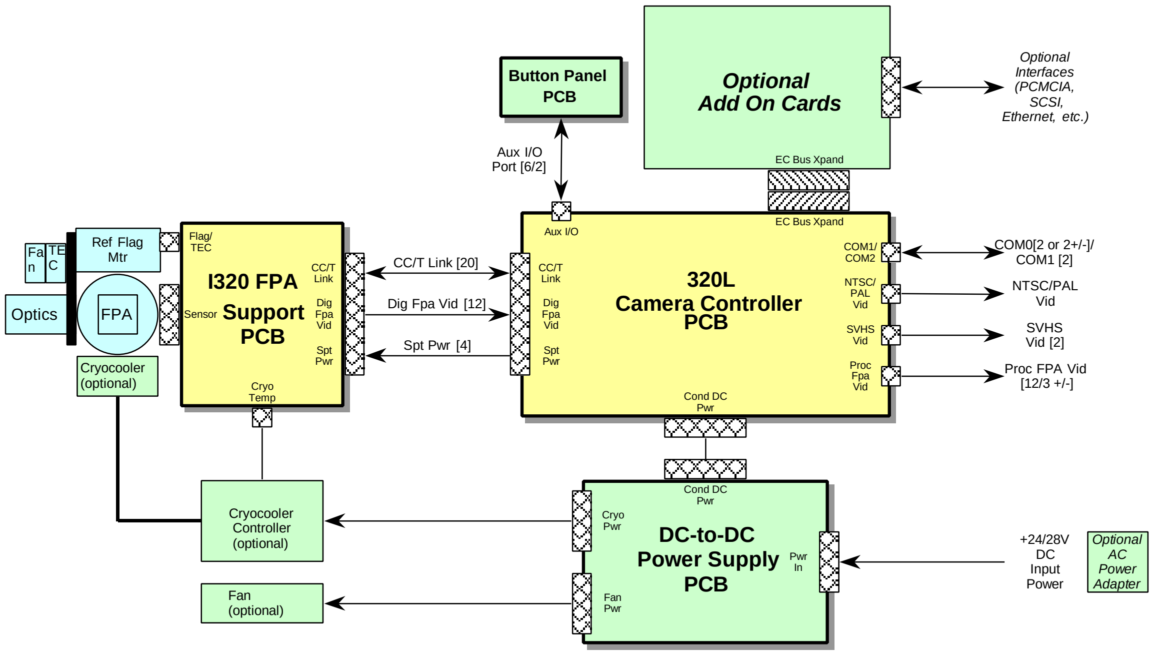

Figure 9. Merlin camera electronics top level block diagram

4.3.1 Camera controller PCB

The camera controller PCB handles all of the digital processing for NUC, AGC, and pixel replacement. The camera controller also generates the video and digital output, processes all camera control inputs and handles serial communication. The camera controller interfaces with the button panel/remote control, and the FPA support board to send FPA control commands and receive 12 bit analog to digital (A/D) converted FPA output. Figure 10 shows a block diagram of the camera controller PCB.

4.3.2 FPA support PCB

The FPA support board generates required FPA clock inputs and bias voltages and supplies the TEC drive. Inputs to the FPA support board come from the proxy board in the form of buffered FPA output, calibration flag temperature sensor output and camera controller input for FPA control. The FPA support PCB is shown in figure 11.

4.3.3 Proxy PCB

The proxy board is an input/output buffer for signal coming from and going to the sensor head (FPA, cryo-cooler, proxy board and calibration flag). The inputs to the proxy board from the FPA support board are clocks and biases. These signals are level shifted and filtered by the proxy board prior to being sent on to drive the FPA. The proxy board also passes through FPA support board signals for the calibration flag operation. The FPA output signal is buffered by the proxy board and driven to the A/D converter on the FPA support board. The proxy board is designed to handle a split of up to three meters between the sensor head and the FPA support board. The proxy board also passes FPA temperature sensor output to the cryo-cooler controller.

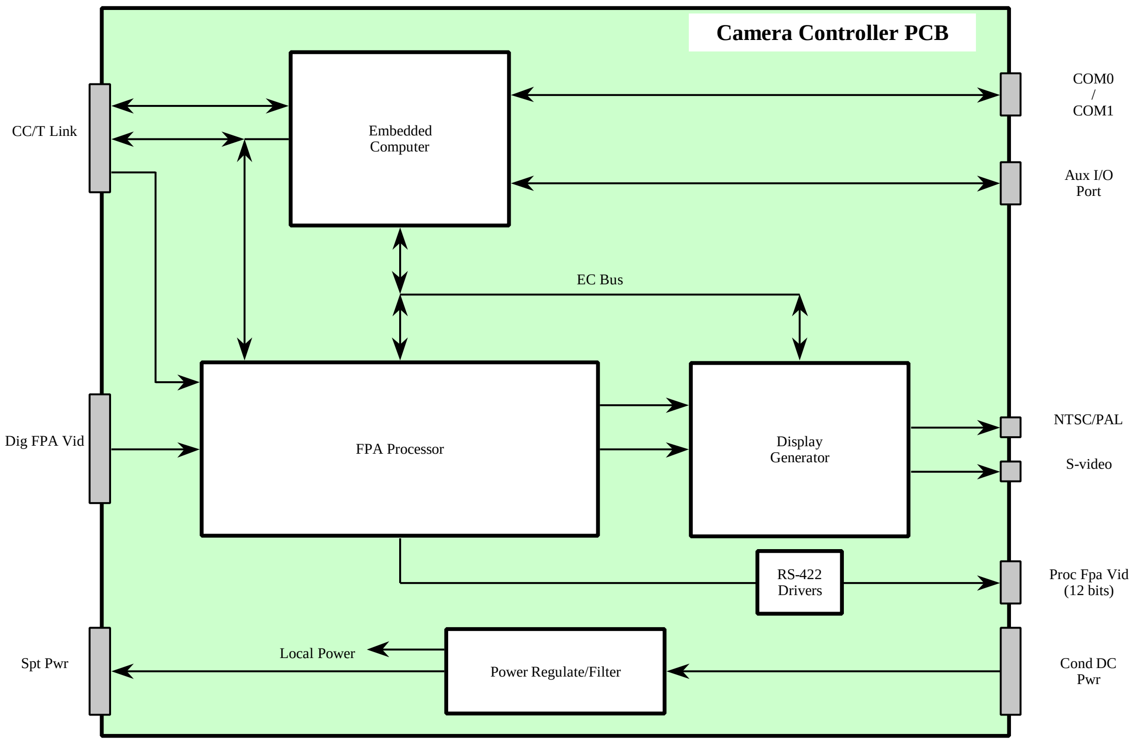

Figure 10. Camera controller PCB block diagram

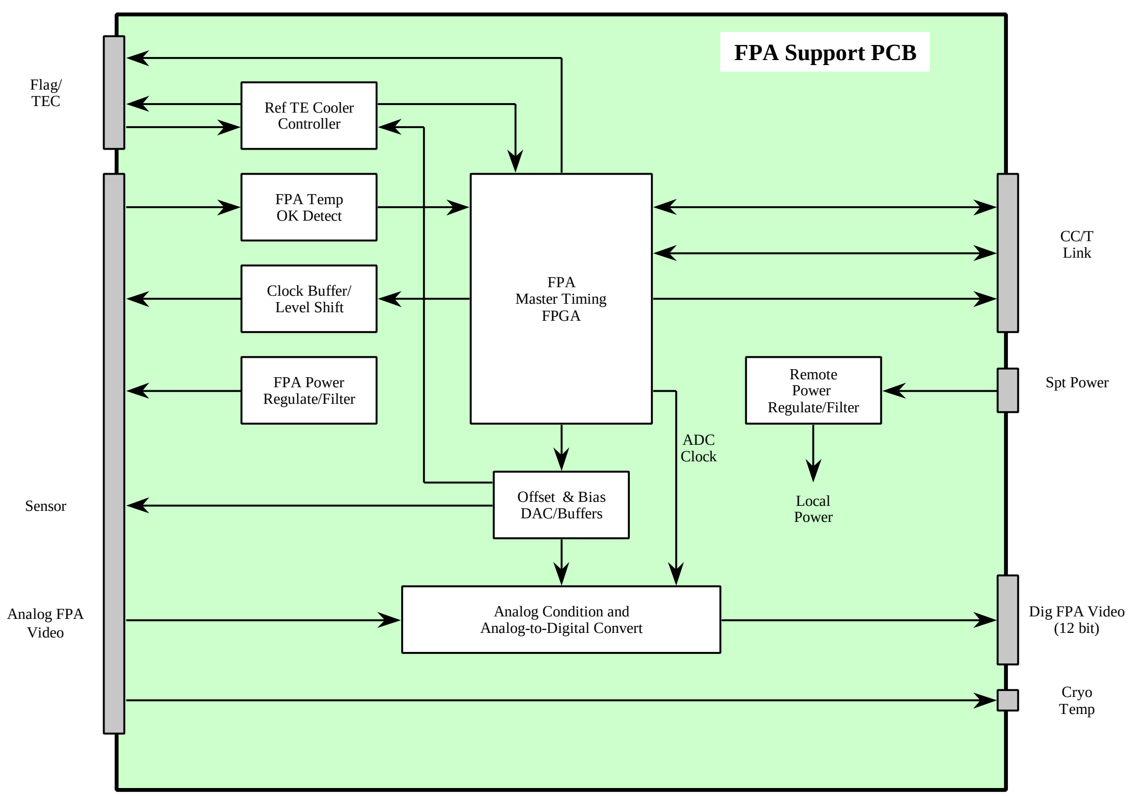

Figure 11. FPA support PCB block diagram

4.4. Optics

The Merlin camera will support a number of different lens designs and mounts, to accommodate specific requirements for the different camera versions and make use of some off-the-shelf designs. Merlin M cameras with InSb FPA's will be base-lined with f/4 cold shields and 3-5 micron cold filters. A family of f/4 lenses is being designed for this camera version. The decision to make Merlin M an f/4 camera, was based on the number of end use applications requiring custom long focal length lenses and the negligible impact an f/4 design has on most short focal length applications. The bandpass for the QWIP cameras was deliberately left open. Since QWIP detectors have spectral response roughly one micron wide, the detector material selects the operating bandpass. The f-number of the QWIP camera was chosen to reduce the diffraction limited blur spot size and to accommodate some existing lens designs. The Merlin S cameras will initially make use of existing C-mount visible wavelength lenses that also transmit SWIR. The f-number for these lenses can be controlled by an external (warm) aperture since in the wavelengths of interest there is negligible signal from the emission of room temperature objects.

Camera	**f-number**	**Spectral band-pass**	**Lens focal length (mm)**	**Lens mount**
Merlin M (InSb)	f/4	3-5 microns	100, 50, 25, 13 and custom long FL	Bayonet
Merlin L (QWIP)	f/2	8-12 microns	100, 50, and 25	Bayonet
Merlin S (InGaAs)	f/1.4 – f/16*	0.8 – 2 microns	100, 50, 25	C mount

* Aperture in lens allows f-number adjustment

Figure 12. Optical specifications for the Merlin camera family

5. CONCLUSION

By standardizing interfaces across all of its commercially available ROIC's, Indigo has sought to make its own camera development easier and less expensive while simultaneously creating simplified upgrade paths for our ROIC customers. The availability and compatibility of multiple detector materials that can be operated on the same ROIC makes the Merlin camera unique among IR cameras and offers the simplicity of a common camera interface to end users. At the time this paper was published, the first Merlin cameras with InSb, LWIR QWIP and InGaAs FPA's were being prepared for the 1999 SPIE conference.