Meteorological imaging instruments on-board INSAT-2E

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INSAT-2E carries two imaging instruments for meteorological applications. One of these payload components is a very high resolution radiometer (VHRR) operating in three spectral bands. A wide panchromatic visible (VIS) band images the earth disc and clouds with a resolution of 2 km × 2 km from geo-synchronous altitude of 36,000 km. A water vapour (WV) band maps the moisture patterns in the atmosphere; while a thermal infrared (TIR) takes thermal images of the earth and cloud patterns. Both these infrared bands provide imagery with a spatial resolution of 8 × 8 km.

The other instrument on-board INSAT-2E is a three-band charge coupled device (CCD) based imager. This instrument provides co-registered images of the earth in visible (VIS, 0.62 to 0.68 μm), near infrared (NIR, 0.77 to 0.86 μm) and short wave infrared (SWIR, 1.55 to 1.69 μm) regions of the spectrum. The subsatellite point ground resolution of these images is 1 km × 1 km for all the three bands. The central wavelengths and bandwidths of the spectral bands as well as dynamic range and saturation radiance set points are so selected that the images can be used both for meteorological and earth resources remote sensing applications.

Both these instruments are equipped with ground commandable flexible scanning geometry to allow trade-off between coverage area and frequency of imaging.

In view of short development cycle, the instruments were conceptualized with an approach that allowed the use of similar features in scanning geometry, optical design, component layout in electro-optical module, electronic package construction and signal processing and formatting strategy. Since their switch-on in mid-April '99, both these instruments have been returning quality images which will be operationally used for a wide range of applications.

Very high resolution radiometer

VHRR is one of the two meteorological payloads on-board the INSAT-2E spacecraft. It is an enhanced version of the two-band VHRR flown on INSAT-2A/2B (ref. 1). In addition to providing images in VIS band (0.55 to 0.75 μm) with 2 km × 2 km resolution and TIR band (10.5 to 12.5 μm) with a resolution of 8 km × 8 km as in the case of INSAT-2A/2B, this instrument is equipped with a WV band (5.7 to 7.1 μm) to map the atmospheric moisture patterns which provide wind velocity and moisture content in various regions of the earth disc.

The configuration of the instrument is modified from its predecessors to accommodate WV channel optics, sensor and electronic chains. A simplified block schematic of VHRR is shown in Figure 1. The following paragraphs describe in brief the configuration and operation of the instrument.

The incoming radiation is reflected onto an 8-inch primary mirror of the reflective telescope by a two-axis gimbal-mounted beryllium scan mirror. A gold film dichroic beam-splitter placed in the converging beam from the secondary mirror of the telescope bifurcates the radiant energy. The visible energy is transmitted through the dichroic while combined WV and TIR energy is reflected at right angles to the original direction. This allows the radiation from the earth to be channelled to visible and combined IR focal planes simultaneously with high optical efficiency.

The detector configuration for the VIS band consists of two staggered arrays of four silicon photodiodes each; while for WV and TIR bands, the detector package contains two sets of dual mercury–cadmium–telluride (MCT) photoconductive detector elements in close proximity to band defining filters. This detector package was specifically designed such that the original design of radiant cooler for INSAT-2A/2B could be utilized with only minor modifications. The IR detectors are operated nominally at a temperature of 105 K to limit thermally generated noise. One of the detectors in each band is energized, while the other set provides the cold redundancy. Both sets are identical in function and can be switched 'on' and 'off' from the ground through radio-command.

The two-dimensional image of the earth is generated by sweeping the instantaneous geometric field of view of the detectors by rotation of the scan mirror-gimbals in two orthogonal axes. For every sweep of the mirror, four contiguous lines of VIS band and one line each of WV and TIR bands are generated in east–west direction. At the end of the sweep, the mirror is stepped south through an angle equivalent to eight kilometres on the ground and data collection is resumed in the reverse direction for the next sweep. This improves the scanning efficiency which, in turn, enables faster coverage rate at reduced noise bandwidth of the system. Three modes of operation

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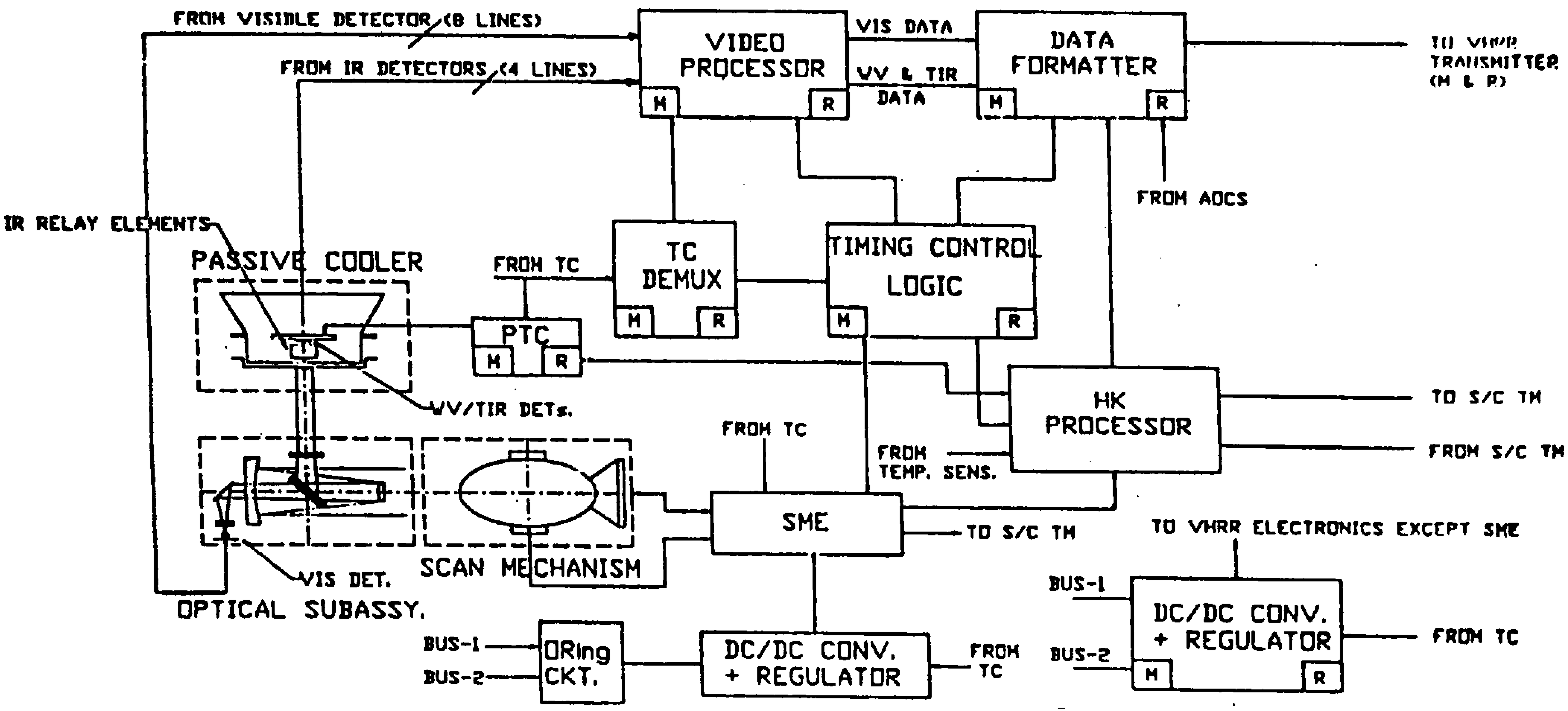

Figure 1. Schematic of 3-channel VHRR for INSAT-2E.

(Figure 2) are provided to allow trade-off between area and frequency of coverage.

- Full frame mode scans 20 × 20 degree in about 33 min covering full earth disc and some space around.
- Normal frame mode coverage in east–west direction is the same as in full frame mode, while in north–south direction, scan extent is 14 degrees, covering 50 degrees N to 40 degrees S latitudes in 23 min.
- Sector frame mode provides 4.5 degrees coverage in north–south direction spanning approximately 2800 km (351 scan lines) in about 7.2 min. The east–west coverage remains unchanged as in full and normal frame modes. The sector can be positioned, through radio command, anywhere in full scan field in steps of 0.5 degree (312 km or 39 lines) in north–south direction. This mode is particularly suited for rapid repetitive coverage during severe weather conditions like cyclones.

The dark and cold space views at the east and west ends are used for establishing reference radiance for all the three bands. A full end-to-end calibration of WV and TIR bands is provided by swinging the mirror to view a black body cavity fitted on the inner side of north plate of the instrument. The physical temperature of the black body is accurately monitored by platinum resistance thermometers at five locations and is telemetered through VHRR data stream. The system response for black body view is available in the video data slot.

These data sets provide calibration coefficients for WV and TIR bands. A comparison of the coefficients with ground values is made to estimate band response variation and to update the ground calibration data.

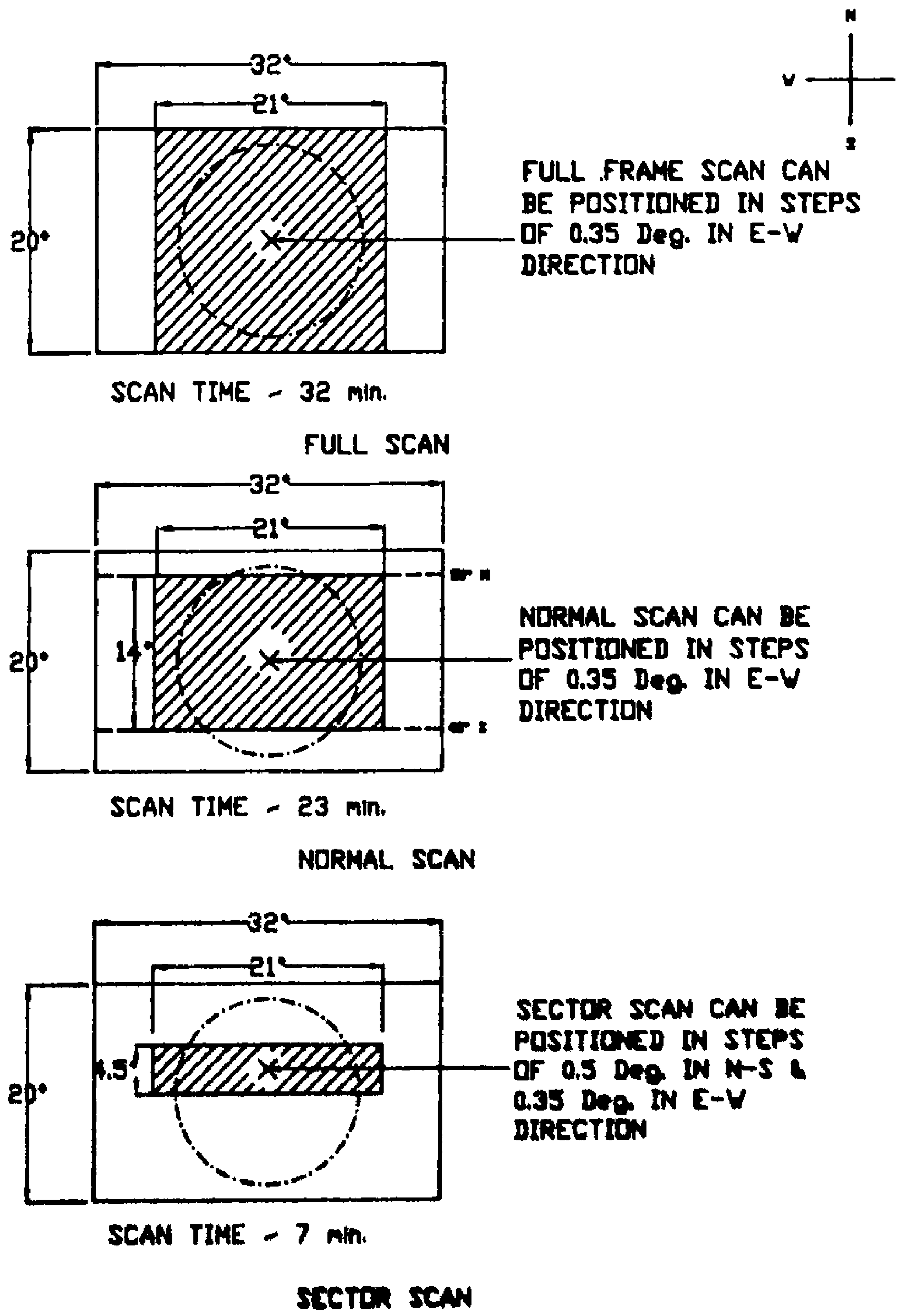

Figure 2. Scan modes of INSAT-2 VHRR. Hatched region indicates the image area during scan.

The detector outputs of all the channels of the three bands are individually amplified, band limited and digitized to 1024 grey levels by A/D converters. The digitized data of all the channels, housekeeping information, calibration data, etc. are formatted, randomized and transmitted serially in extended C band. VHRR shares solid state power amplifier (SSPA) with the CCD instrument for data transmission. The major specifications of the instrument are given in Table 1.

The following sections describe the design features of major subsystems of VHRR.

Functional design description

VHRR consists of the following major subsystems:

Scan mechanism assembly

Scan mechanism consists of two-axis gimbal-mounted beryllium mirror. This gimbal is servo-driven in two orthogonal axes by independent servo-motors to give precise movements to an elliptical beryllium scan mirror mounted in the gimbals at 45 degrees to the optical axis. The scan mirror is fabricated from a 19 mm thick beryllium block with major axis of 340 mm and minor axis of 210 mm. The back side of the mirror is scooped with square pattern to reduce weight. The minor axis of the mirror is the fast scan axis. The mirror swings ± 5 degrees (mechanical) per second about this axis to provide effective optical sweep of 20 degrees to the detector field of view to generate one scan line per second. The other axis which is orthogonal to the fast scan axis is called slow scan axis. The mirror is stepped through 224 microradian about this axis after completion of one fast scan. In the fast scan direction, data is collected for both forward and reverse sweeps of the mirror. The number of steps in the slow scan direction depends on the mode of operation of the instrument. The instrument is mounted in the spacecraft in such a way that fast scan lines are parallel to the equator while slow scan steps correspond to north to south movement.

Table 1. INSAT-2E VHRR major specifications

Parameter	Band	Specifications
Spectral bands (μm)	VIS	0.55–0.75
	TIR	10.5–12.5
	WV	5.7–7.1
Spatial resolution (km)	VIS	2 × 2 (≤ 56 uR IFOV)
	TIR	8 × 8 (≤ 224 uR IFOV)
	WV	8 × 8 (≤ 224 uR IFOV)
MTF	VIS	≥ 0.23
	TIR	≥ 0.21
	WV	≥ 0.21
Dynamic range	VIS	0–100% Albedo
	TIR	4 K–340 K
	WV	4 K–320K
Noise performance	VIS (S/N @ 2.5% albedo)	≥ 6
	TIR (NEDT, K)	≤ 0.25
	WV (NEDT, K)	≤ 0.5

In addition to 20 degrees stepping in north–south direction, there is a provision to rotate the mirror through 90 degrees about the slow scan axis to view a black body which is fitted on the inner face of the north panel of EO module. There is also an in-built offset capability in east–west direction to position the earth disc at the centre of the image for any position of the satellite from 70 degrees E to 100 degrees E longitudes.

Mechanical limit stops on the west and south ends provide mechanical reference for fast and slow scan axes, respectively. A precise 256 pole inductosyn angle encoder is used to provide position information in the servo loop. The system operates in null seeking mode to maximize sensitivity and linearity of the system.

Radiant cooler

IR detectors are required to be maintained at a precisely controlled low temperature between 105 and 115 K to reduce the detector thermal noise. In addition, precise temperature control ensures that the offset measured during space look remains valid during the actual image period and that the response of the detector through a picture frame is unaltered.

A passive radiant cooler is used to cool the IR detector package below its operating temperature of 105 K. The cooler consists of three stages called patch, radiator and vacuum-housing-sunshield. The patch is the coldest stage on which the detector is mounted. It is effectively a high emittance honey-comb cavity mimicking a black body which is north oriented to radiate to deep space all the time. The patch is supported in the radiator by means of four fibreglass rods. The radiator surface is co-planar with the patch and is painted white to minimize radiator temperature. The rear surfaces of the patch and the radiator are gold-plated to reduce radiation heat load.

The radiator is attached to the vacuum housing by eight fibreglass supports. The housing supports the patch–radiator assembly as well as IR optical components such as focusing lens, vacuum window, etc. To avoid direct viewing of the sun by the patch, a pyramidal sunshield assembly made of four trapezoidal panels is attached to the vacuum housing. The sunshield surfaces facing the patch are highly polished for high specularity and low emissivity to minimize heat input to the patch. The external surfaces of the vacuum housing and sunshield are covered with silverized teflon tape to reject heat to deep space. The complete assembly is mounted on an interface plate through eight fibreglass support rods to provide thermal isolation to the cooler from the electro-optic module.

Heaters are fixed on the patch, radiator, vacuum housing and sunshield to heat up these parts to 300 K for decontamination in-orbit before the commencement of normal operation.

Patch heaters and platinum resistance thermometers mounted on the patch are used in a closed loop proportional servo to control the patch temperature at any of the eight set points from 105 to 115 K with an accuracy of better than 0.25 K. The set points are selected through ground commands to optimally use available cooling capacity.

Optics assembly

The VHRR optics assembly consists of telescope, dichroic beam splitter, IR collimating lens, IR relay optics and visible band optical elements as shown in Figure 3.

The telescope is a Richy-Chretian type with 200 mm diameter concave hyperboloid primary mirror and 55 mm diameter convex hyperboloid secondary mirror separated by 285 mm. The primary and secondary mirror-mounts as well as the barrel are made of INVAR to precisely maintain the separation of mirrors over the temperature excursions from 0 to 40°C.

The convergent light beam from the secondary mirror is intercepted by a specially designed dichroic which reflects 85% of IR energy and transmits 75% of visible energy without distortion of the wavefront. The energy paths for two beams are now separated by 90 degrees. The transmitted VIS band energy is reflected by a fold mirror onto an array of visible detectors, while the reflected IR energy is collimated before exiting the telescope. This scheme enables independent optimization of performance of TIR and WV bands inside the radiant cooler before it is mounted on the electro-optics module.

Camera electronics

The major functions of camera electronics are: (i) to amplify, DC restore and digitize detector outputs; (ii) to control IR detector package temperature; (iii) to generate master clock and other control pulses; (iv) to format, code and randomize data

In addition, the electronics monitors and formats various housekeeping parameters and contains spacecraft interfaces.

Signal processing

The photo current from visible detectors is 1 nA full scale. This is amplified by a trans-impedance pre-amplifier having a gain of 30×10^6 V/A.

The pre-amplifiers for WV and TIR bands have supermatched bipolar transistors in the input stage to amplify very low level voltage signals (300 μV full scale) from the detectors in respective bridge configurations.

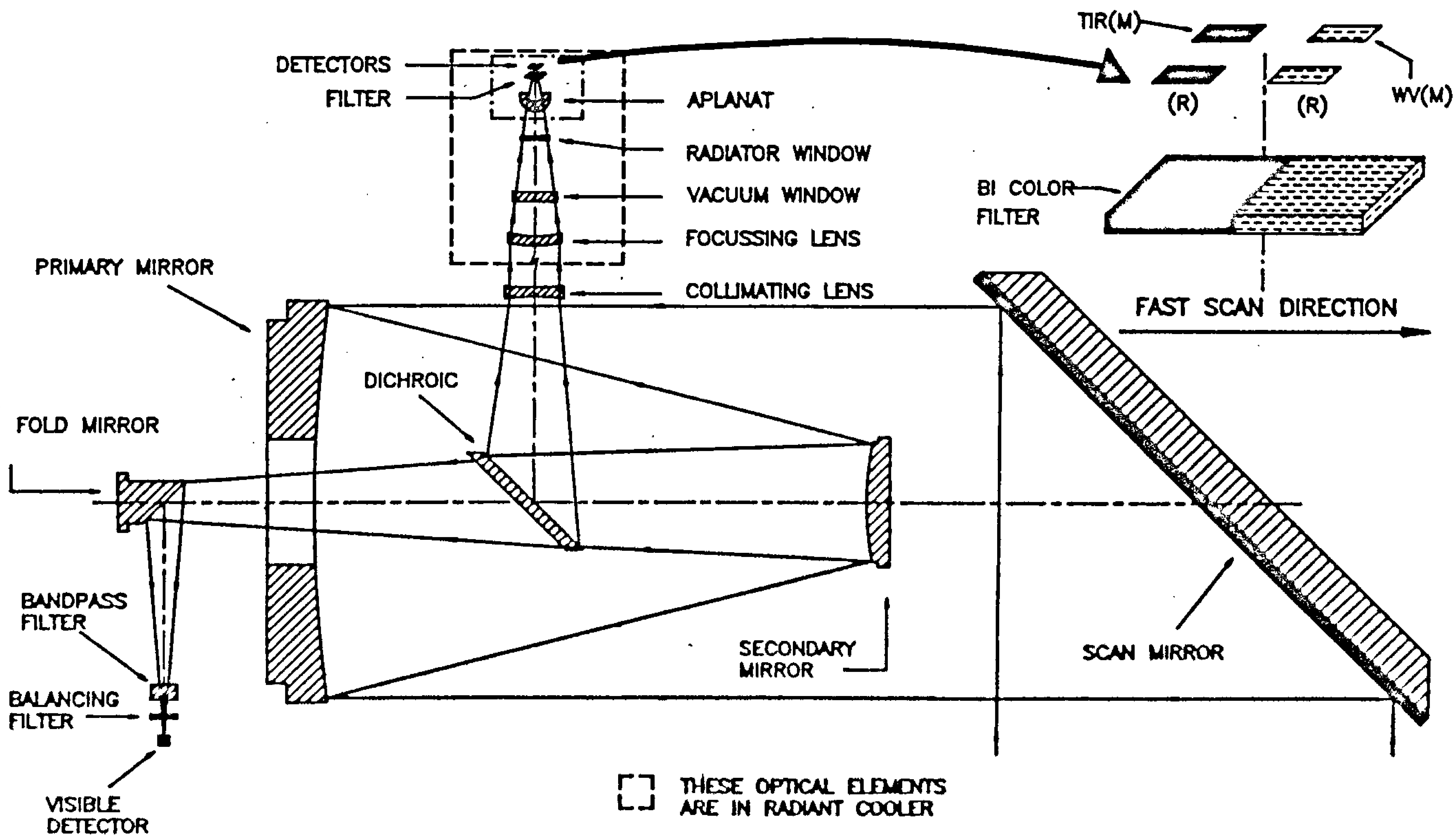

Figure 3. Optical schematic of INSAT-2E VHRR.

All pre-amplifiers are placed in the vicinity of detectors to minimize noise pick-up in signal lines.

In order to extract useful signals from pre-amplifier outputs, large zero-signal offset has to be subtracted before further amplification. This offset is sampled when the mirror is looking towards space. The precise offset subtraction is achieved by digitization and storage of offset through a dual loop sampling. During subsequent signal amplification, this offset, converted to analogue voltage through DAC, is subtracted from pre-amplified detector output, so that full dynamic range is used for actual video signal. The amplified output is passed through noise limiting, anti-aliasing filter before being digitized. The digitized output is serialized, formatted with housekeeping information and transmitted to the ground after modulation on extended C band carrier. The total chain gain for visible channel is of the order of 7500×10^6 V/A and for IR channels, 35,000 V/A.

IR detector temperature control

WV and TIR detectors are operated at controlled cryogenic temperature to reduce their thermal noise significantly below the minimum useful signal level. The temperature of the detectors is controlled by first cooling the detectors passively through the radiant cooler and then stabilizing the temperature using a proportional temperature controller. The temperature controller uses platinum resistance thermometer (PRT) temperature sensors as feedback elements and heaters as actuators to control the temperature at slightly above the limiting temperature achieved by the cooler. This allows the detector temperature to be maintained at the selected set points with an accuracy of 0.25 K in presence of diurnal and annual patch temperature variations due to heat load cycles.

The temperature control has provision to automatically switch-off bias to the detectors when temperature exceeds 125 K. This feature protects detectors from inadvertent operation at higher temperature.

The patch temperature control, being a vital function, has complete functional redundancy and cross-coupling between heaters and controllers.

Control logic and formatter

This is the master controller for the instrument. It generates bit rate clock at 526.5 kHz which is used by all timing and control blocks as a basic timing signal. All the video processing circuit functions are also synchronized with this clock. The formatter takes data from video processors, scan mechanism, attitude control and analog/digital telemetry circuits and inserts them in instrument output stream along with frame synchronization code. The final output is randomized and given to the transmitter for down link.

Table 2. INSAT-2E CCD payload major specifications

Parameter	Specifications
Spectral bands (μm)	0.62–0.58 (VIS) 0.77–0.86 (NIR) 1.55–1.69 (SWIR)
Spatial resolution	1 km × 1 km
MTF	≤ 0.23
Dynamic range	0–100% Albedo
Noise performance	SNR ≤ 128 @ 100% albedo
Coverage	6250 km × 300 km per scan line (Max. no. of lines: 31)
Image repeativity	One scan line per minute
Weight	< 55 kg
Power	< 50 W

Charge coupled device payload

The CCD payload is designed to carry out earth imaging in three spectral bands. The bands are selected to have applications in meteorology as well as vegetation mapping. All the three bands provide co-registered images with a ground resolution of 1 km × 1 km. The payload retains the basic telescope and scan mechanism of the VHRR instrument. The separation of three bands is achieved by two dichroic beam splitters. The first dichroic reflects SWIR energy and transmits VIS/NIR energy; while second dichroic reflects NIR energy and transmits VIS energy. The VIS and NIR band detector arrays (Si, CCDs) are placed directly in the split focal plane of the telescope, whereas an auxiliary lens doublet refocuses the telescope beam to a secondary focus where the SWIR charge coupled photodiode (CCPD) array detector is placed. This optical configuration is selected to accommodate two different sizes of detector elements for identical foot prints on the ground. Ground processing is further facilitated by selecting a unidirectional scanning in fast scan direction in view of hybrid scan concept used for this payload. In this type of scanning, mechanical scanning and electronic scanning are simultaneously carried out in two orthogonal axes. This scan geometry generates a three-band image strip of 300 km wide (north–south) and 6300 km long (west–east) for each sweep of scan mirror from west to east in one minute.

Flexible programmable scan modes allow generation of images with up to 24 contiguous strips covering an area of 6300 km × 6300 km. Again, a positioning mechanism enables this image field to be positioned anywhere in a scan field of 20 degrees × 20 degrees covering full earth disc. Table 2 gives major specifications of the instrument.

Functional design description

The CCD payload (Figure 4) consists of the following major functional blocks:

Scan mechanism assembly

The scan mechanism consists of a gimballed scan mirror which sweeps the composite detector field of view in two orthogonal axes to generate wide-field two dimensional imagery. The fast scan sweep of the mirror generates 300 video lines over 6300 km east–west span every minute. The stepping of the mirror south by about 0.4 degrees after each west to east scan helps to generate successive image strips. Earth imaging is done only during west to east scan of the mirror, while retrace is much faster to improve scan efficiency; retrace time being only about 1.25% of active line time.

The total scan field of mirror is ± 13 degrees in east–west direction and ± 10 degrees in north–south direction, while active image field is ± 5 degrees in east–west direction and a maximum of ± 5 degrees in north–south direction. This active image field can be positioned anywhere in the total scan field to generate imagery of any part of visible earth disc.

For linear and precisely controlled motion of the mirror in two orthogonal axes, inductosyn encoders are used as angular position feedback devices and servo motors are used as actuators. The two independent servo loops are synchronized to initiate north–south stepping during fast scan retrace.

The scan mechanism also includes a linearity enhancing function such that a stored mirror image pattern of ground measured error is superimposed on the mirror drive signal, point-by-point, as the mirror scans in the fast scan direction. The ground measurements have shown that this scheme substantially improves the fast scan linearity when energized. There is a provision to disable this function through ground command if required.

Optics and detector assembly

The optics schematic of INSAT-2E CCD payload is shown in Figure 5. This configuration was selected after exploring different design approaches where image quality, compactness, ease of assembly/disassembly, accessibility for alignment and co-registration of detectors, spacecraft size constraints and polarization sensitivity were some of the main design considerations.

The optical system simultaneously images a north–south strip of 300 km on three separate detector arrays, each having 300 equivalent pixels and individual spectral filter for band definition.

The scan mirror, telescope, dichroic beam splitters, fold mirror, lens doublet and band pass filters together constitute the optical assembly.

The front end of the system consisting of the scan mechanism and telescope is identical to that of VHRR payload except that the telescope performance has been upgraded to provide required image quality over larger field of view of ± 0.25 degrees at twice the spatial frequency of VHRR.

The detectors used for VIS and NIR bands are 2048 element linear silicon CCD arrays. The outputs of three consecutive detector array elements are added together. Thus 900 pixels of each array are utilized to construct 300 image pixels for each band. A customized readout chronogram has been designed to read the unused pixels at a dump rate ten times faster than useful pixel readout

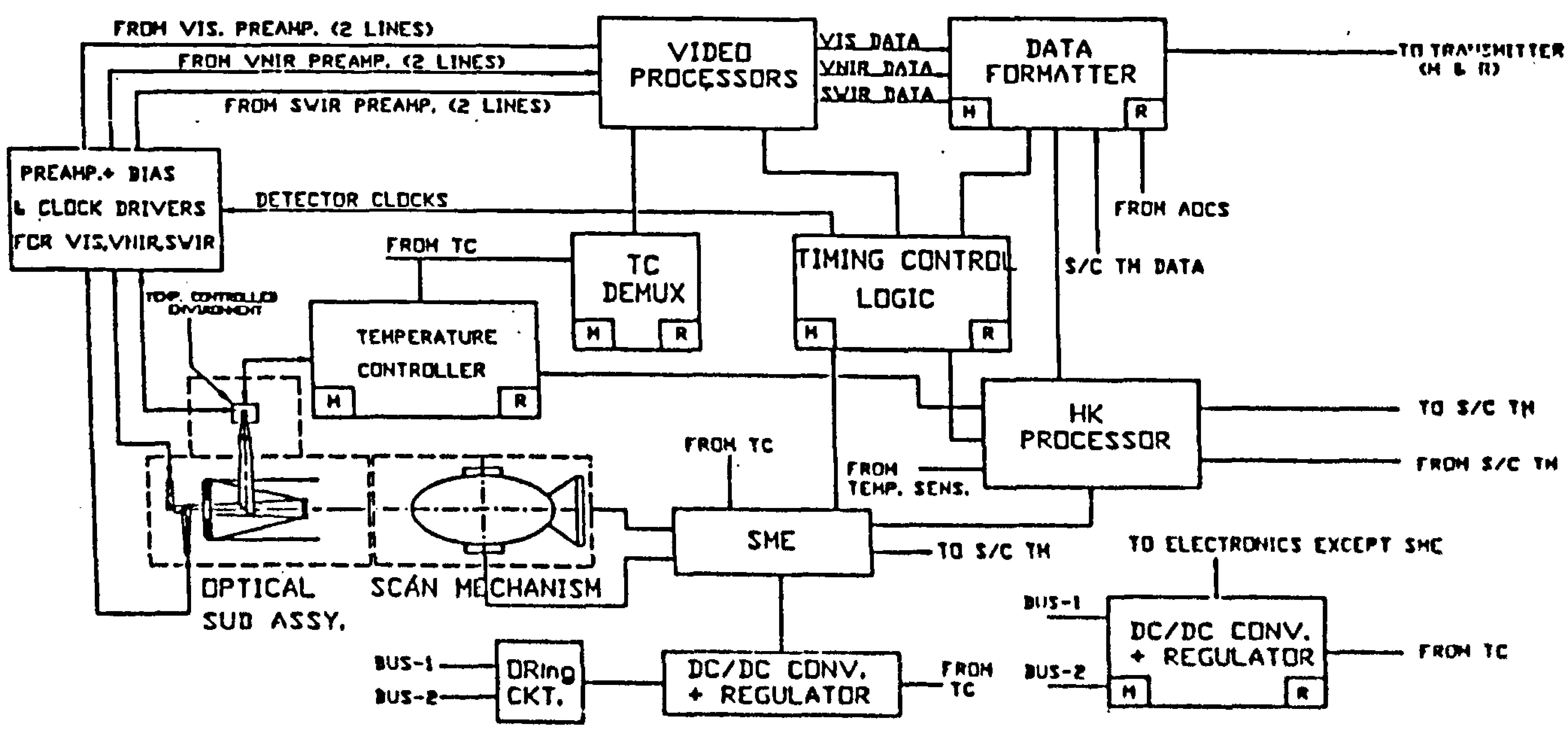

Figure 4. Schematic of 3-channel CCD payload for INSAT-2E.

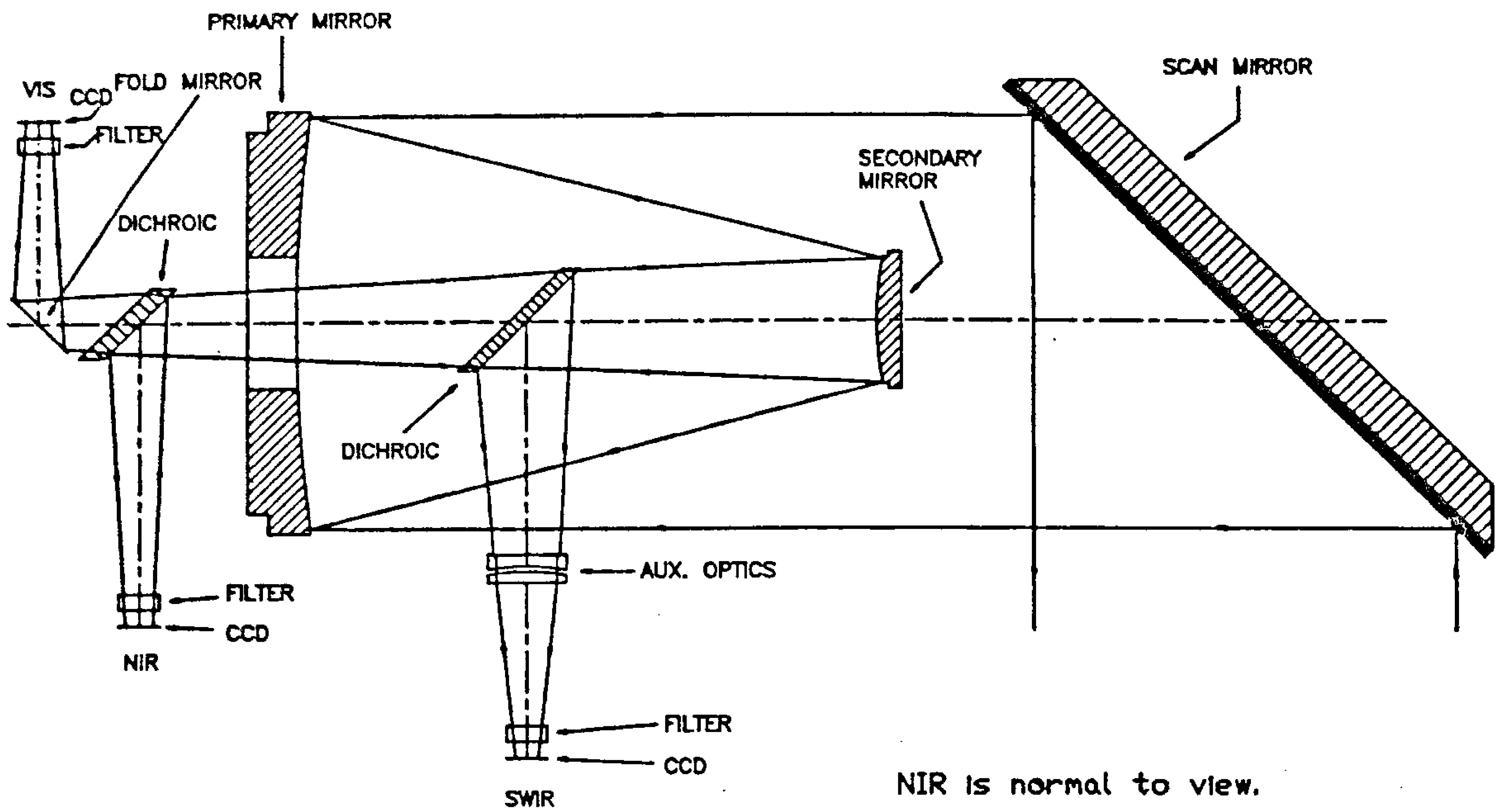

Figure 5. Optical schematic of 3-channel CCD payload.

rate. This scheme optimizes the performance requirements for signal amplifiers and A/D converters and economizes on the data transmission rate at the cost of complexity in generation of drive signals. The excellent signal to noise ratio performance obtained through the instrument has established the soundness of this readout scheme.

The SWIR detector consists of a 300 element linear CCPD array. This is a hybrid assembly where InGaAs photodiodes are coupled to silicon CCD readout shift registers. A low noise signal extraction has been achieved by operating the detector in 'vidicon mode'. In this mode of operation, during signal integration period, the photocurrent discharges an initial fixed charge placed on the junction capacitance of the detector element. A measured charge injected into the CCD shift register potential wells restores the initial value of charge on the junction capacitance at the end of integration period. The remaining charge is skimmed back into the potential wells of the shift registers and is extracted as 'inverted video' signal through shift register clocking mechanism.

As the pixel sizes of VIS/NIR and SWIR CCD arrays are different, effective focal lengths are adjusted by auxiliary optics in SWIR band to give identical ground resolution of better than 1 km × 1km for all the three bands.

Camera electronics

The camera electronics performs the following functions: (i) provides clock and bias inputs to detectors; (ii) processes and digitizes detector outputs; (iii) formats video signal along with auxiliary information; (iv) monitors instrument status through analog and digital telemetry; (v) interfaces with other spacecraft bus subsystems and (vi) controls the SWIR detector temperature through feedback loop.

Detector driver and bias circuits. All three detector arrays require various bias voltages and clock waveforms for their operation. These signals are provided by voltage regulators and clock drives placed close to the detector arrays to minimize the noise pick up and reflections due to long cable length.

The following parameters were considered while designing the clock driver and bias circuits: (i) voltage levels; (ii) control of noise on sensitive lines; (iii) rise and fall time for clock levels; (iv) delay between clocks; (v) drive requirements for different waveforms.

Video processing chains. The functions of video processing chains are to condition the output signal from detector, perform DC restoration, extract the video information and digitize it with ten bit resolution and accuracy.

For VIS and NIR bands, video output from CCD is a three level pulse amplitude modulated (PAM) signal riding on 4 to 11 V DC level. The RMS input noise is about 1.2 mV for VIS band and 0.7 mV for NIR chain for an integration time of 8.334 milliseconds. This requires an amplifier bandwidth of 530 kHz for proper signal conditioning.

The saturation signal is about 775 mv for VIS and 490 mv for NIR bands, dark signal being less than 4% of

Table 3. Radiometric performance

Channel	Parameter	Specifications	Measured value
VHRR			
VIS	S/N @ 2.5% albedo	> 6	10–15
TIR	NEDT @ 300 K	< 0.25 K	0.1 K
WV	NEDT @ 300 K	< 0.5 K	0.2 K
CCD payload			
VIS	S/N @ 100% albedo	> 128	1045
NIR	S/N @ 100% albedo	> 128	1500
SWIR	S/N @ 100% albedo	> 128	1240

saturation signal for operating temperature range of the detectors. To guard against the possible radiation-induced increase in dark signal, a provision is made for all three bands to subtract ground command controlled offset from video signal. This helps in utilizing available dynamic range more effectively even after possible long-term radiation effects.

The design of the SWIR pre-amplifier is similar to VIS/NIR pre-amplifiers except that the bandwidth required is about 230 kHz. However, the further amplification and conditioning circuits are different as the DC restored signal needs to be subtracted from preload reference level to extract the video signal.

Control logic and formatter. The control logic generates waveforms required for the detector operation and for the control of video processor functions. It also generates the control pulses for multiplexing the video signal into the data formatter along with analogue and digital housekeeping information.

Telemetry circuits. Instrument health is monitored through analogue and digital telemetry channels, both in CCD data stream as well as in main spacecraft telemetry. Here, various voltage and current levels, scan mechanism position and drive current status, temperatures at different locations in the instrument and configuration of the instrument in various modes of operation are telemetered to ground for continuous monitoring.

In addition, full spacecraft telemetry which operates at 1 kbits/sec is sandwiched into 1.3 Mbits/sec CCD data stream to provide added redundancy for spacecraft telemetry. The hardware and data rate overhead due to this addition is small enough to justify its inclusion in CCD data stream considering its usefulness.

SWIR detector temperature controller. The temperature of the SWIR detector is maintained at 15 ± 1°C to control its dark current variation. For this, the detector mount is first cooled down through passive radiation to below 15°C. A temperature controller, operating in feedback control mode, controls the temperature at selected set point (15°C or 20°C) using heaters as actuators and thermistors as feedback elements. An on-off type of controller has been used to reduce power dissipation in driver transistors in view of its adequacy for required degree of control.

Integration and testing

After fabrication, all the major subsystems were individually evaluated for their performance and interface requirements. Subsequently, these subsystems were integrated in the instrument and performance was optimized to conform to or exceed the specification requirements. The instrument was rigorously tested over the full operational environmental conditions for specification compliance before integration with the spacecraft.

The spacecraft level tests verified all the interfaces and retention of instrument level performance in spacecraft environment. These tests also established a reference for in-orbit tests.

The in-orbit performance of the instrument has been evaluated and all the performance parameters have been met with satisfactory margin over all the specification requirements. As an example, Table 3 gives radiometric performance of all the bands as measured during in-orbit tests.

Conclusion

Two meteorological instruments namely, a VHRR and a three-band CCD-based imager were developed and integrated successfully with INSAT-2E spacecraft. The instruments underwent complete in-orbit testing after the spacecraft was placed in geo-stationary orbit. The performance of all spectral bands is satisfactory and all the major specifications are met within comfortable margins.

1. Very High Resolution Radiometers for INSAT-2, *Curr. Sci.*, 1994 66, 42–56.

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