Cameras for Indian remote sensing satellite IRS-1C

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As a part of its commitment to use space technology for national development, Indian Space Research Organization has successfully developed and placed four operational Remote Sensing Satellites, IRS-1A, 1B, P2 and 1C in orbit. The first two satellites carried 4-band CCD cameras to image the earth from polar sun synchronous orbits at spatial resolutions of 72 and 36 m respectively. IRS P2 carried a 4-band 36 m resolution camera. The data from these remote sensors have been extensively used by a variety of user agencies in various programmes for national development.

To expand and continue the operational services to the user community, ISRO launched the second generation IRS satellite IRS-1C on 28 December 1995, with significantly increased capabilities for remote sensing. The IRS-1C carries three distinct and mutually complementing imaging payloads, providing considerable improvements in spatial resolution, spectral coverage, and capability for stereoscopic imaging. Improved temporal resolution is catered for through the inclusion of a sensor with a wide field of view coverage. In this article we briefly survey the design features of these three cameras.

INDIA has been pursuing a well laid out policy of using space programmes for the economic benefits of the country. Pursuant to this policy, Indian Space Research Organization successfully developed and launched the operational first generation remote sensing satellite IRS-1A in March 1988. This satellite carried two imaging payloads with Linear Imaging Self-Scanning (LISS) sensors. The remote sensing instruments on IRS-1A consisted of:

- A LISS-I camera operating in four bands in the 0.45–0.86 μm region with geometric resolution of 72.5 m and a swath of 148.48 km.
- Two LISS-II A/B cameras operating in four bands, similar to LISS-I but with a geometric resolution of 36.25 m and each with a swath of 74.24 km. The fields of view of the two LISS-II cameras were displaced laterally so as to provide a combined swath of 145.48 km with an overlap of 3 km. Both, LISS-I and LISS-II operated in the push-broom scanning mode using linear CCD arrays of 2048 elements.

A second satellite IRS-1B, similar to IRS-1A, was launched in August 1991. A third operational remote sensing satellite IRS-P2 was launched in October 1994 using the Polar Satellite Launch Vehicle (PSLV) developed by ISRO. IRS-P2 carried only the LISS-II camera, now modified to provide the combined swath of LISS-II A/B of IRS-1A/1B in a single optics module.

IRS-1B and IRS-P2 are presently in use providing information on earth resources to various user agencies on an operational basis. The IRS-1C carries three distinct and mutually complementing imaging payloads which enhance the capabilities of IRS-1C as compared to IRS-1A/1B in terms of spatial, spectral and temporal resolutions.

Camera configurations

IRS-1C spacecraft carries three cameras: Panchromatic camera (PAN), Linear Imaging Self-Scanning sensor (LISS-3) and Wide Field Sensor (WiFS).

All the three cameras operate in the push-broom scanning mode employing linear array charge coupled devices.

The PAN camera provides a spatial resolution of 5.8 m at nadir and operates in a single (0.5–0.75 μm) panchromatic spectral band. This camera covers a ground swath of 70 km which is steerable up to ±26° from nadir in the across track direction. This off-nadir viewing provides the capability to acquire stereoscopic pairs from two different orbits and an ability to revisit any given site with a maximum delay of five days.

The LISS-3 camera is a multispectral system operating in four spectral bands, three in the visible-near infrared (VNIR) range which are identical to B2, B3 and B4 of IRS-1A/1B and one in short wave infrared (SWIR)-band B5. LISS-3 provides a ground resolution of 23.5 m in VNIR and 70.5 m in SWIR with a swath of 141 km and 148 km respectively for VNIR and SWIR.

The WiFS camera has a spatial resolution of 188 m and covers a swath of 804 km. This wide swath coverage results in a repeatable observation of the same ground location after every 5 days. The WiFS operates in the B3 and B4 spectral bands of LISS-III (0.62–0.68 μm and 0.77–0.86 μm). Table 1 summarizes the specifications of the three IRS-1C camera systems.

The optical subsystems

Quite early in the design study it was apparent that the high spatial resolutions and sizable field of view required for the PAN camera cannot be met by the traditional centrally obscured reflector telescope designs. Weight and volume considerations also precluded designs with Schmidt correctors. The PAN camera uses an all reflective off axis f/4.5 unobscured three mirror telescope of 980 mm focal length. The optical design features an off axis primary hyperboloid mirror, a spherical secondary mirror and an off-axis ellipsoidal tertiary mirror. By using off-axis sections of conic surfaces, obstruction of the incoming radiation is avoided, resulting in higher modulation transfer function for a given aperture. The optical configuration is shown in Figure 1. Since the image format (85 mm) is too large to be covered by a single CCD, an arrangement of 3 CCDs is used to cover the full swath using a reflective prism. The configuration of the PAN camera is shown in Figure 2 and Figure 3 shows the flight instrument of PAN camera.

The LISS-III and WiFS cameras are realized using refractive optics. In the case of LISS-III, the camera for each band is realized using a lens with the detector at its focal plane. The basic design of all the four lenses of LISS-III is similar. The lens design is derived from the double Gauss architecture and is optimized separately in each spectral band to obtain the best MTF performance. The design features a very low sensitivity of effective focal length (EFL), flange focal distance and stability of collinearity to temperature variation. The lenses for bands B2, B3 and B4 are f/4.35, with a focal length of 347.5 mm and operate at 50 lp/mm; whereas band B5 has focal length of 301.04 mm and is f/4.35 operating at 20 lp/mm.

Hard coated 4 cavity interference filters have been used in these lenses for spectral selection, and an entrance thermal filter, made of fused silica, makes one degree angle with the optical axis of the lens assembly to avoid ghost images at the CCD plane. The LISS-3 flight instrument is shown in Figure 4.

The total field to be covered by the WiFS camera is 52°. If this were realized using single lens for each band, due to large variation in the incidence angle at the interference filter, there would be a considerable shift in the band edge positions over the field of view. To minimize the above effect, the total FOV is realized by two lenses for each band. The two lenses are mounted with their optical axes canted 13° either side of nadir. The basic optical design is similar to LISS-III except for the focal length of 56 mm. The WiFS camera is shown in Figure 5.

Table 1. Features and specifications of cameras of IRS-1C

Parameter	Specifications: PAN	LISS-III	WiFS
Instantaneous geometric field of view (m)	5.8	B2, B3, B4: 23.5 B5 70.5	188
Swath (km)	70	140	804
Spectral band (μm)	0.5–0.75	B2 0.52–0.59 B3 0.62–0.68 B4 0.77–0.86 B5 1.55–1.70	B3 0.62–0.68 B4 0.77–0.86
Camera SWR (at nyquist frequency)	≥ 20	B2≥ 40 B3≥ 40 B4≥ 35 B5≥ 30	B3≥ 35 B4≥ 30
Quantization (bits)	6	7	7
SNR (at saturation radiance)	≥ 64	≥ 128	≥ 128
Saturation radiance (mw/cm^2-sr-μm)	47 ± 2	B2 29 ± 1.5 B3 28 ± 1.5 B4 31 ± 1.5 B5 3.5 ± 0.3	B3 28 ± 1.5 B4 31 ± 1.5
Size (EO module) (mm)			
Roll	605	455	250
Pitch	903	522	335
Yaw	861	500	170
Weight (kg)			
EO module	105	76	18
Camera	125	95	23
Power			
Imaging mode	55	74	22
Calibration mode	65	78	—
Data Rate (Mbps)	84.903	35.7904 (VNIR) 1.3906 (SWIR)	2.0616

Detector assembly

The choice of the CCD device depends on element size, array length and read out configuration etc. CCDs are available in various element sizes from 7 μm × 7 μm. The element size decides a number of important system parameters such as focal length of the optics, spatial frequency of operation, F/no. of the optics, pixel size, number of pixels per detector and the number of CCD output ports.

Three 4 K, 4 port, 7 μm × 7 μm linear array CCDs operate at 70 lp/mm in the PAN camera. A metallic strip is provided at the back of the detector for detector mounting, and also serves as a heat sink.

The CCDs selected for PAN have the drawback of leaving a small residual signal at the photosite even after a read out. This would produce a radiometric error and an along track smear. To overcome this problem a constant optical bias is provided creating a 'fat zero'.

The detector, optical butting prism, LEDs for optical bias and calibration and a thermistor for monitoring the temperature are suitably mounted on the detector heads.

The detector for VNIR bands of LISS-III is a 6000-element linear silicon CCD array with pixel size of 10 μm × 7 μm with 10 μm pitch. The SWIR band (B5)

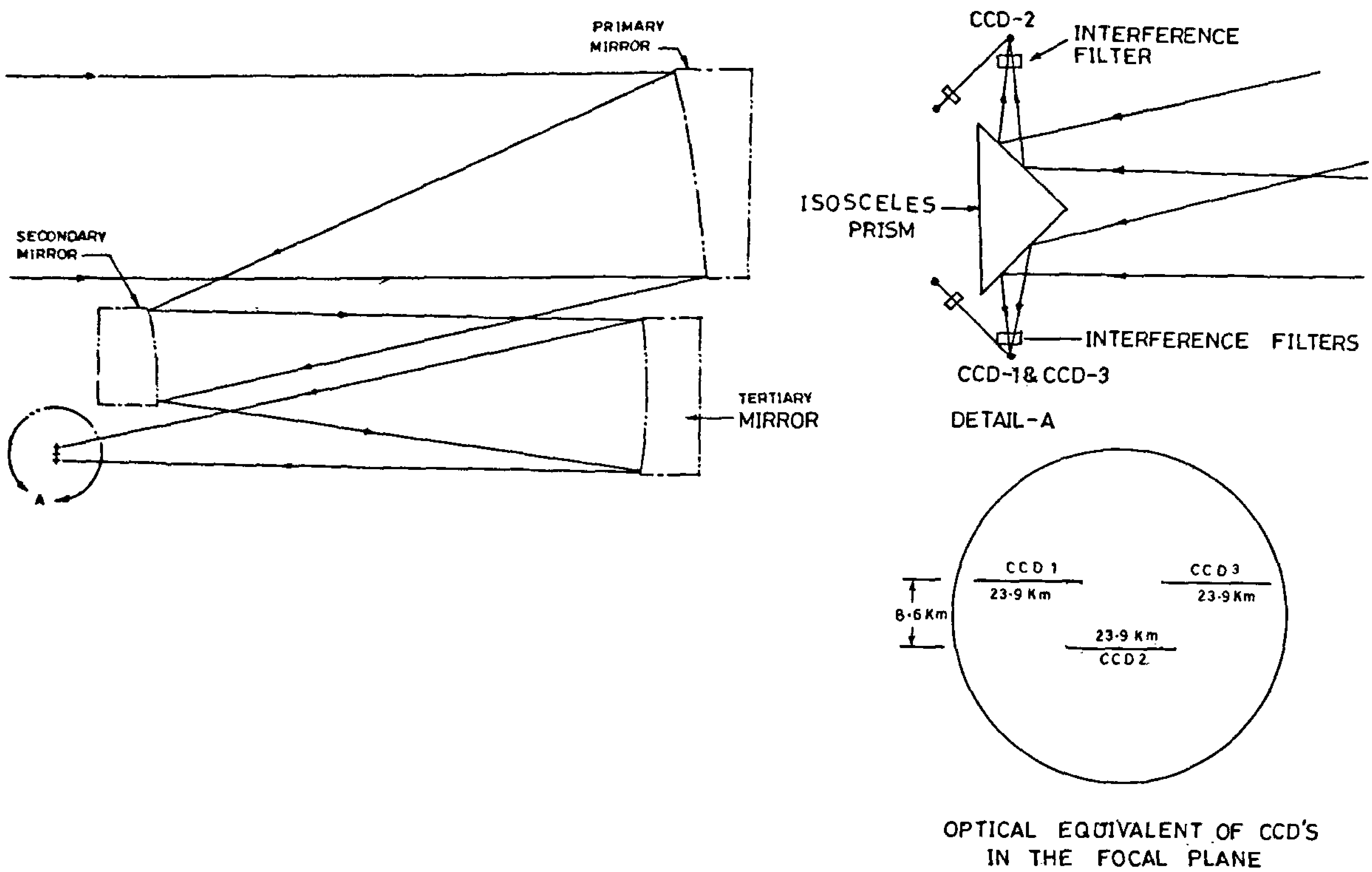

Figure 1. Optical schematic of panchromatic camera.

uses a linear array of Irridium Gallium Arsenide as the photon detector and silicon CCDs as shift registers for the read out. The 2100-element linear array is made up of 7 modules of 300 elements, each with element size of 30 µm × 30 µm at 26 µm pitch. The even and odd pixels are staggered with an along track separation of 52 µm. The SWIR detectors are cooled to –10°C to reduce thermal noise and thus improve the signal to noise ratio. The detector for each band is mounted on separate detector heads each with its own calibration LEDs. The detectors are mounted rigidly on the electro-optical head structure enabling geometrical registration between them and the final adjustment is done by moving the head as a whole relative to a reference band.

The WiFS camera uses two pairs of lenses, each in conjunction with its 2 K, 13 µm × 13 µm size linear CCD detector.

Camera electronics

The system and sub-assemblies of IRS-1C camera electronics are custom-designed to meet the detector requirements, payload specifications and the stringent space hardware requirements. The system is configured to achieve detector/quantization noise limited system performance and high reliability. The electrical band width and the configuration are selected in such a way that the electrical system does not reduce the MTF and cause any inter detector/band misregistration. The other considerations in the electrical design are avoidance of single point failures leading to a loss of the entire camera data, minimum volume, low power consumption, ease of fabrication/inspection and testability.

The typical configurations of PAN, VNIR, SWIR and WiFS camera electronics are given in Figure 6. It consists of timing and control logic, detector drive electronics, video-processors, calibration electronics and spacecraft interface. The VNIR camera electronic system is similar to that of PAN except for the fewer number of ports and non insertion of 'fat zero'.

Considering the complexities of baseband signal handling at high frequencies, power dissipations and associated component temperature rise, camera electronics of each of the detectors are realized as separate and identical units. Black painted aluminum sheets, inserted between the boards, contain temperature rise of high power dissipating subassemblies and electrical interference. The detector drive electronics including the bias generators, clock drivers and pre-amplifiers are housed in a separate package for each detector and are located close to the respective detectors.

Timing and control logic

The timing and control logic generates various clocks required for detector operation, commands for signal processing, onboard calibration, etc., using the bit rate clock (BRC). The logic systems have cold redundancy and main and redundant systems are cross coupled to enhance the reliability and improve the operational flexibility. The clock frequencies of all the cameras are derived from a single source to achieve synchronization and improved system noise performance. Considering the high frequency of BRC, the sensitivity of camera performance to timing delays and the timing logics are realized with FTTL and LSTTL devices. Panchromatic electronics is designed around 4 K CCD with four output ports, all the four ports of a detector are readout simultaneously to optimize the performance.

VNIR makes use of 6 K, two port silicon CCDs. The CCD clock transitions are aligned to the accuracy of few nano-seconds to minimize interference within the detector.

The seven modules of SWIR detector are readout sequentially to minimize processing hardware. The inter clock delays are very critical, in this detector, for the realization of the optimum detector performance. Each module of the detector is readout such that 72 extra pixels are available for each of the set of 150 useful pixels of a port. This enables derivation of pre-load and provides dummy words required for the data rate matching.

A common logic controls all the four CCD143A detectors of WiFS. Both the ports of a detector are readout simultaneously with 180° phase delay, thereby facilitating time multiplexing of video hardware. As the dark signal of CCD is significant, the system dynamic range is improved by over sampling the scene in the along track direction. The transmitted data of the detectors are spaced out and the detectors are physically offset in the focal plane.

Data generated by the three VNIR bands, a SWIR band and the WiFS are formatted and transmitted together. The readout rates of these detectors are selected to match the generation and the transmission rates of

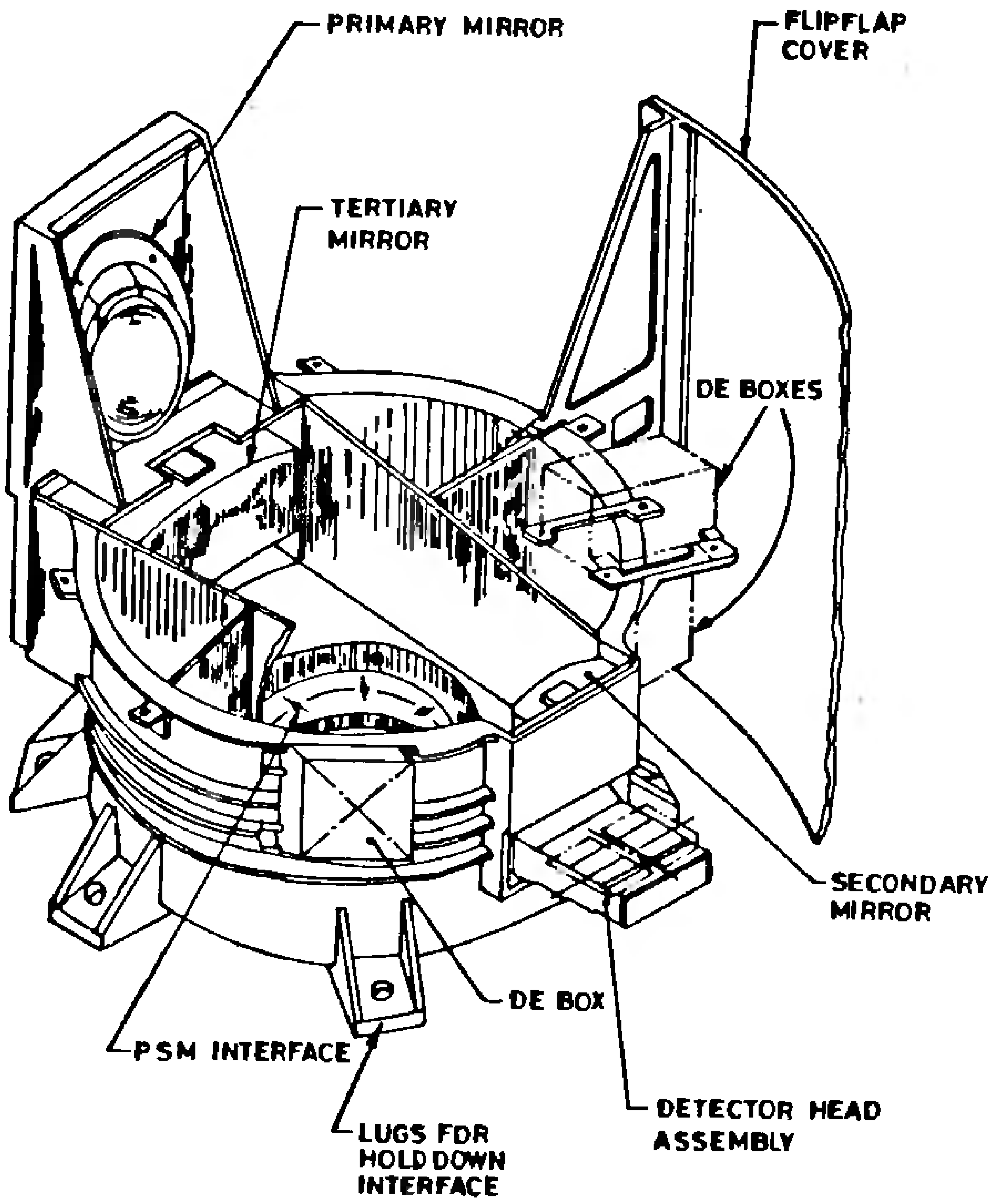

Figure 2. PAN EO-module.

Figure 3. Panchromatic camera.

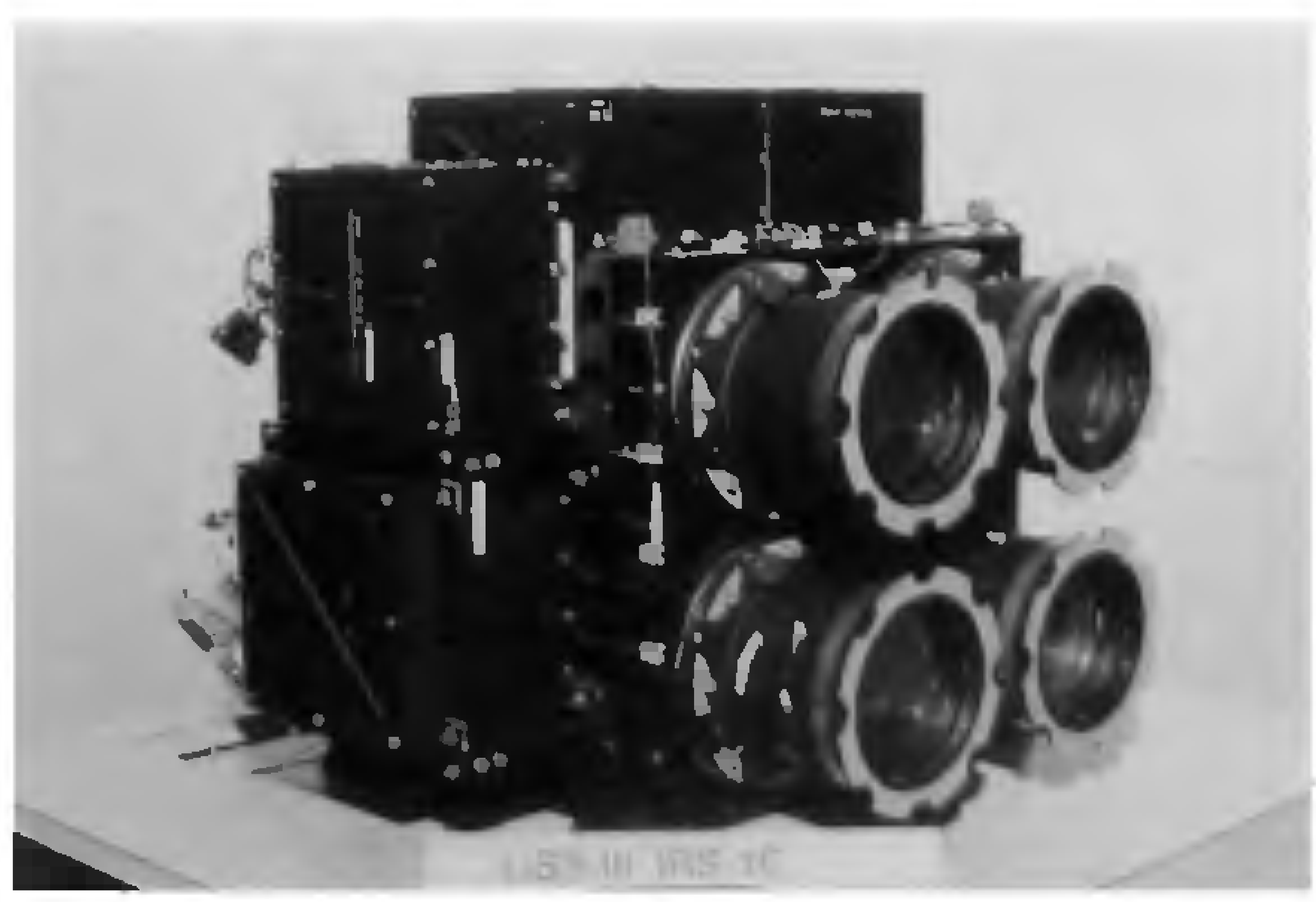

Figure 4. Linear imaging self-scanning III camera.

data with no memory elements for VNIR and minimum memory in case of SWIR and WiFS. Accordingly, additional dummy pixels are introduced in the readout to facilitate the formatter design.

Detector drive electronics

This provides various bias voltages and clocks required for the CCD operation. The bias voltages are derived using a linear regulator – capacitive multiplier filter to ensure low noise on bias lines. The circuit configuration is tuned for bias voltage, load, noise and tolerance requirements of each of the detector types. The DC and AC load requirements are met with appropriate current boosters and bypass capacitors. Current limiting is incorporated on some of the critical lines. PAN detectors are illuminated by constant DC current-driven LEDs for 'fat zero' insertion and improve along track MTF performance.

The TTL clocks generated in timing logic are buffered in clock drivers to meet the simultaneous CCD drive requirements of large voltage swings, high capacitive loads and fast rise/fall times. The clock drivers are powered through an on-card linear regulator with high ripple/spike rejection to eliminate the asynchronous noise on clock levels. The negative spikes on clock low levels are arrested to contain charge injection into shift registers and the dark signal.

Video processing electronics

The video processing involves amplification, DC restoration, true video extraction, multiplexing of ports, digitization and realization of detector/quantization limited noise performance. The detector-generated signals are of PAM type superimposed on about 11V DC. The signals are AC coupled and pre-amplified close to the detector to minimize noise pickup at low signal levels and to reduce the settling time degradation due to high output impedance of the detector. No additional sample and hold is warranted, due to the PAM nature of the signals. The processor bandwidth has to be high to realize ion settling time for ±0.5% error band. The larger bandwidth requirements necessitated use of very low noise components and optimal circuit configurations. The system saturation can be set, in the range of 1:3.5, by telecommanding the programmable gain amplifier. The overall gain of processor is selected taking into consideration the efficiency of optical system, detector responsivity, integration time and the full scale range of ADC. The stability of the amplifiers is ensured with detailed modelling, optimized placement, test selection of the devices, precise trimming, and detailed testing at various stages and environments.

Precise DC restoration of the high speed coupled signals is carried out for each pixel w.r.t. the reference level with fast switching, low charge injection CMOS switches, low soak hold capacitor and FET input fast settling op-amps. The true video extraction in PAN involves subtraction of a bias signal corresponding to the introduced 'fat zero'.

The InGaAs detector of SWIR produces 'reverse video'. The true video extraction involves accurate measurement of the preload signal, storing the same in memory and subtracting it from the readout signal in the subsequent line. The preload signal is measured after subtracting a reference voltage just less than the lowest preload encountered by the processor, amplified and digitized for enhanced accuracy. Fault tolerance with respect to the localized failures/single event upsets of the preload storage CMOS memory is incorporated by provisions of page selection.

Figure 5. WiFS camera.

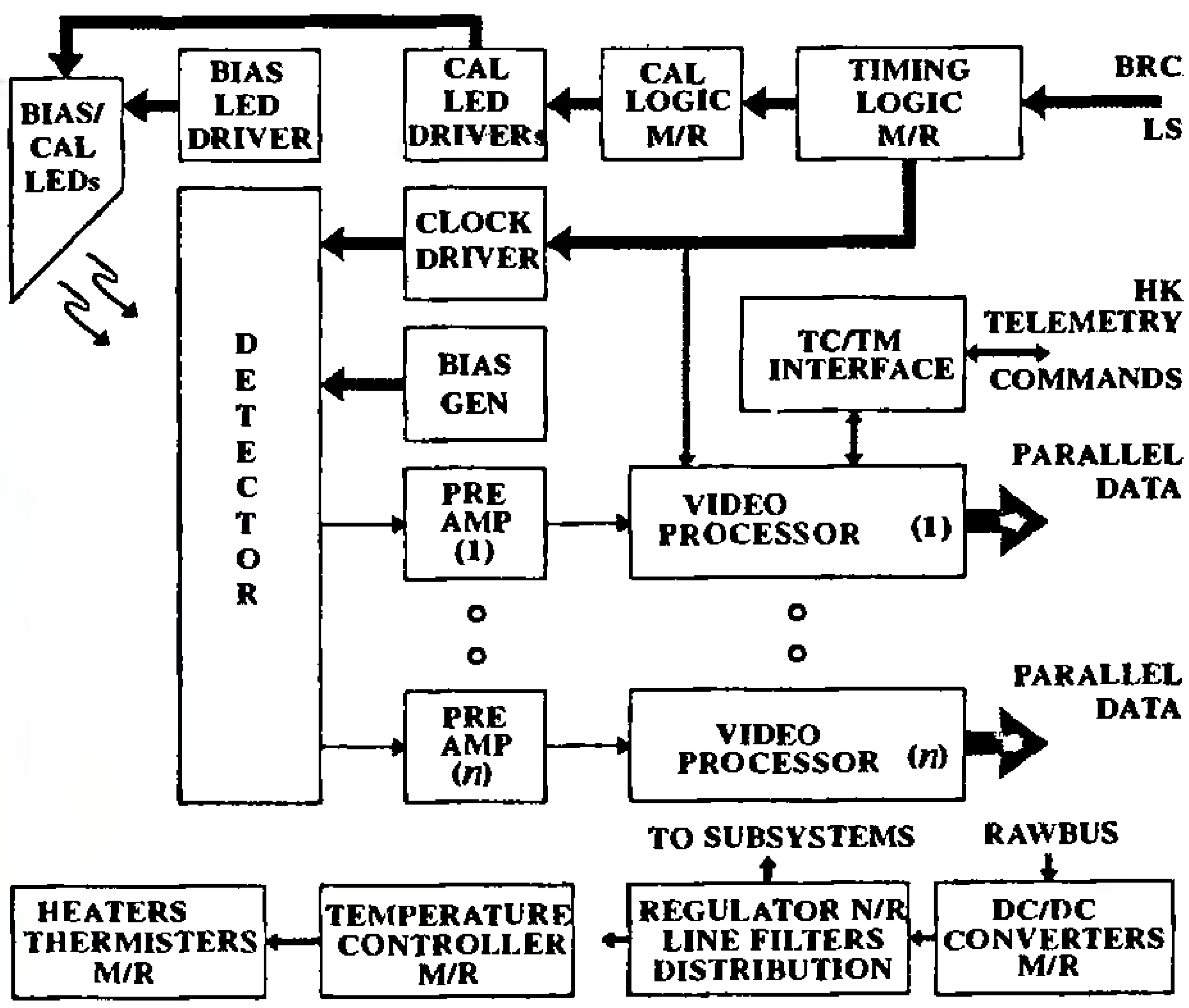

Figure 6. Block schematic of camera electronics.

Separate video processors are realized for each of the ports of PAN and VNIR detectors wherein the high-speed readout results in very small usable pixel time. Sequential readout of the shift registers, analogue multiplexing of pre-amplified odd/even channels separately optimize the hardware in SWIR. The DC restored odd/even channels of WiFs are analogue-multiplexed.

Digitization is accomplished using successive approximation ADCs in WiFS and SWIR electronics while flash CMOS converters digitize the high-speed signals of PAN and VNIR cameras. The parallel data of ADCs are latched, buffered, serialized, word multiplexed, formatted and stored/transmitted.

Mechanical configuration

In order to have good dimensional stability under varying temperatures, the EO module on which the optics and detector are mounted are made of Invar (thermal coefficient of expansion 1.5×10^{-6}). The PAN camera EO module is basically a cylindrical structure of 630 mm inner diameter with an extended bracket for supporting the primary mirror mount.

In order to scan $\pm 26°$ field of view w.r.t. nadir, the optical axis is tilted by rotating the whole payload. The whole platform can be rotated with a step size of $\pm 0.09°$ up to $\pm 26°$. The total time required to cover $-26°$ to $26°$ is 30 minutes.

The EO module of LISS-III (Figure 4) is made out of a single block of forged INVAR material scooped from inside. The lenses are mounted on one face of the main structure and the detector heads are mounted on the opposite surface. The three detector electronics (DE) boxes meant for MIR band are mounted on the side face of the main structure towards the positive pitch direction.

Two DE boxes, one each for band 3 and 4, are mounted on the top surface of the main structure. The DE box meant for band 2 is mounted directly on the spacecraft just behind the band 2 detector head. The entire EO module is enclosed in a thermal cover fixed on the deck. Four hoods, one for each lens, are mounted on this thermal cover. The EO module is fixed on the spacecraft deck by six lugs provided on the main structure.

The EO module of WiFS camera is made of Invar plates in a box structure. The lens plates and detector plates are canted at $\pm 13°$. WiFS EO module also carries four hoods, one for each band.

Inflight calibration

The calibration system is required to correct the response variations of individual detector elements over a dynamic range of interest. Accordingly, all the elements of a detector are uniformly illuminated at various intensity levels to derive radiometric correction coefficients. About six uniform exposures with source stability better than 0.4% are required to characterize the response. An elaborate ground calibration system satisfying all the above requirements is developed and the response of detector elements characterized. With this, the onboard calibration data are required only to study the degradation of the camera system, if any.

The inflight calibration of the entire camera system, including the optics, can be achieved only by using a moving mechanism to bring the calibration source into the field of view of the optics. Considering these aspects, it was planned to calibrate the cameras, excluding the optics, during the night passes.

LEDs are selected as calibration sources and operated in pulsed mode to achieve higher intensities and facilitate linear intensity control with both the exposure durations and forward currents. They are placed close to the CCDs due to low power dissipation and small size.

The calibration sequence with pulsed mode illumination is achieved using digital circuitry and repeats every 2048 scan lines. The detector integrates the incident light during an integration period for exposure pulse widths less than the read out period and generates signal proportional to the pulse width and intensity. The LED exposures are spaced out to give 1/8 duty factor and are selectively turned on/off to get six non-zero exposures with two pulse widths. A switched constant current source provides required current drive to the LEDs.

The calibration system enables functional verification of onboard electronic hardware and ground systems, photosite to shift register crosstalk of the detector and BER of the entire transmission chain.

Concluding remarks

IRS-1C payloads have been operating in orbit since 5 January 1996 sending excellent imagery. The specification parameters have been met based on primary analysis. The detailed and quality analysis is in progress.

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