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COURSE ON BASIC TELECOMMUNICATIONS SCIENCE

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EARTH OBSERVATION SYSTEM

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RS optical instruments and missions: key words.

Principles and concepts of Remote sensing optical sensors: Spectral signatures, the sun and the atmosphere. Visible, panchromatic, infrared. Spectral windows, reflective and absorption bands. Reflected and emitted radiation. Relation with ground measurements.
Some key features in optical instruments: Pushbroom and mechanical scanning. Istantaneous field of view, geometric resolution. Radiometric accuracy.
Overview of existing and planned optical instruments and missions. Landsat Multispectral Scanner and Thematic Mapper, SPOT, Marine Observation Satellite, TIROS Advanced Very High Resolution Radiometer, Meteosat.

1 PRINCIPLES OF RADIOMETERS

1.1 Remote sensing instruments

The list of existing and planned instruments for Earth Observation is very long:

Scintillation counters (gamma-ray);
Photomultipliers (x-ray, ultraviolet);
Cameras (visible and near-infrared, b/w, colour);
Lidar (visible, near-infrared);

Radiometers -scanning and solid state (visible,infrared);
Spectrometers (all regions);
Radiometers (passive microwave);
Radar (microwave).

1.2 Radiometers: basic concepts

A Radiometer (visible, infrared, microwave) is a passive electromagnetic sensor. Constituent of received signal is sun light reflectance or ground emittance (i.e. thermal infrared).

Radiometers have been demonstrated to be very capable instruments as they can be operated:

- with low power consumption;
- small physical size and not complex electronics;
- multi spectral bands are easy to be obtained;
- mapping geometry is relatively simple.

1.3 Radiometers: basic concepts (cont'n)

A radiometer is a sensor that measure the intensity of electromagnetic radiation from all object within its filed of view and wavelength range. Space borne radiometers generally include:

- primary optical system (collector of incident radiation);
- scan mirror (or alternative systems as linear detector arrays);
- reference sources (calibration);
- optical filter (bandpass filter);
- secondary optical system;
- detector(s).

Such instruments normally include also the capability to handle electronically the received signal (amplifiers, analog to digital converters, power unit) and to storage the transformed signal in digital data.

2 THE ROLE OF ATMOSPHERE

2.1 The Electromagnetic spectrum

The electromagnetic radiations propagate with the speed of light c = 300 10**6 m/sec. For the electromagnetic radiations it is valid the relation

lambda = c / f

where lambda is the wave length and f is the frequency.

The visible, infrared and the microwave radiations have particular interest in Earth Observation.

The visible radiations correspond to the wavelength range of 0.4 to 0.7 microns and the human eye is sensitive to all of them.
The infrared radiations correspond to the range of 0.7 microns to 1 cm and some of the infrared radiations are sensitive to the temperature.

Some key words: Spectral windows, Panchromatic, Near Infrared, Reflective and absorption bands.

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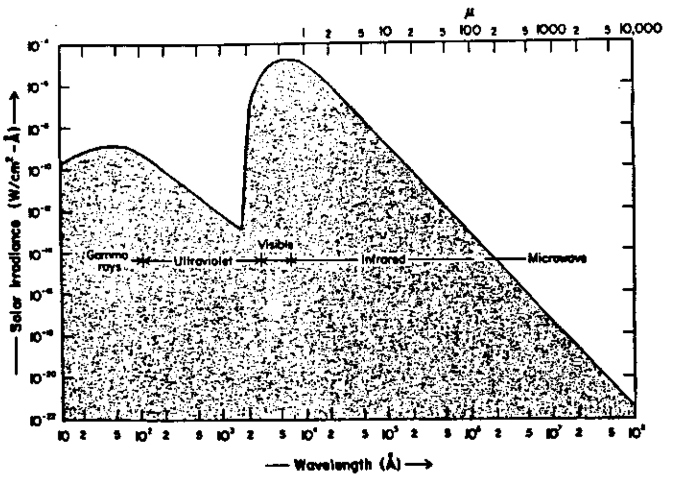


Figure 2.2. Spectral nature of the sun's energy as it irradiates the earth. (Adapted from Estes, 1974)

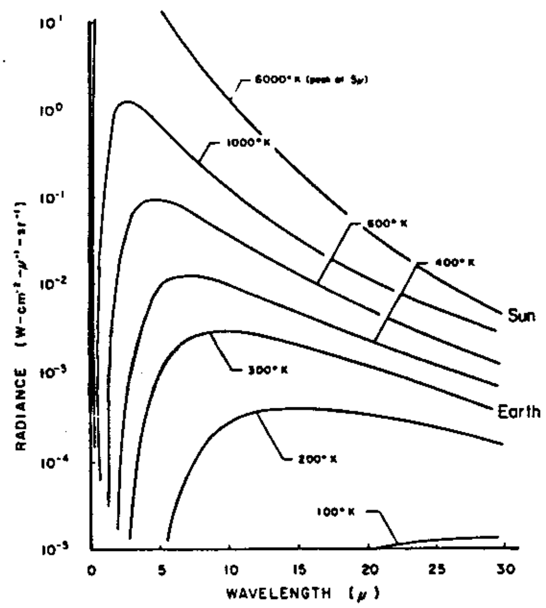


Figure 2.3. Plot of blackbody radiance and wavelength with temperature as a variable. (Adapted from Estes, 1974)

2.2 The atmosphere attenuation

Not all of the incoming solar radiant flux will be transmitted through the atmosphere; part of it is absorbed by the air's constituents and the remainder is reflected from gaseous molecules and particles.

Some key words: Reflective and absorption bands, Reflected, absorbed and emitted radiation.

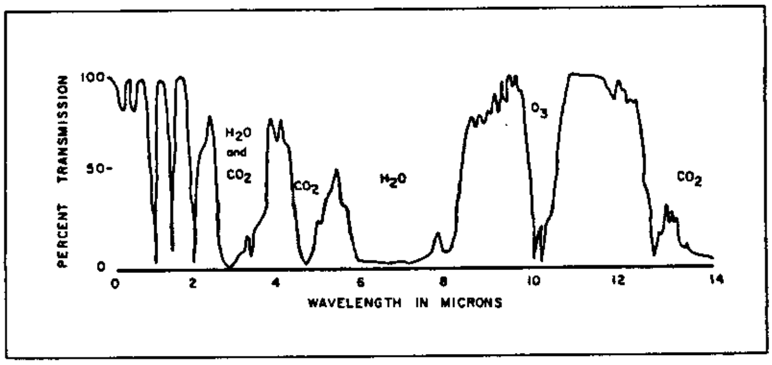


Figure 2.12. Atmospheric absorption schematic for the ultraviolet, visible, infrared, and that portion of the thermal infrared recorded by remote sensors (3.5 μm – 14 μm). (Adapted from Estes, 1974)

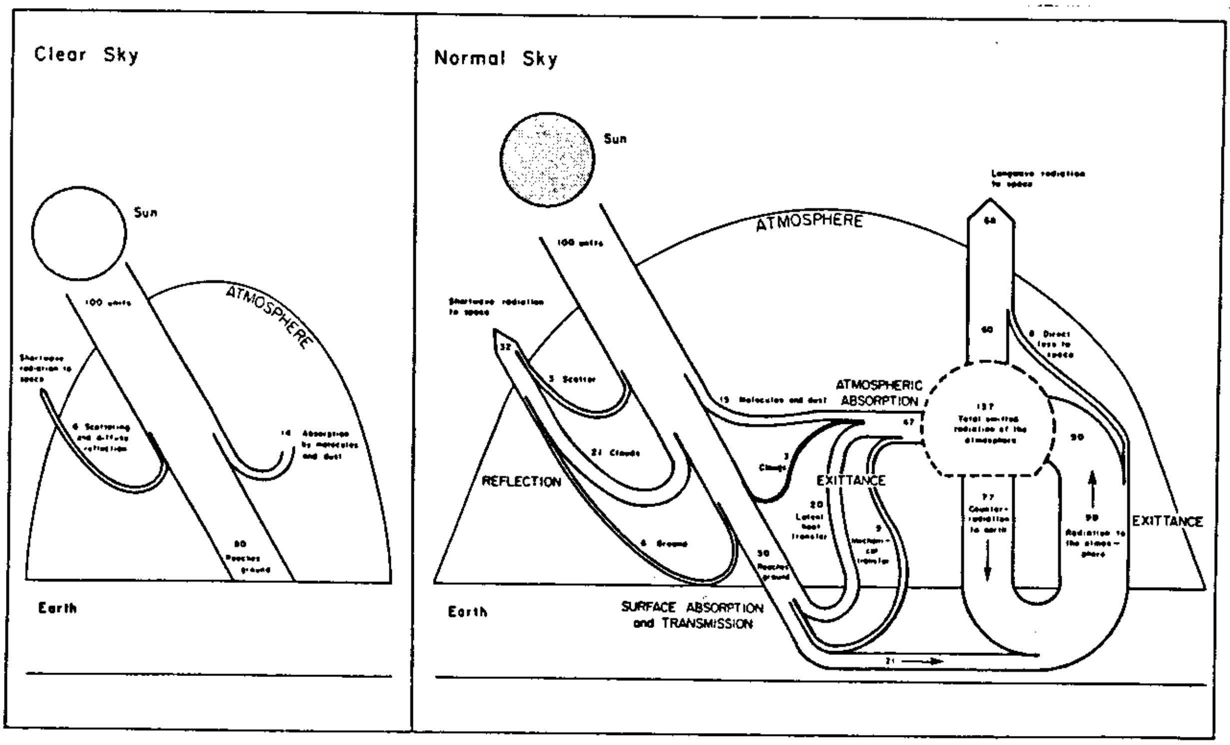


Figure 2.14. Atmospheric energy flow diagram. (Adapted from Estes, 1974)

2.3 Spectral signatures

Different environmental features exhibit different and distinctive spectral patters.
Near infra-red sensors can distinguish between healthy and dying plants before the distinction is apparent in the visible bands.
Once the "signature" of a particular type of ground feature is established, it can be used to identify other, like, features.

3 OPTICAL INSTRUMENTS FOR EO

3.1 An example of Optical instrument: AVHRR

The TIROS satellites, which are labeled NOAA-A, -B, etc. before launch and NOAA-1, -2, etc. after successful launch, provide operational coverage of the entire Earth four times per day. They are a principal source of environmental data for the 80% of the globe that is not covered by conventional data. The purpose of these satellites is to make measurements of temperature and humidity in the Earth's atmosphere, surface temperature, cloud cover, water-ice boundaries, and proton and electron flux near the Earth. They have a capability of receiving, processing, and retransmitting data from balloons, buoys, and remote automatic stations distributed around the globe, and can also track stations that are in motion. The satellites also carry the Search and Rescue transponder described elsewhere in this presentation. The current series of satellites is the Advanced Tiros N or ATN.

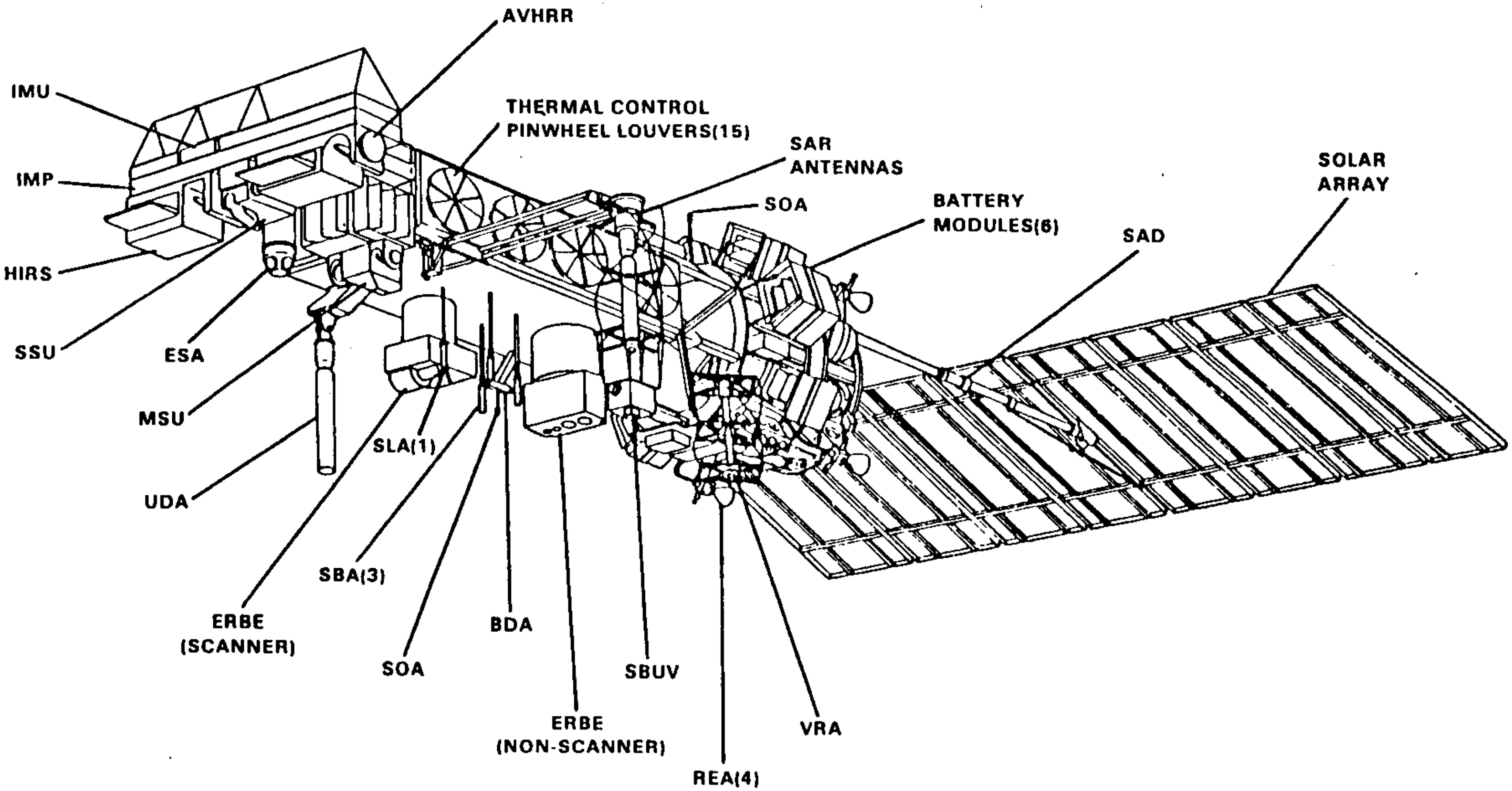
The sensor systems on the satellite include:

- TIROS Operational Vertical Sounder (TOVS)
- Advanced Very High Resolution Radiometer (AVHRR)
- Space Environment Monitor (SEM)
- ARGOS Data Collection and Platform Location System (DCS)
- Search and Rescue System (SARSAT)

In addition to the normal command, telemetry, and data communications capabilities of the satellite, direct service to users is provided via:

- High Resolution Picture Transmission (HRPT)
- Automatic Picture Transmission (APT)
- Direct Sounder Broadcast (DSB)

Advanced TIROS — N (ATN)



The TOVS combines data from three complementary sounding units to provide improved temperature and moisture data from the Earth's surface up through the stratosphere.

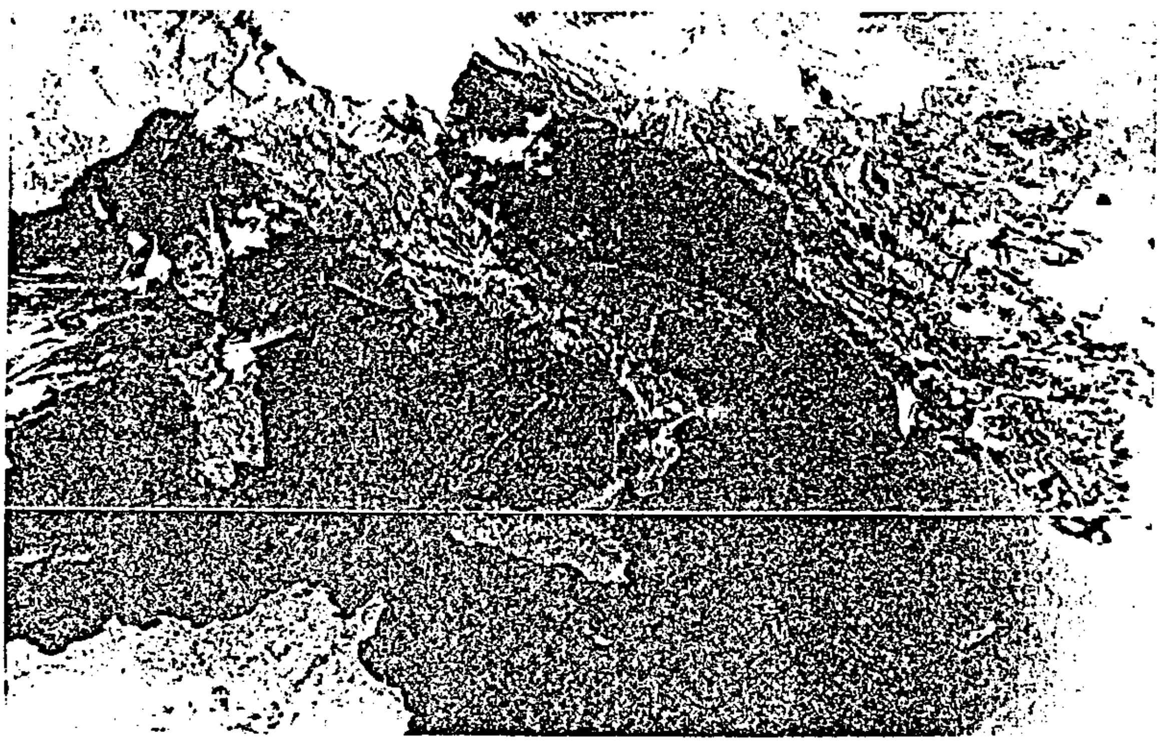
The AVHRR is the most versatile scanning radiometer yet flown on an environmental satellite. It gathers and stores for direct readout and later playback visible and infrared measurements and images in a greater number of channels than ever before, permitting more precise evaluation of land, ice, surface water, cloud conditions, and sea surface temperatures.

AVHRR data are transmitted in real-time to both Automatic Picture Transmission and High Resolution Picture Transmission users. TOVS provides Direct Sounder Broadcasts in real time of temperature and moisture data.

An improved Space Environment Monitor allows measurements of energetic particles emitted by the Sun over essentially the full range of energies and magnetic field variations in the Earth's nearspace environment. These are of tremendous value in measuring solar radiation activities.

An advanced ARGOS data collection and platform location system not only permits collection and transmission of environmental data from platforms on land, at sea, and in the air, but also determines the geographic location of platforms in motion on the sea surface or through the air.

Fundamental Polar Satellite Products: Automatic Picture Transmission (APT)



APT is provided in real time from the polar orbiting satellites at VHF frequencies. Low resolution imagery (0.725 – 1.10μm visible and 10.3 – 11.3 μm infrared) provided by this system is the only source of satellite data for many areas of the world. It is an important data source to DOD field facilities and to weather services in more than 100 nations around the world. There are 1,000 known APT stations located in 120 countries.

Advanced Very High Resolution Radiometer (AVHRR)

The AVHRR is a five channel* scanning radiometer which provides imagery and quantitative radiance data at both 1 km and 4 km resolution.

Data are broadcast in real time to both Automatic Picture Transmission (APT) and High Resolution Picture Transmission (HRPT) users. Data are also recorded on board the spacecraft, played back once per orbit, and centrally processed.

*Channel 1	0.58 – 0.68 µm	Daytime cloud, snow, and ice mapping.
Channel 2	0.725 – 1.10 µm	Surface water delineation, vegetation/agriculture assessments.
Channel 3	3.55 – 3.93 µm	Nighttime cloud mapping, sea surface temperature measurements, land/water distinctions, hot spot detection (forest fires, volcanic activity).
Channel 4	10.3 – 11.3 µm	Day/night cloud mapping, sea and land surface temperature measurements, soil moisture, and volcanic eruptions.
Channel 5	11.5 – 12.5 µm	Sea surface temperature measurements, soil moisture.

3.2 Optical instruments: spectral aspects

The spectral characterisation of the different radiometers on existing missions can be done through the following key words:

Multispectral imaging systems.
Number of spectral bands.
Spectral response.
Radiative cooler.
Narrow bands.
Panchromatic bands.

As example we will describe in the following the AVHRR, the Landsat MSS/TM and the SPOT HRV instruments.

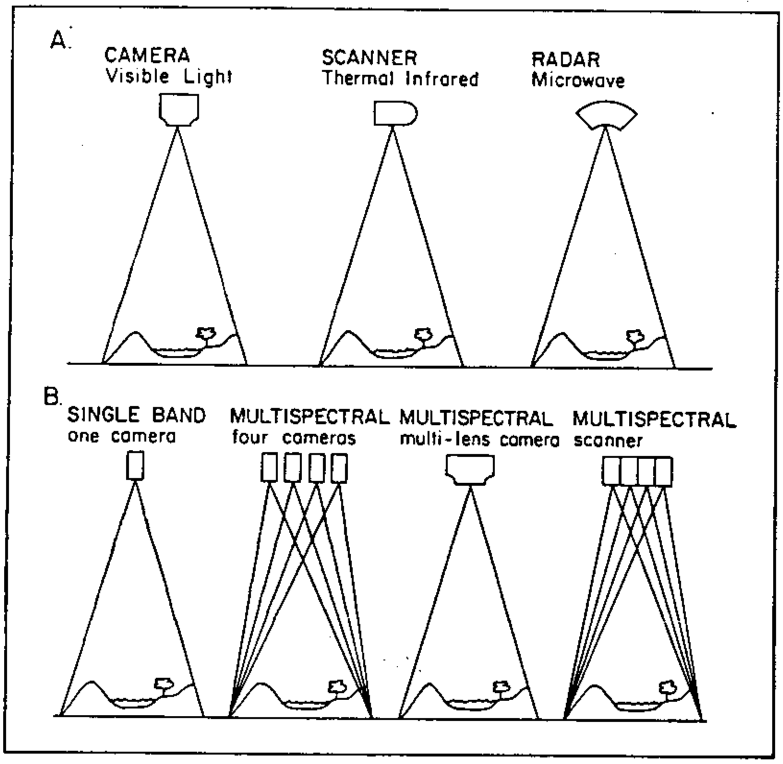
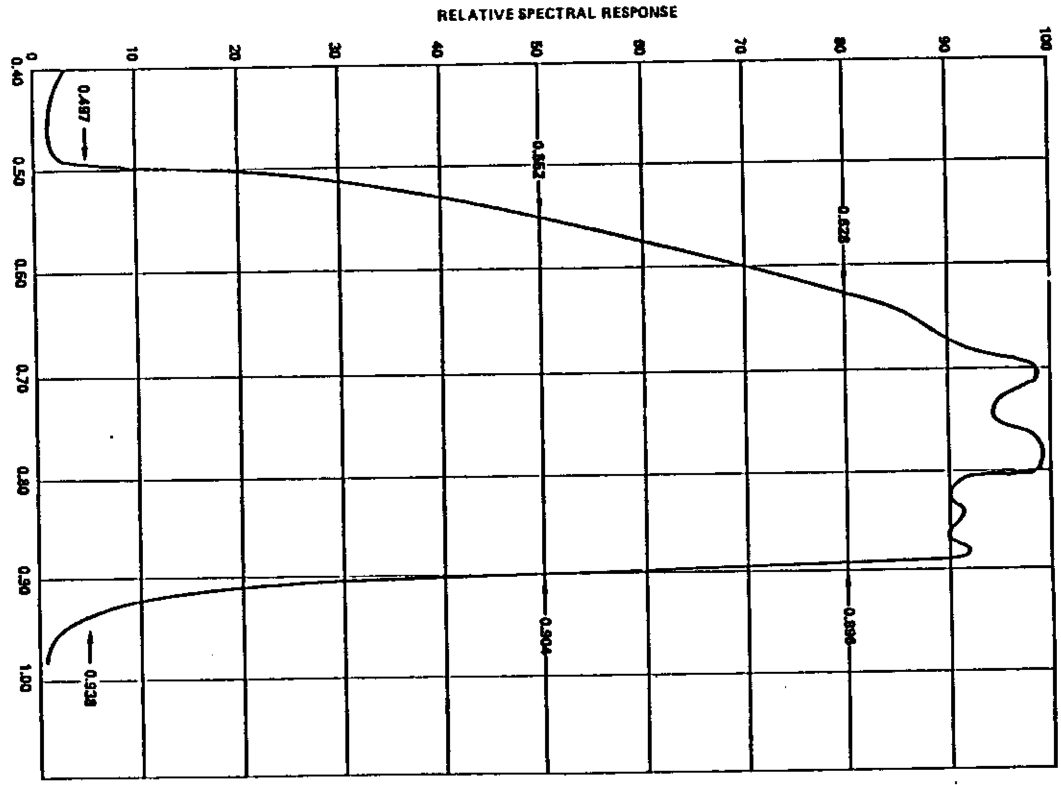
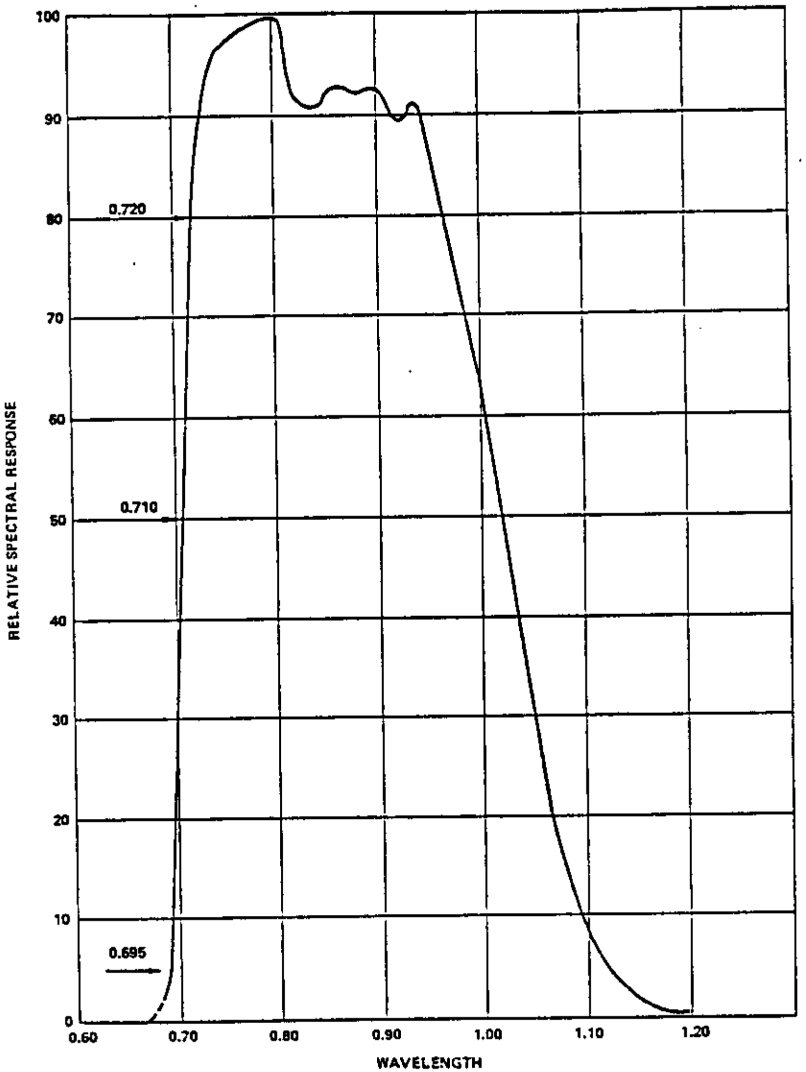


Figure 4.1. Multispectral remote sensing. (A) The sensing of the same target by different sensors representing different regions of the electromagnetic spectrum. (B) The sensing of the same target by different sensors used in multispectral remote sensing.



Channel #1. AVHRR Spectral Response



Channel #2. AVHRR Spectral Response

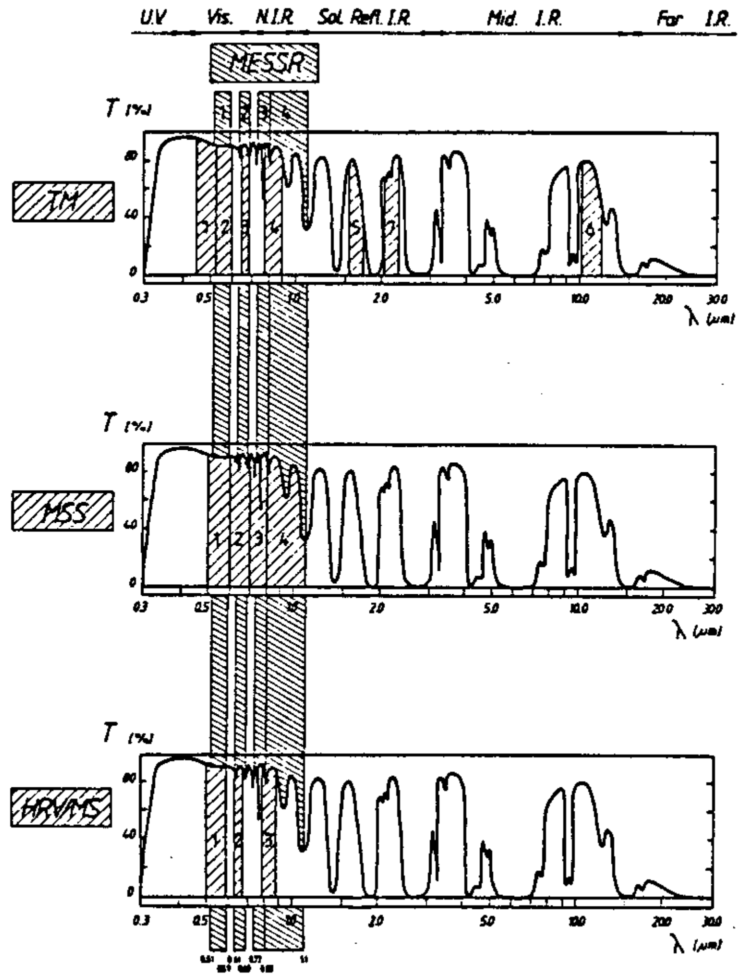


Fig. 2-3: Localization of MESSR spectral bands in atmospheric windows as compared to MSS, TM and HRV.

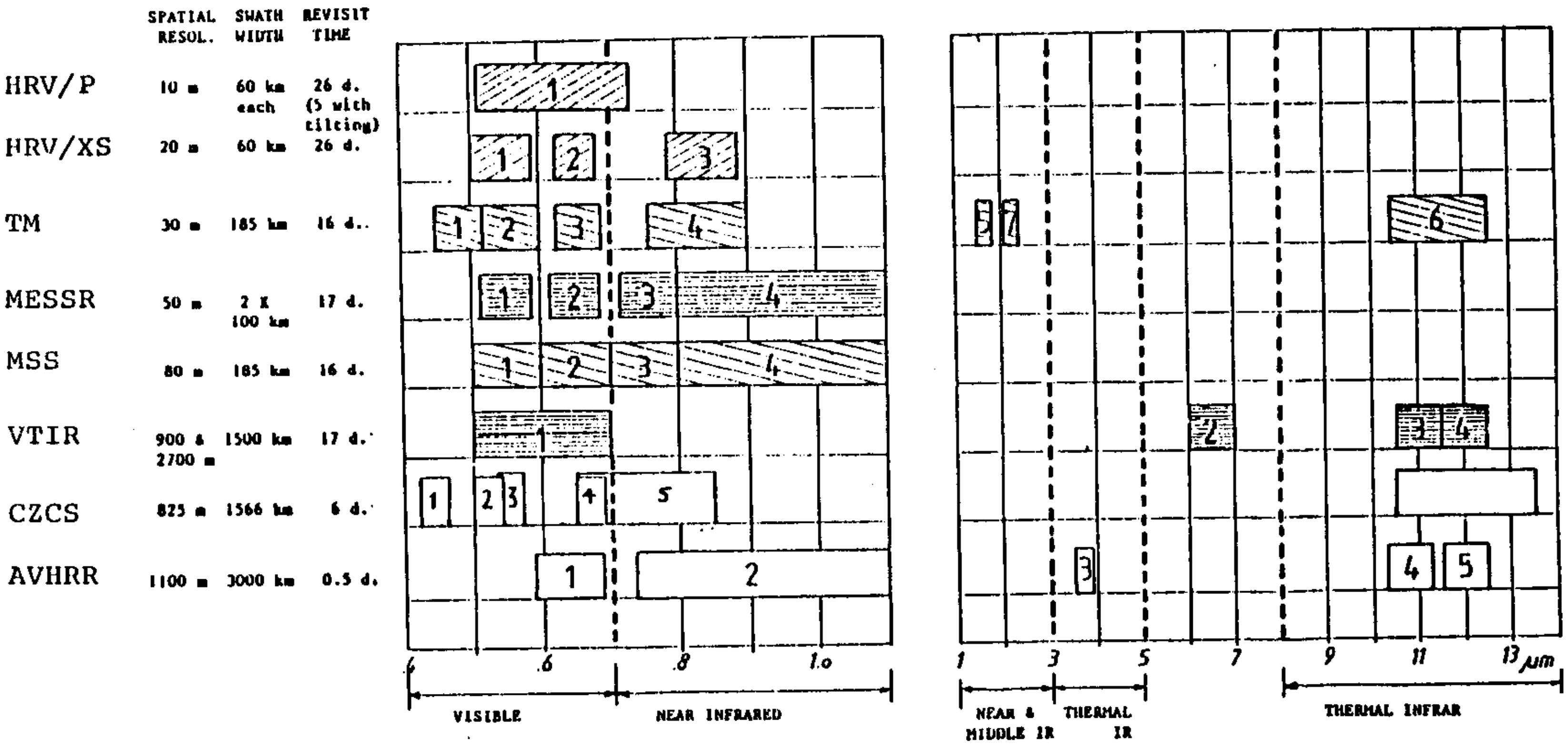


Fig. 2-2: Waveband ranges of selected optical/infra-red sensors of decreasing ground resolutions.

3.3 Optical instruments: scanning aspects

The scanning characterisation of the different optical instruments on existing missions can be done through the following key words:

Scan mirror.
Forward and reverse mechanical scanning.
Push broom.
Nadir and off-nadir viewing.

As example we will describe in the following the Landsat MSS/TM and the SPOT HRV instruments.

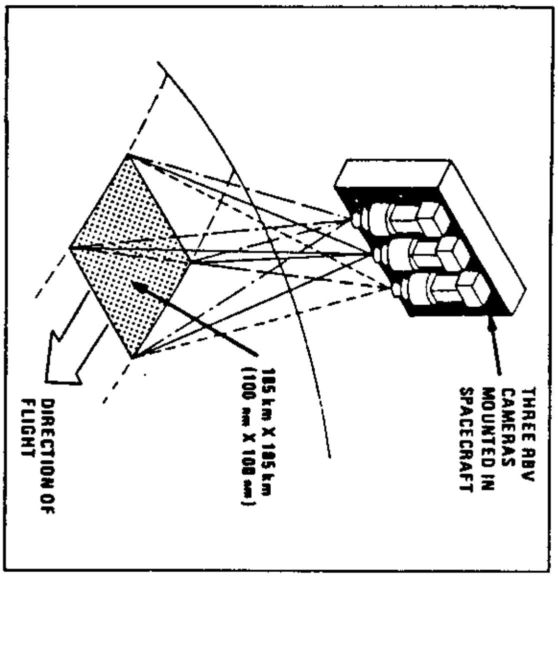


Figure 9.4. The Return Beam Vidicon system on Landsat. (From *Data Users Handbook*, NASA)

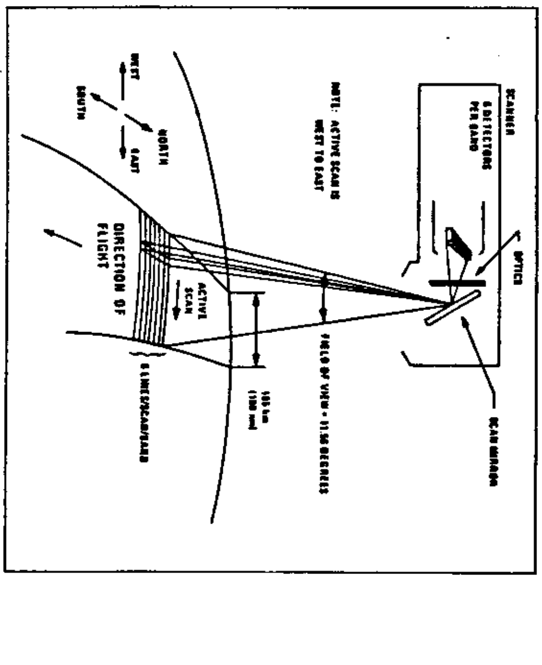
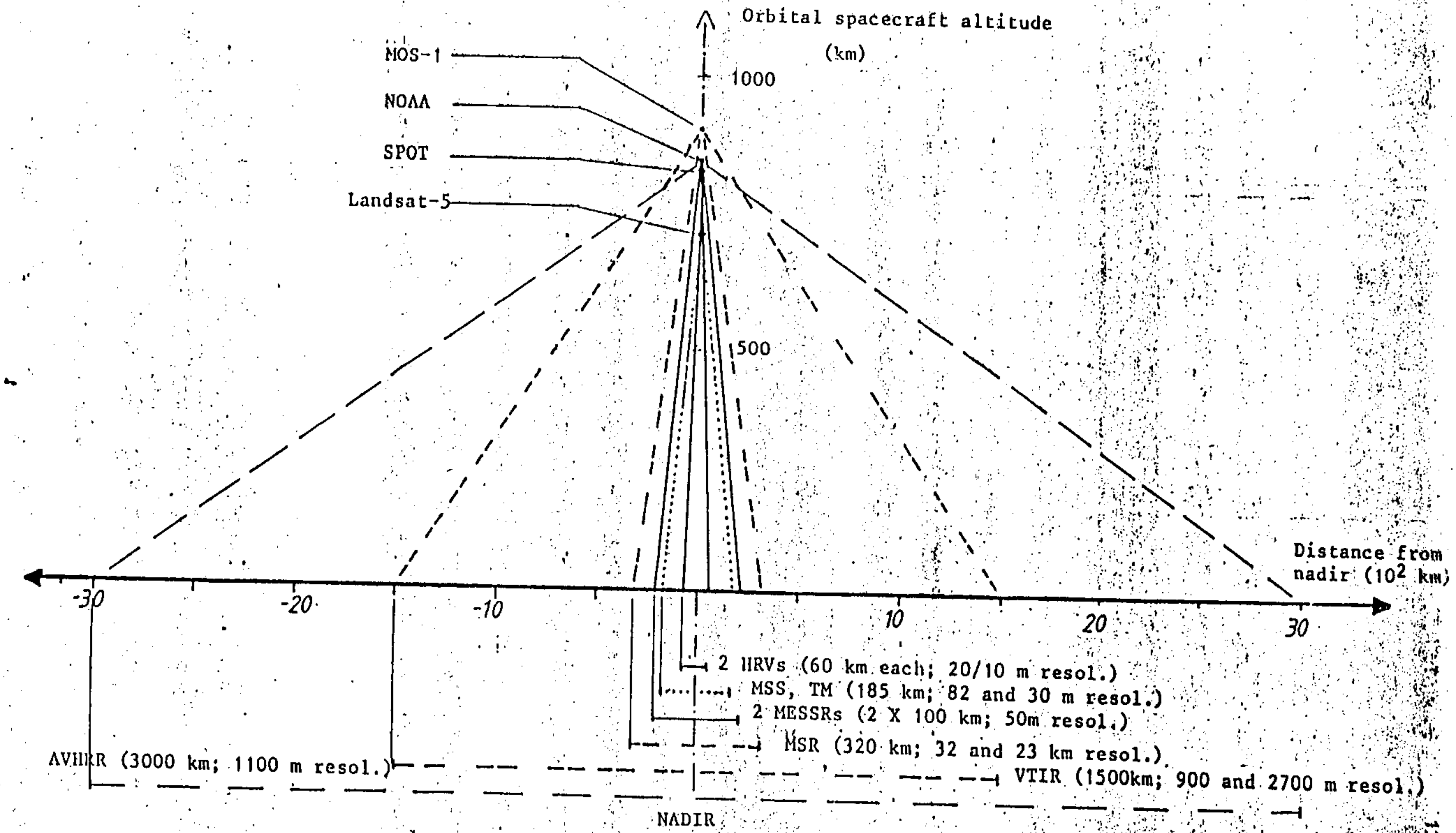


Figure 9.5. MSS System (From *Data Users Handbook*, NASA)

Figure 1 - Orbital altitudes of selected Earth observation satellites and corresponding sensors swath width.



3.4 Optical instruments: signal amplitude aspects

The characterisation of the different radiometers which are available on Earth Observation missions can be done using the following parameters:

Radiometric sensitivity.
Signal to noise ratio.
Number of bits per pixel (Analog to Digital conversion).
Max radiance.
NE deltaT.
Square wave response.
Low/High gain.
Calibration.

As example we will describe in the following the AVHRR, the Landsat MSS/TM and the SPOT HRV instruments.

3.5 Optical instruments: spatial aspects

The characterisation of the different available optical instruments can be done using the following parameters:

Spatial resolution.
IFOV (istantaneous filed of view).
Band to band registration.
Ground swath.
Number of pixel per line.
Number of detectors per band.

As example we will describe in the following the AVHRR, the Landsat MSS/TM and the SPOT HRV instruments.

SENSORS

The remote-sensor instruments mounted on Landsat 4 are the Thematic Mapper (TM) and the Multispectral Scanner (MSS).

THEMATIC MAPPER

The Thematic Mapper is an advanced, multispectral scanning, Earth resources sensor designed to achieve higher image resolution, sharper spectral separation, improved geometric fidelity, and greater radiometric accuracy and resolution in comparison to Multispectral Scanner performance characteristics. TM data are sensed in seven spectral bands simultaneously. Table 4.1 lists the specific TM spectral bands and their principal applications. Bands 1-5 and 7 have an instantaneous field-of-view (IFOV) equivalent to a 30-meter square when projected to the ground; band 6 has an IFOV equivalent to a 120-meter square on the ground.

The TM (fig. 4.1) is mounted in the spacecraft in a horizontal position with the sun shade pointing toward Earth. Directly above the sun shade aperture is a scan mirror surrounded by its drive mechanisms, control electronics, and scan monitor hardware. The primary mirror mounts about halfway down the length of the telescope of the device, preceded by optical baffling and the secondary mirror. Directly behind the primary mirror are the scan line corrector, internal calibrator, and the visible detector focal plane with its mounting hardware and alinement mechanisms. The radiative cooler (containing the cooled focal plane assembly), relay optics, and infrared detector arrays are located on the instrument's aft end. Electronic equipment is packaged above the telescope in a wedge-shaped box containing the multiplexer, power supplies, signal amplifiers, and filters for all channels.

Table 4.1 TM SPECTRAL BAND APPLICATIONS

BAND	SPECTRAL RANGE	PRINCIPAL APPLICATIONS
1	0.45-0.52 μm	COASTAL WATER MAPPING, SOIL/VEGETATION DIFFERENTIATION; DECIDUOUS/CONIFEROUS DIFFERENTIATION
2	0.52-0.60 μm	GREEN REFLECTANCE BY HEALTHY VEGETATION
3	0.63-0.69 μm	CHLOROPHYL ABSORPTION FOR PLANT SPECIES DIFFERENTIATION
4	0.76-0.90 μm	BIOMASS SURVEYS; WATER BODY DELINEATION
5	1.55-1.75 μm	VEGETATION MOISTURE MEASUREMENT; SNOW/CLOUD DIFFERENTIATION
6	10.4-12.5 μm	PLANT HEAT STRESS MEASUREMENT; OTHER THERMAL MAPPING
7	2.08-2.35 μm	HYDROTHERMAL MAPPING

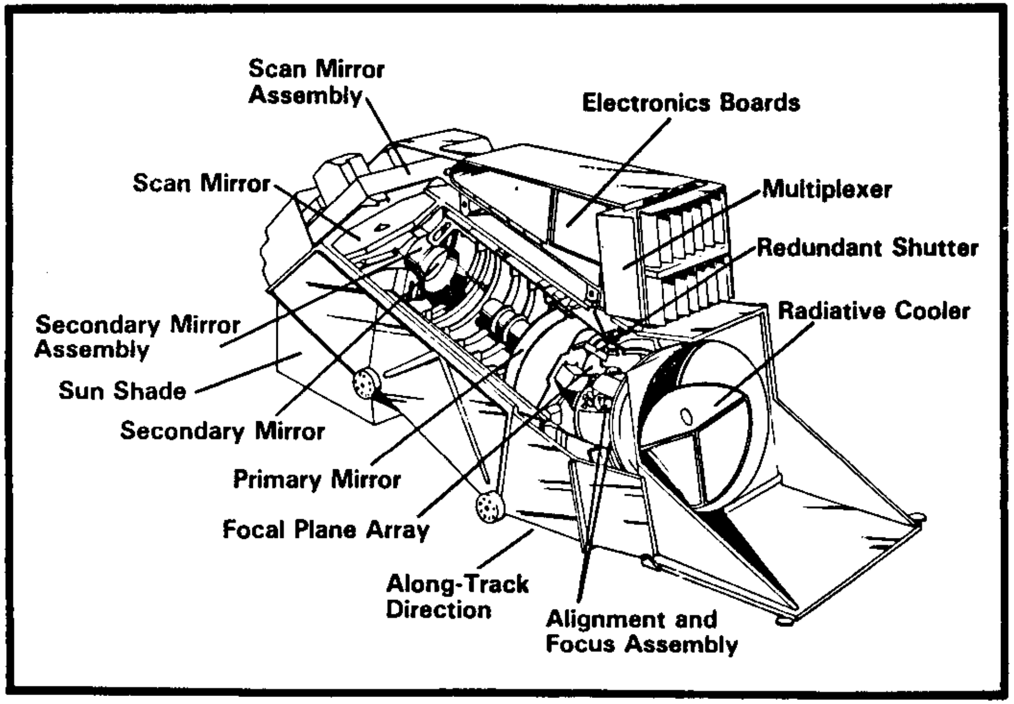


Figure 4.1 CUTAWAY VIEW OF THEMATIC MAPPER

The detector assemblies for spectral bands 1-4 are located at the primary focal plane and employ 16 detectors for each band. The detector assemblies at the cooled focal plane consist of two near infrared bands (5 and 7) with 16 detectors each and one thermal band (6) with four detectors. Thus, during each scan mirror sweep, 16 scan lines of data are generated for each of bands 1-5 and 7, and four are generated for band 6.

A scan angle monitor on the scan mirror passes signals to the timing mechanism in the multiplexer to indicate the beginning (P_0), midscan (P_1), and end (P_2) of the period in the scan mirror's travel when data are taken in the forward scan direction (fig. 4.2), and equivalent signals (P_3, P_4, and P_5) for beginning, midscan, and end of the reverse scan. A "line stop" signal (P_2 and P_5) indicates the end of the format-ting period and is buffered and retransmitted to the scan line corrector to initiate motions that correct for overlap. A second signal, delayed from "line stop" by a programmable period, acts as a synchronization signal to the calibration shutter. These scan angle monitor pulses provide for synchronization of the scan line corrector, calibration shutters, filter shutter, and dc restore circuits.

The scan line corrector (located in front of the prime focal plane) rotates the TM line-of-sight backward along the ground track to generate scan lines that are straight and perpendicular to the ground track. (See figure 4.6.) During each turnaround period of the scan mirror, the internal calibration stimulates the individual channel voltages for all seven spectral bands that provide routine monitoring of detector condition for use in ground processing of images. The calibration signals for bands 1-5 and 7 are derived from three regulated tungsten filament lamps, and the calibr tion source for band 6 is a commandable blackbody with three selectable temperature settings. A black surface of known temperature is used to restore the outputs of all channels to known levels.

As the scan mirror sweeps the

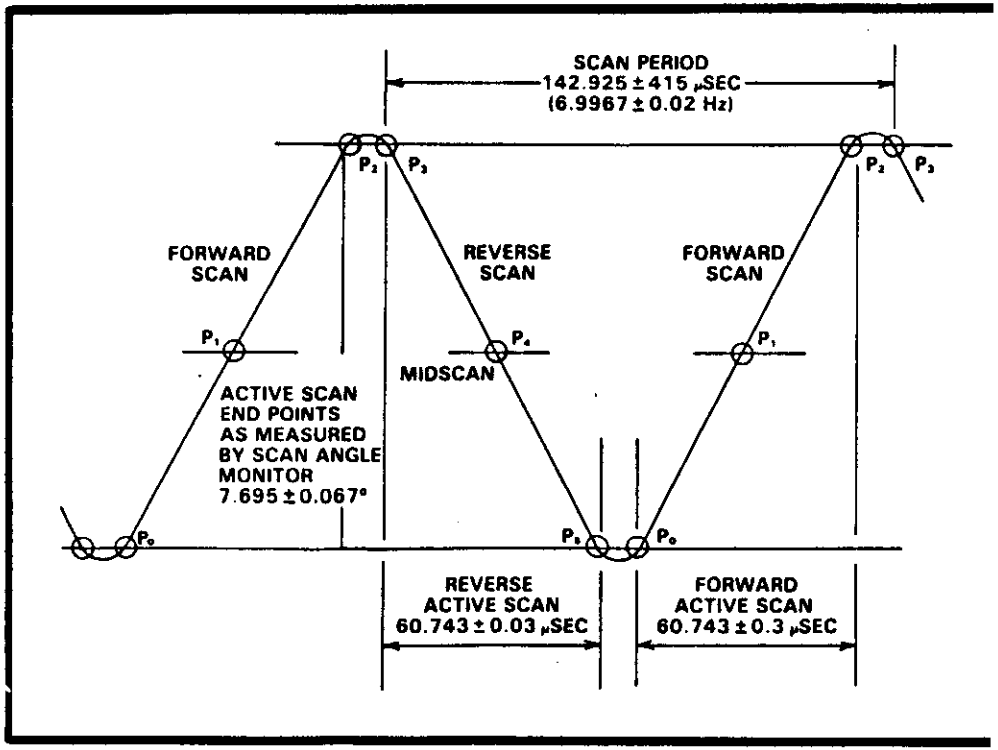


Figure 4.2 SCAN MIRROR DYNAMICS

ᴧ line-of-sight back and forth even times per second in a irection normal to the ground rack, it forms a raster of 16 nes in bands 1-5 and 7, and our lines in band 6 for each weep direction. Data are collected during both the forward west-to-east) and reverse (east-o-west) scans. (Note that nighttime data are collected in the scending mode, reversing eographic motion and scanning directions.) The Ritchey-hretien telescope images the canned scene energy onto the rime focal plane as the scan ne corrector is operating to rovide forward and reverse can swaths adjacent to each ther. At the prime focal plane ands 1-4 each employ a 6-element detector array to ranslate the sensed scene energy into low-level electrical signals that are amplified, converted to 8-bit digital words, and then multiplexed into the 84.9-megabit-per-second (Mbps) data stream transmitted to the ground. A two-mirror, all-reflective relay re-images the incoming energy onto the cooled focal plane located in the radiative cooler, where bands 5 and 7, each utilizing a 16-element detector array and band 6, utilizing a four-element detector array, translate the scene energy into low-level electrical signals. These signals are amplified and converted into 8-bit digital words that are multiplexed into the 84.9-Mbps data stream transmitted to the ground.

THEMATIC MAPPER DESIGN AND FUNCTION

The TM functions as shown in the block diagram (fig. 4.3). Scene energy passes through several major subsystems before it is collected by the solid-state detectors at the focal plane. These subsystems are:

- Scan Mirror Assembly
- Primary Telescope
- Scan Line Corrector
- Primary Focal Plane Array
- Relay Optics
- Cooled Focal Plane Array
- Internal Calibrator

Scan Mirror Assembly

Scene energy enters the system through the Scan Mirror Assembly that moves with the spacecraft in the along-track direction and oscillates across track in the forward (west-to-east) and reverse (east-to-west) directions during the descending (daylight) portion of the orbit. The scan mirror is designed to operate linearly over a mechanical scan angle of 7.7° at a 7-Hz rate with the required turnarounds at scan end points occurring in 10.7 microseconds. Figure 4.4 illustrates the scan mirror angular position as a function of time, indicating scan angle monitor points. The scan mirror is elliptical (53.47 x 41.28 cm), sized to provide an equal area at all scan angles. The size of the mirror required that a light, brazed-beryllium, egg-crate design be used for its construction (table 4.2) to minimize the mass and moment of inertia of the mirror while making scan turnarounds.

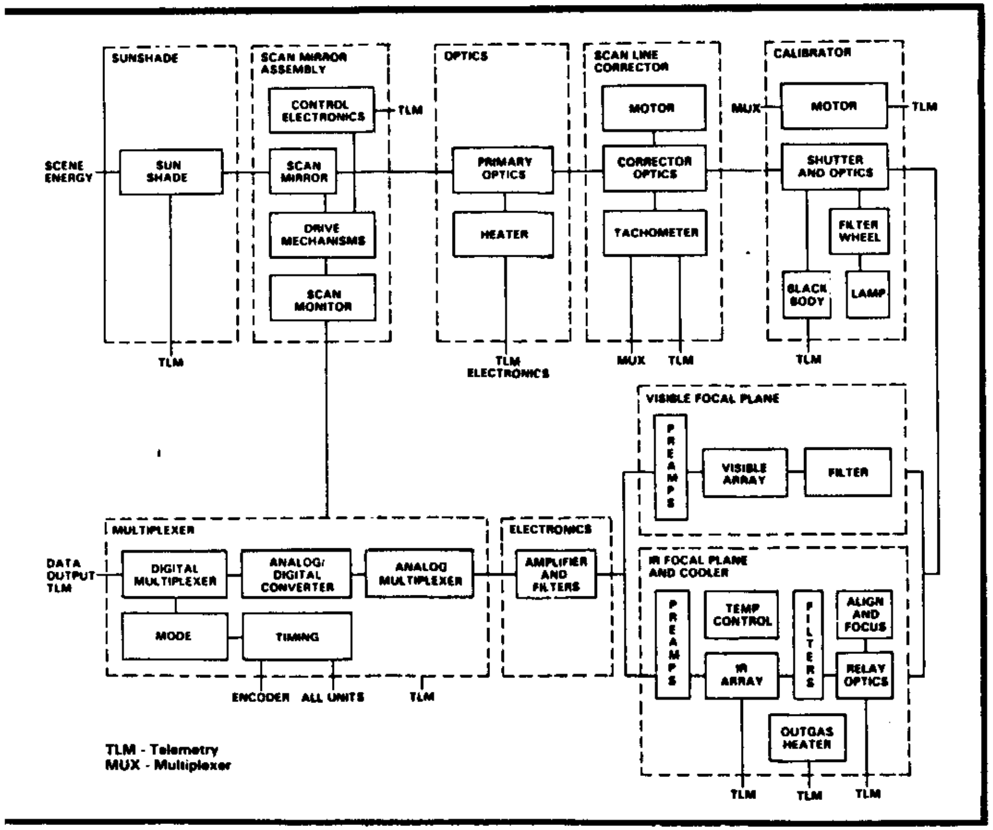


Figure 4.3 TM FUNCTION

Primary Telescope

The 41-cm Ritchey-Chretien telescope uses primary and secondary mirror surfaces to provide simultaneous correction of spherical aberration and coma. Both primary and secondary mirrors are fabricated from ultra-low expansion glass and incorporate a weight-saving, internal egg-crate structure. Design parameters of the primary telescope are shown in table 4.3.

Scan Line Corrector

The scan line corrector consists of a pair of parallel beryllium mirrors. These mirrors are mounted at an angle of 45° with respect to the optical axis and rotate about an axis normal to the axis of the scan mirror in a sawtooth fashion as shown in figure 4.5. The scan line corrector is located behind the primary optics and compensates for the forward motion of the spacecraft, allowing the scan mirror to produce usable data in both scan directions (scan lines straight and perpendicular to the ground track). The corrector jumps ahead at the mirror turnarounds so that the next set of raster lines is contiguous to the previous set. Figure 4.6 illustrates the scan lines with and without scan line correction.

Prime Focal Plane Array

The prime focal plane, which contains the silicon detectors and preamplifier components for the first four visible spectral bands, is located at the prime focus of the primary telescope. The prime focal plane is packaged in a high-density arrangement to maintain a minimum band-to-band spacing of 2.5 mm, which dictates that the critical first-stage preamplifier field-effect transistors (FET's) and 10^9 ohm feedback resistors be located on substrates behind and normal to the focal plane. The remainder of the preamplifier

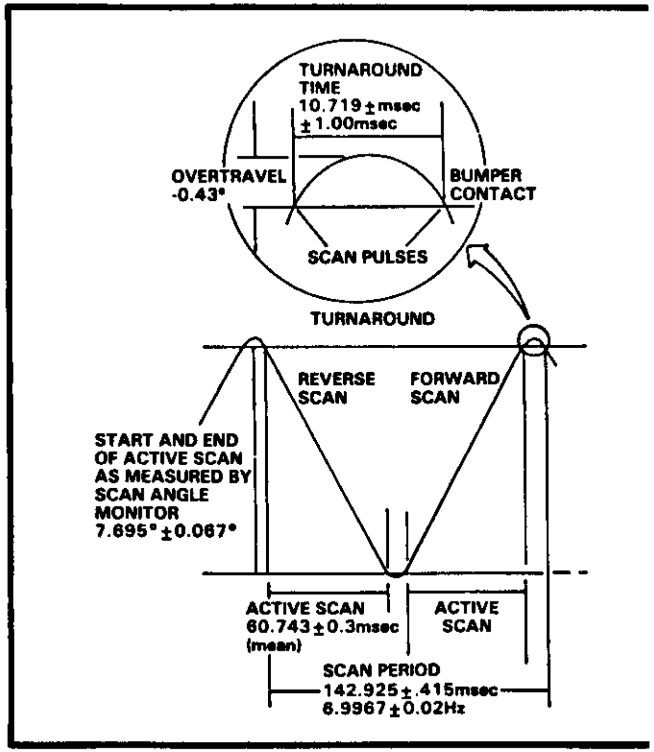


Figure 4.4 TM SCAN MIRROR ANGULAR POSITIONS

Table 4.2 SCAN MIRROR DESIGN PARAMETERS

SWATH LENGTH	185 km
SCAN PERIOD	142.925 msec
SCAN FREQUENCY	6.9967 Hz
SCAN EFFICIENCY	0.85
ACTIVE SCAN TIME	60.743 msec
TURNAROUND TIME	10.719 msec
IFOV DWELL TIME	9.611 msec
LINE LENGTH	6320 IFOV
SIZE	21.050 x 16.250 in. (53.47 x 41.28 cm)
MATERIAL	NICKEL-PLATED BERYLLIUM (EGGCRATE) SILVER COATING WITH SiO_2 OVERCOAT

4.3 PRIMARY TELESCOPE DESIGN PARAMETERS

CONFIGURATION	RITCHEY-CHRETIEN
f/NO.	6.0
MIRROR MATERIAL	GLASS (TITANIUM SILICATE), EGGCRATE CONSTRUCTION, SILVER COATING WITH SiO_2 OVERCOAT
PRIMARY MIRROR CLEAR APERTURE DIAMETER	16.20 in. (41.15 cm)
SECONDARY MIRROR BAFFLE DIAMETER (OBSCURATION)	6.173 in. (15.7 cm)
TELESCOPE CLEAR APERTURE	1056 cm²
EFFECTIVE FOCAL LENGTH	96 in. (243.8 cm)

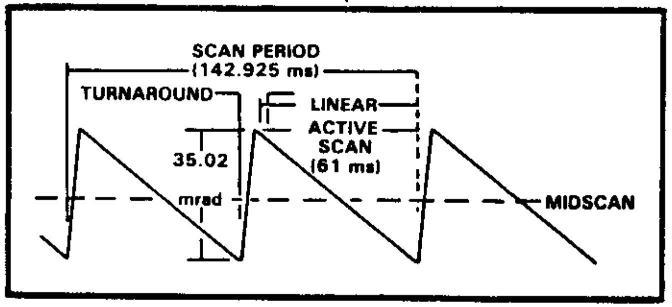


Figure 4.5 TM SCAN LINE CORRECTOR MOTION

components are mounted in hybrid circuits that are connected to the focal plane through flexible cables.

For bands 1-4, each detector assembly uses a 16-element monolithic silicon detector array with an instantaneous field-of-view (IFOV) of 42.5 microradians to convert the sensed scene energy into low-level electrical signals that are then amplified by current mode preamplifiers and frequency boosting post-amplifiers. The odd-numbered detectors are arranged in a row normal to the scan direction (fig. 4.7); even-numbered detectors are aranged in a parallel row, offset one IFOV in the cross-scan direction.

The relative position of detector elements in the focal plane illustrates the spatic.. relationship of the sensors. Figure 4.8 provides an understanding of relative sensor positions as they are projected on the ground (those detectors that are at the cooled focal plane are shown in their projected positions at the prime focal plane as well as on the ground).

The detector arrays are swept back and forth approximately normal to the ground track by the scan mirror. Sensed energy at each high-resolution band detector (bands 1-5 and 7) is sampled every 9.611 microseconds, which equals one IFOV (42.5 microradians). The detector data are sampled in the following sequence:

Bands 1-5 and 7: All **odd** detectors of every band sense and are **held** simultaneously every 9.611 microseconds; the resulting samples are read out before the next sample cycle begins.

All **even** detectors of every band sense and are **held** simultaneously one-half sample time later (4.81 microseconds).

With the nominal 2.5-IFOV spacing between odd and even numbered detectors, this creates a 2-IFOV odd-to-even detector spacing on forward scans and a 3-IFOV spacing on reverse scans.

Band 6: With a detector four times larger than bands 1-5 and 7, band 6 requires only one-sixteenth of the number of samples. The sampling sequence is timed to create this ratio and is performed in the following order:

Detector 1 and detector 3 of band 6 sense and are held simultaneously immediately after scan line start. Detector 1 imagery is then sampled, followed by that of detector 3. The identical sequence then occurs for sampling data from detector 2, followed by detector 4.

In this manner, the data are acquired by holding each one-half (odd or even) detector-set for each band at a specific time. During the hold period, the signal level of the detectors is read out by the multiplexer element for each band. The eight detector outputs per each band are analog-to-digital (A/D) converted by a submultiplexer. The output of the submultiplexer is serialized by the main digital multiplexer, resulting in a digital stream of data and associated telemetry for all of the odd-numbered detectors that will be acquired at time (T_0) and for all of the even-numbered detectors acquired at a time T_0 + 4.81 microseconds.

Relay Optics

The relay optics mechanism, consisting of a folding mirror and a spherical mirror, are used to transfer scene energy onto a second focal plane (cooled focal plane array) located in the radiative cooler. The two mirrors are mounted in a graphite composite structure containing cylindrical assemblies located on 120 centers that provide a capability for on-orbit alinement and focus of the cooled focal plane (with detectors for bands 5 through 7) with respect to the prime focal plane. The relay system has an optimum magnification of 0.5 to allow the use of smaller detectors in the cooled focal plane.

Cooled Focal Plane Array

The detector assemblies at the cooled focal plane consist of bands 5 and 7, arranged as the bands of the prime focal plane array, and band 6, which has four detectors with an IFOV of 170 microradians, located in the radiative cooler.

Bands 5 and 7 each employ a 16-element monolithic indium antimonide (InSb) detector array; band 6 employs a 4-element monolithic mercury-cadmium-telluride detector array. The cooled focal plane has a thin-film heater that maintains the focal plane temperature within ± 0.2K of three selectable temperatures, 90K, 95K, and 105K. (Figure 4.9 shows the cooled focal plane substrate assembly with and without spectral filters.) The focal plane signals are routed off the substrate assembly through a distribution board to extremely thin, flexible, low-thermal conductance cables that interface with the preamplifier assemblies of the radiative cooler.

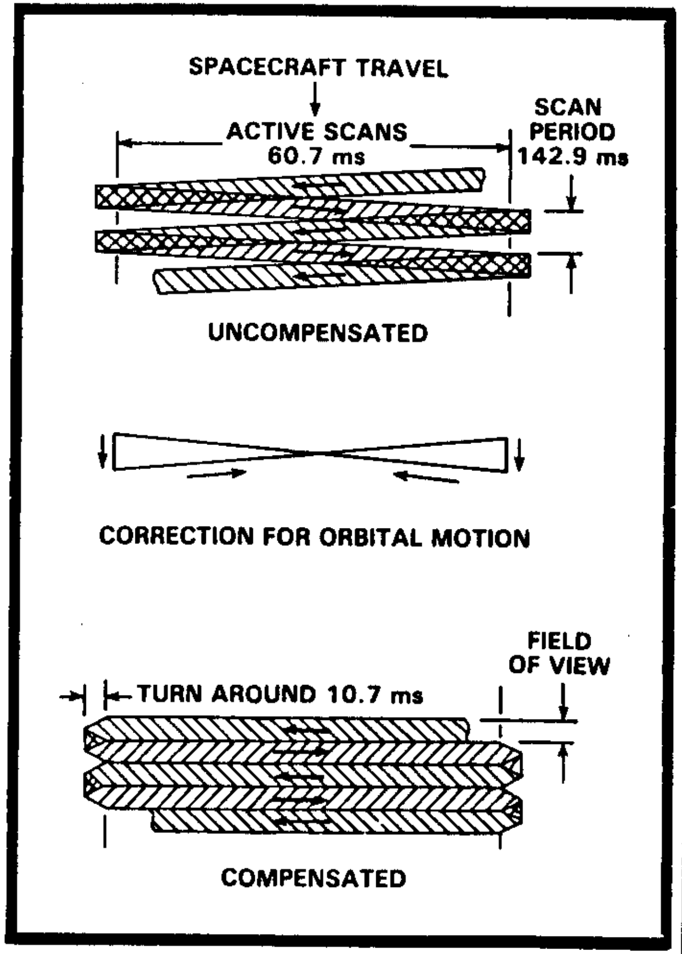


Figure 4.6 TM SCAN LINE CORRECTION

Radiative Cooler

The radiative cooler provides cooling for the detectors of bands 5 through 7. The energy for these detectors passes through the prime focal plane and is refocused by relay optics at the cooled focal plane. The design uses two cooling stages with open-faced honeycomb for the radiator emitting surfaces. The radiations are shielded from direct view of the Sun, Earth, or spacecraft surfaces. Table 4.4 summarizes the radiative cooler design parameters.

Internal Calibrator

The on-board calibrator (fig. 4.9) is mounted in front of the prime focal plane (three tungsten filament lamps for bands 1-5 and 7, a blackbody for band 6, and a flex-pivot-mounted resonant shutter). The shutter oscillates at the same frequency (7 Hz) as the scan mirror assembly. Thus, the shutter introduces the calibration source energy and a black dc restoration surface into the detector fields-of-view during the turn-around time of each scan mirror cycle. An imaging scheme is used on the output end of the shutter to assure uniform calibration without stray radiation; that is, the method for transmitting radiation to the moving calibration shutter allows the lamps to provide radiation independently and to contribute proportionately to il-

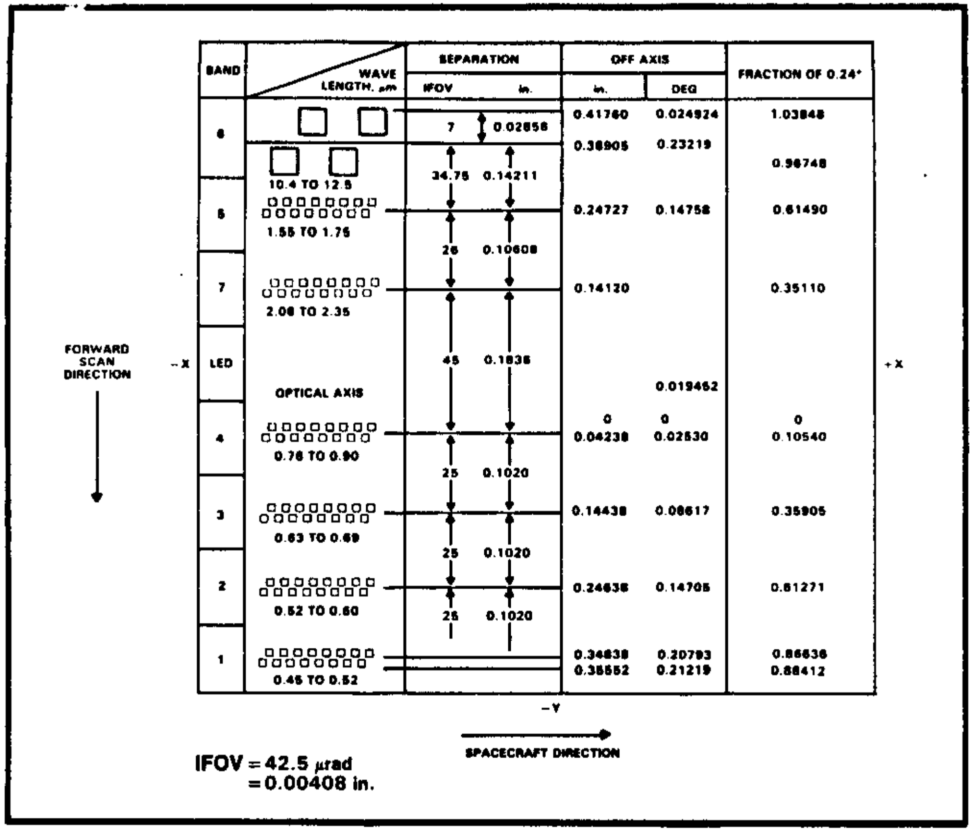


Figure 4.7 VIEW OF DETECTORS AS PROJECTED ON PRIME FOCAL PLANE LOOKING FROM −Z TOWARDS +Z (OPTICAL SYSTEM COORDINATES)

lumination of all detectors.

Electronics Module

The electronics module contains the power supply, the printed wiring boards containing the drives and control electronics for all the mechanisms and heaters, the command and telemetry distribution and collection circuitry, the signal processing postamplifiers that limit the system frequency response, and the multiplexer. The multiplexer encodes all the radiometric data (100 channels of signal data), analog multiplexes all detector channels, makes the A/D conversion, and converts all the radiometric data and telemetry information into 8-bit words that form the 84.9-Mbps data stream transmitted to Earth by the Landsat 4 spacecraft. The multiplexer contains the master clocks that synchronize the system timing for the TM.

THEMATIC MAPPER PERFORMANCE

TM performance results are based on TM/Protoflight (PF) tests conducted at Santa Barbara, California and Valley Forge, Pennsylvania. The TM/PF device is the actual instrument carried on Landsat 4.

The TM/PF performance results are presented in four key areas: (1) spectral response, (2) radiometric sensitivity, (3) square-wave response (modulation transfer function), and (4) band-to-band registration.

Spectral Response

Table 4.5 illustrates the Landsat 4 TM/PF spectral performance. This performance is based on measurements of all protoflight components (mirrors, spectral filters, windows, and detectors) that affect the spectral coverage of the system.

Radiometric Sensitivity

Table 4.6 illustrates radiometric sensitivity for bands 1-5 and 7. Signal-to-noise ratios (SNR) for two levels of scene radiance are shown. The radiometric performance of band 6 is shown in table 4.7 in terms of the noise equivalent

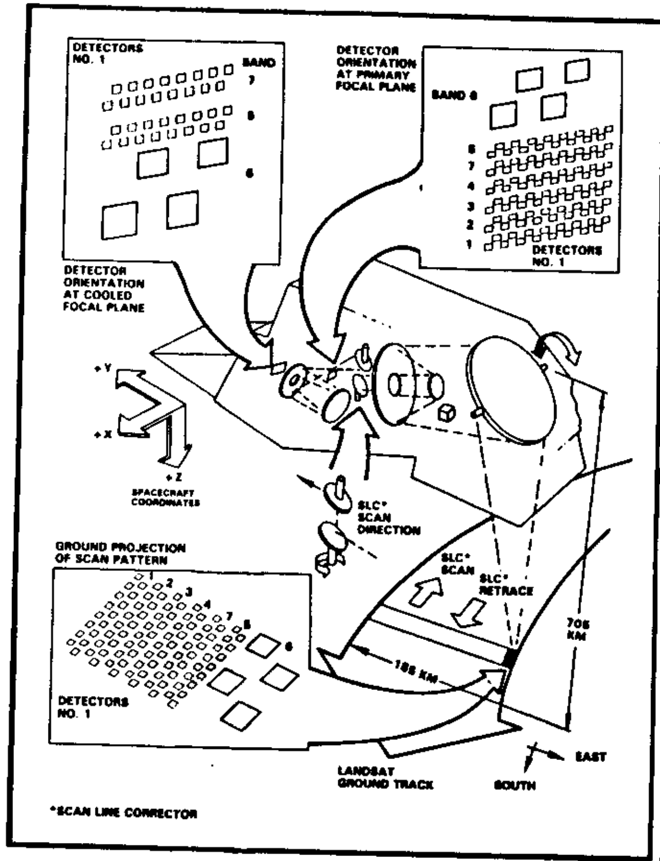


Figure 4.8 RELATIVE POSITIONS OF DETECTOR ELEMENTS

temperature difference (NEΔT).

Square Wave Modulation

Table 4.8 presents the band average response of each spectral band to high-contrast bars of the noted spatial size. The standard deviations (δ) indicate the magnitude of the channel-to-channel response variance for the 16 channels in each of bands 1-5 and 7 and four channels in band 6.

Band-To-Band Registration

Dynamic band-to-band registration was measured at 29 locations throughout both the forward and reverse scan profiles. The data in table 4.9 are the largest registration errors measured throughout either profile. The measured data are presented in terms of fractional IFOV.

MULTISPECTRAL SCANNER

The MSS on Landsat 4 is similar to the MSS instruments that were flown on Landsats 1, 2, and 3. (See fig. 4.10). However, in order to provide MSS data compatible with those acquired from the higher orbits flown by Landsats 1, 2, and 3 (about 920 km), the optics of the Landsat 4 MSS system have been adjusted so that the IFOV size still approximates an 80- x 80-m ground area. In addition, a new numbering system is being used to designate the four spectral bands of the Landsat 4 MSS. What are known as bands 4, 5, 6, and 7 on the previous MSS sensors are now known, respectively, as Landsat 4 MSS bands 1, 2, 3, and 4. This is a change in designation only. The spectral coverage of the instrument remains the same.

Scanning Arrangement

Figure 4.11 illustrates the Landsat 4 MSS scanning geometry. During every mirror MSS retrace period, the radiance from the Earth scene is blanked out by a mechanical shutter. During every other mirror retrace, the individual sensors in bands 1-4 are exposed to a rotating, variable density-wedge optical filter illuminated by an on-board calibration lamp. The resulting calibration data are subsequently utilized to make radiometric corrections on the MSS detector signals.

Fiber Optics Array and Detector Sampling

The MSS electronic subsystem is designed to sample sequentially the individual MSS detectors to produce a serial digital data stream.

Figure 4.12 illustrates the physical arrangement of the square light pipes placed in the focal plane of the MSS telescope. Each light pipe conducts radiance at the focal plane to an individual detector. S1...S24 denotes the order in which the resulting detector signals are sampled. Detectors A, B,...F designate detectors within a given spectral band. The light pipe array dimensions, physical arrangement, and sampling process are directly related to mirror velocity and spacecraft motion. An understanding of this relationship is essential to the calculation of effective field of view as well as to the understanding of computer-compatible tape (CCT) production.

The MSS mirror is driven at a frequency of 13.62 Hz, derived by counting down the frequency of a crystal-controlled clock using a countdown factor of 135 X 2^{13} = 1,105,920. Thus the 13.62 Hz is derived from a frequency of 15.0626 MHz + 0.01%. This frequency is significant in that it represents the maximum bit rate that can be accommodated during detector sampling. Time per bit is 0.0664 microsecond. Each detector represents a channel of data, and 24 such channels (of 25 available) are used on the Landsat 4 spacecraft. Each detector analog output is encoded as a 6-bit digital word, with each word corresponding to one picture element (pixel). The word period is then 0.398 microsecond (6 X 0.0664),

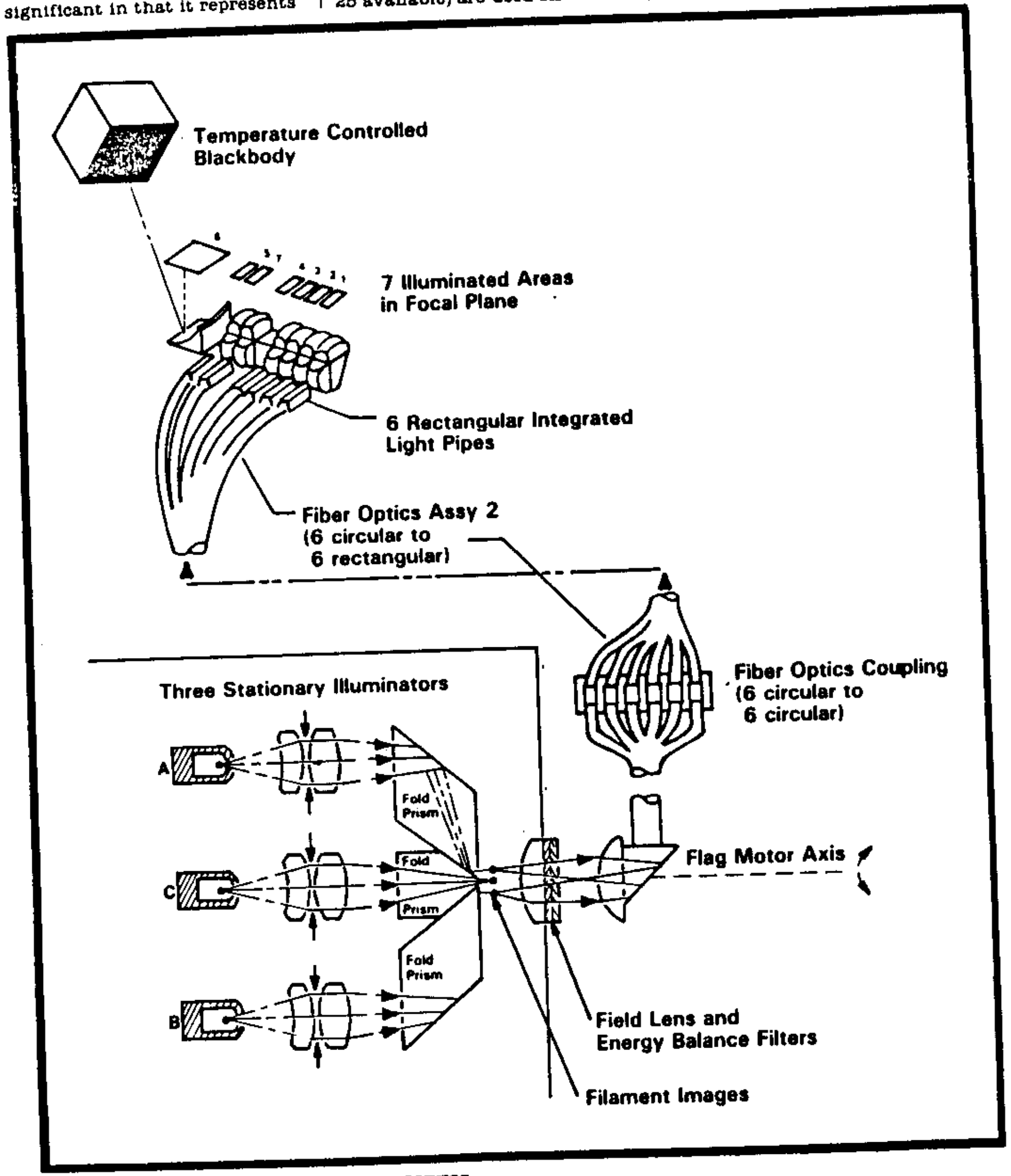


Figure 4.9 CALIBRATOR OPTICAL SYSTEM

which is the sampling time per detector. Because there are 24 channels involved, each detector is sampled once in every 9.968 microseconds.

Consider a ground scene composed of a single 83-by 83-meter object, imaged on detector A, band 1, at a time t = 0. The active scan time during which video is acquired is 33 milliseconds. In the west-to-east active scan period, a scan monitor sensor determines the mirror angular position to start and stop detector sampling. The scan monitor sensor ensures that the cross-track optical scan is 185 km at nominal altitude regardless of mirror scan nonlinearity or other perturbations of mirror velocity. Cross-track image velocity is nominally 6.82 meters per microsecond. After 9.968 microseconds, the 90-by 80-meter image has moved 67.9 meters. The S1 sample taken at this instant represents 16 meters of previous information and 68 meters of new information. Therefore, in practice the "effective" IFOV of a detector in the cross-track direction must be considered to be 68 meters corresponding to a nominal pixel area of 68 by 83 meters (at nadir point). Use of the "effective" IFOV in area calculation therefore eliminates the overlap in area between adjacent samples (pixels).

Table 4.4 TM RADIATIVE COOLER DESIGN PARAMETERS

HORIZONTAL FIELD OF VIEW	160
VERTICAL FIELD OF VIEW	114
INTERMEDIATE STAGE RADIATOR AREA	660 cm,
COLD STAGE RADIATOR AREA	430 cm,
COLD STAGE MINIMUM TEMPERATURE CAPABILITY (ALL BANDS ON)	84.4K
RADIATION SURFACE	BLACK PAINTED HONEYCOMB
INTERMEDIATE STAGE TEMPERATURE	≈147K
INTERMEDIATE STAGE HEAT LOAD	2.2 watts
COLD STAGE HEAT LOAD	117 mw

Table 4.5 TM PROTOFLIGHT SPECTRAL PERFORMANCE OBSERVED BAND LOCATIONS

BAND	LOWER BAND EDGE AT HALF MAXIMUM		UPPER BAND EDGE AT HALF MAXIMUM		BANDWIDTH AT HALF MAXIMUM	
	OBSERVED λL (NM)	DIFFERENCE λL- λLS (NM)	OBSERVED λU (NM)	DIFFERENCE λU- λUS (MN)	OBSERVED Δλ (NM)	DIFFERENCE Δλ - Δ λS (NM)
1	452	2	518	-2	66	-4
2	529	9	610	10	81	1
3	624	6	693	3	69	9
4	776	16	905	5	129	-11
5	1568	18	1784	34	216	16
7	2097	17	2347	-3	250	-20
6 (μM)	10.422	.002	11.661	-.839	1.239	-.861

Band 1 data precedes band 4 data by 64.926 microseconds. Also, band 2 precedes band 4 data by 44.612 microseconds, and band 3 precedes band 4 by 20.314 microseconds. This spatial misregistration is corrected by inserting the appropriate number of dummy bytes prior to the data in band 1, 2, and 3 during CCT production. In using the term "byte," it is important to distinguish between "spacecraft" bytes an in-band bytes. For example, band 4 detector A is sampled

Table 4.6 TM PROTOFLIGHT RADIOMETRIC SENSITIVITY BANDS 1-5 & 7

BAND	NOISE EQUIVALENT REFLECTANCE	SIGNAL-TO-NOISE RATIOS: MINIMUM SCENE MEASURED	SIGNAL-TO-NOISE RATIOS: MAXIMUM SCENE MEASURED
1	0.8%	52	143
2	0.5%	60	279
3	0.5%	48	248
4	0.5%	35	342
5	1.0%	40	194
7	2.4%	21	164

ınce in this time period. The ıumber of bytes generated in ıll bands during this period is 25. Bands 1, 2, 3, and 4 are off-set from each other by two in-band bytes.

Within a spectral band there is also a time delay between the outputs of detector A and F of 3.98 microseconds or 22.3 meters (for a nonrotating Earth), which is compensated for during the production of film images.

Table 4.7 RADIOMETRIC PERFORMANCE OF BAND 6

CFP TEMP	SCENE TEMP	NEΔT, K
95K	300K 320K	0.10 0.12
105K	300K 320K	0.28 0.21

Signal compression, via four-segment, quasi-logarithmic amplifiers, is generally employed to improve the signal-to-noise ratio in bands 1, 2, and 3. By compressing high radiance level signals, the quantization noise more nearly matches photomultiplier noise. Band 4 signals, derived from silicon photodiodes, are never compressed because equivalent load resistor noise is best matched by linear quantization. The available ground commandable analog processing options are illustrated in figure 4.13. In the high gain mode applied to bands 1 and 2, amplifier gain is increased by a nominal factor of 3. This increase allows greater use of system dynamic range for those scenes producing low sensor irradiance.

There are two signal compression amplifiers in the spacecraft. One is used to process sensor data from bands 1 and 3, and the second is used exclusively for band 2 data. In subsequent processing, decompression of the signals is performed using separate decompression tables for bands 1 and 3 and for band 2. Calibration-wedge signals from each band are decompressed through the same tables before data calibration.

sor data, all data are encoded into 6-bit (1-byte) digital words representing sensor amplitudes in terms of 64 discrete steps, 0-1-2-...63. Six-bit encoding is used regardless of whether the data were linearly processed or compressed. Additional data must be combined with the digital data, so that the sensor data can be properly processed. As an example, the start and end of each active mirror scan time must be indicated. A preamble is added to maintain mirror-scan to mirror-scan bit synchronization. A line-length code that represents the number of pixels encoded from each detector during the mirror active scan time is added.

A vital addition to the sensor data is spacecraft time code. This is essential to identify when and, thereby, where the data were acquired. Time code is basic to framing MSS data to coincide with Worldwide Reference System (WRS) image

Table 4.8 TM PROTOFLIGHT SQUARE WAVE RESPONSE (SWR) — (Band Average)

BAND	30 METER BAR SWR	σ	45 METER BAR SWR	σ	60 METER BAR SWR	σ	600 METER BAR SWR	σ
1	0.46	0.01	0.76	0.03	0.94	0.02	1.0	0.0
2	0.44	0.02	0.72	004	0.96	0.03	1.0	0.0
3	0.41	0.01	0.72	0.02	0.91	0.02	1.0	0.0
4	0.43	0.01	0.76	0.03	0.95	0.03	1.0	0.0
5	0.42	0.02	0.78	0.03	0.89	0.03	1.0	0.0
7	0.44	0.02	0.76	0.02	0.92	0.02	1.0	0.0

BAND	120 METER BAR SWR	σ	180 METER BAR SWR	σ	240 METER BAR SWR	σ	2000 METER BAR SWR	σ
6	0.44	0.04	0.78	0.01	0.94	0.00	1.0	0.0

Analog Sensor Signal Processing

The analog sensor samples are to be eventually digitized into a single 15.0626-Mbps data stream; however, analog processing, including amplification, track and hold, and dc restoration are performed before A/D conversion. In addition, provision is made for linear amplification or nonlinear amplification, which can be selected by commands to the spacecraft.

Formation of the Serial Digital Data Stream

After analog processing of sen-

Table 4.9 TM PROTOFLIGHT DYNAMIC BAND-TO-BAND REGISTRATION

ALONG SCAN REGISTRATION	
WITHIN PFPA	<0.1 IFOV
WITHIN CFPA	<0.08 IFOV
CFPA TO PFPA	<0.19 IFOV
CROSS SCAN REGISTRATION	
WITHIN PFPA	<0.13 IFOV
WITHIN CFPA	<0.10 IFOV
CFPA TO PFPA	<0.27 IFOV

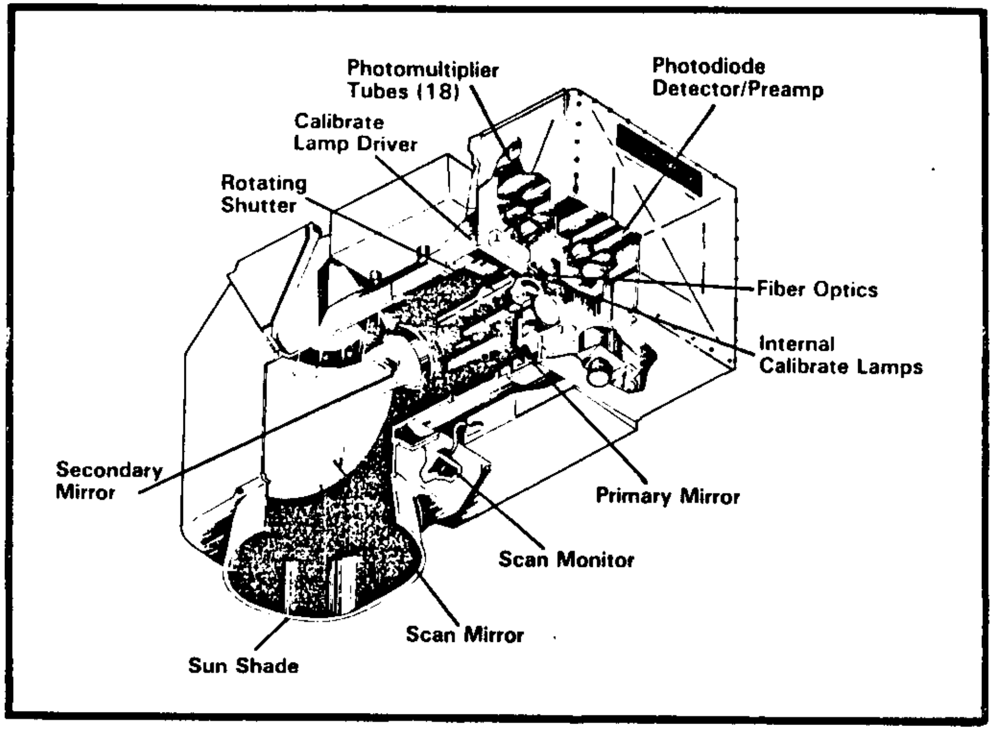


Figure 4.10 CUTAWAY VIEW OF MULTISPECTRAL SCANNER

center points. In addition, scene identification, which is applied to all Landsat photographic and tape products, is derived from spacecraft time code (Greenwich Mean Time).

A typical data sequence may be described as follows: Preamble maintains bit synchronization from scan to scan. As the mirror angular position arrives at the western edge of the area to be imaged, a line-start code is produced. This code interrupts the detector sampling sequence and causes detector A, band 1 to be sampled. A minor-frame synchronizing digital word (MNFS) is also produced (on channel 25). Each time the MNFS or its complement is generated, it indicates that a new sequence of detector video, starting with detector A, band 1, is being produced. In this manner, data are tagged throughout each line scan.

At line start and generation of the first MNFS, video is preempted to permit insertion of 2 bytes of spacecraft time code. The complete time code consists of a 4-byte identifier followed by 44 bytes of time-code data. The first mirror scan contains the four identified bytes followed by 20 bytes of time code. The 24 bytes are distributed, 1 byte per detector (bands 1, 2, 3, and 4) channel. The next line start (mirror scan) contains an alternate 4-byte identifier and the remaining 20 bytes of time code. Therefore, the complete time code can be recovered from two consecutive mirror sweeps. For Landsat 4, the alternate 4-byte identifier is coded to provide spacecraft identification as follows: 0010 = Landsat 4, 0000 = Landsats 1-3.

After time-code insertion, detector video, MNFS and its complement are transmitted until an end of scan code is produced by a position sensor, which detects that the angular position of the scan mirror has reached the eastern edge of the imaged area. At this time, an end of line code is transmitted. A line-length code (LLC) is computed then for each sensor channel. The code provides information on the number of bytes generated by each detector during active scan time. During ground processing, byte variations between sensors can be eliminated to equalize the line length through the introduction of dummy bytes of synthetic video.

On alternate mirror retraces, after the LLC is completed, calibration data are transmitted in digital form. Precisely 6,060 word-periods after line-start code, the preamble code preempts all data and the process repeats.

The 26 channels with all necessary codes are multiplexed into a 15-megabit-per- second digital stream and transmitted at S-band to ground receiving stations.

At the receiving station, the data are recorded on magnetic tape recorders. Figure 4.14 illustrates a typical channel of data after demultiplexing.

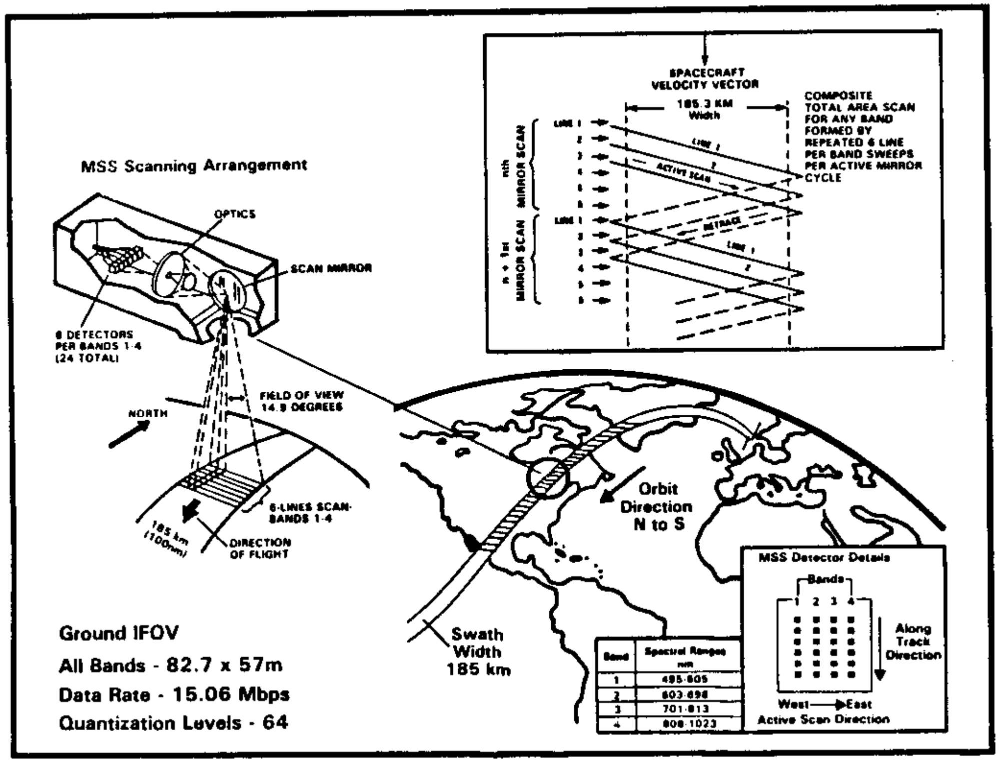


Figure 4.11 LANDSAT 4 MSS SCANNING GEOMETRY

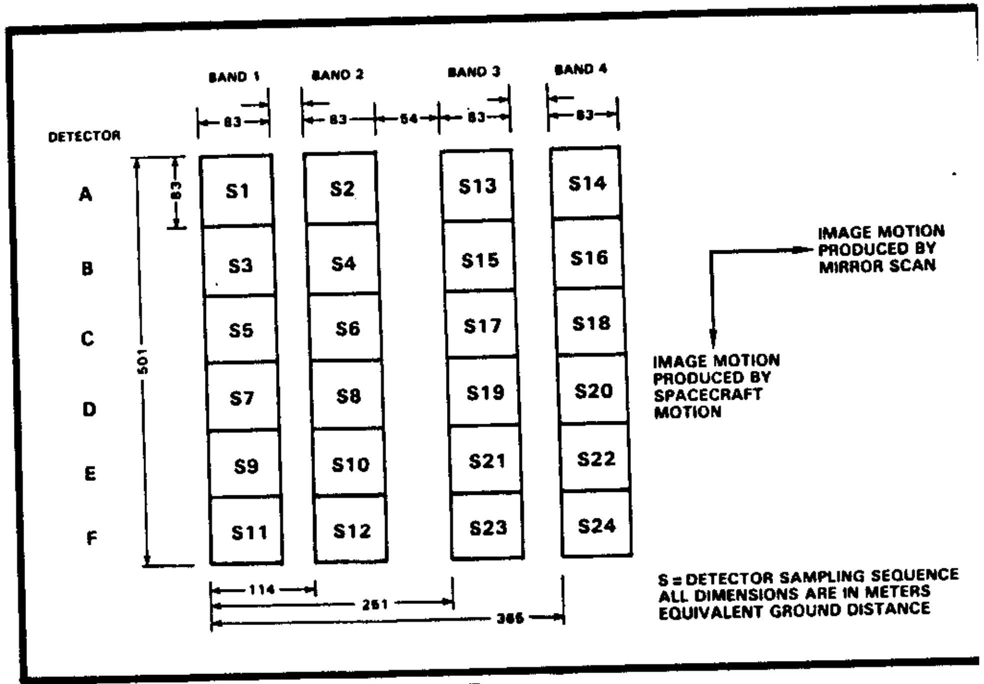


Figure 4.12 MSS LIGHT PIPE ARRANGEMENT

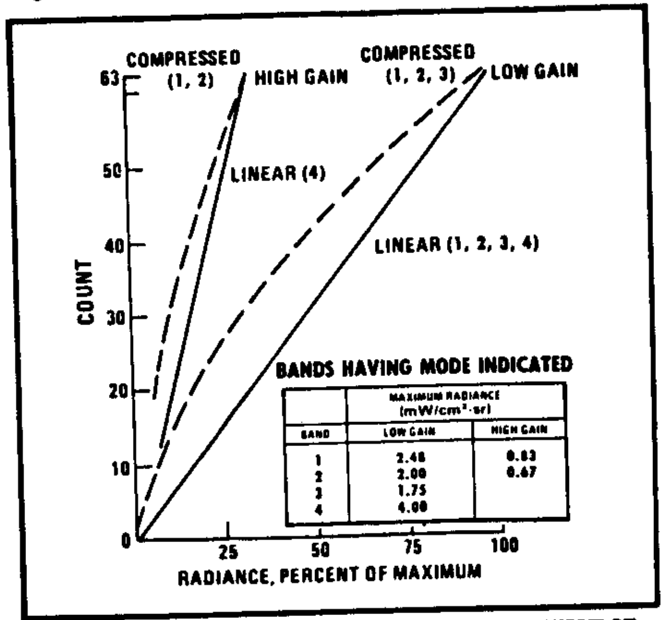


Figure 4.13 MSS DIGITAL OUTPUT COUNT AS A FUNCTION OF RADIANCE, COMPRESSED AND LINEAR MODES

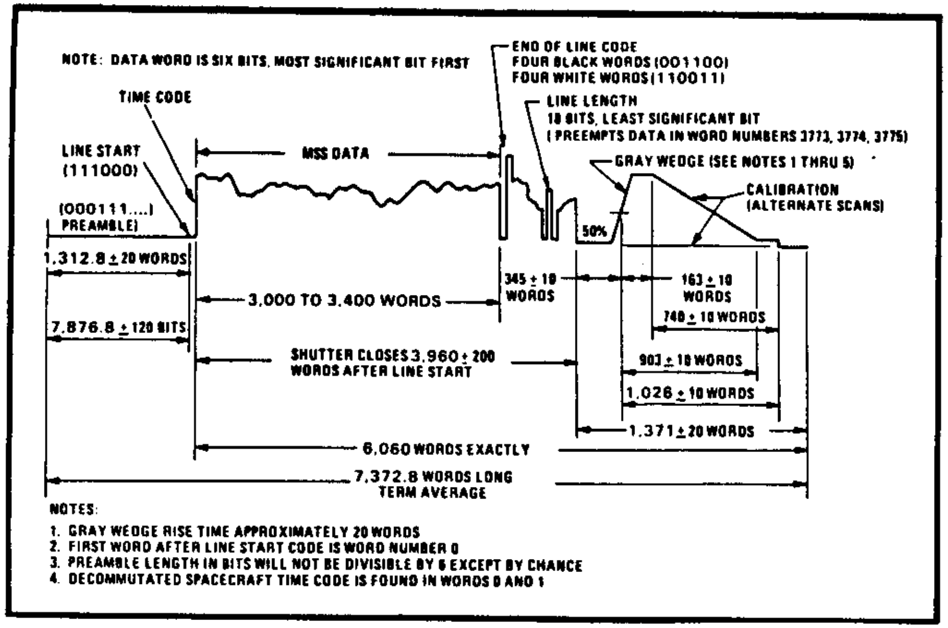
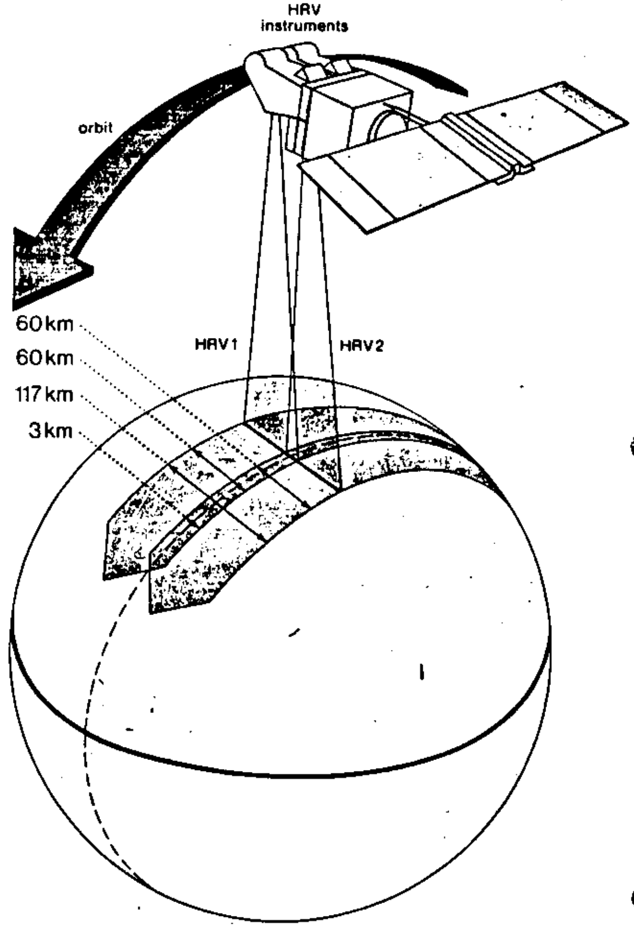


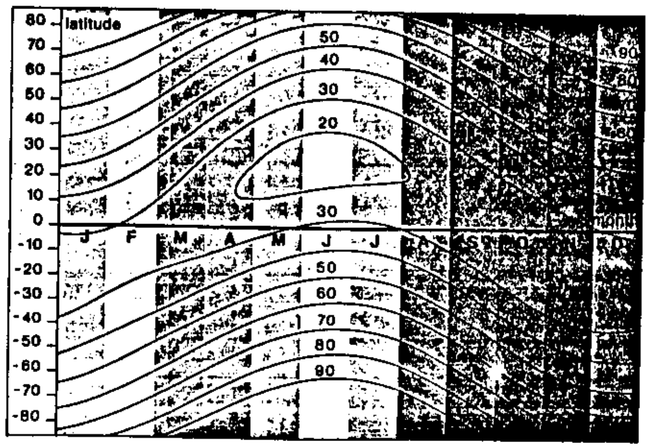
Figure 4.14 DEMULTIPLEXED DATA CHANNEL

nadir viewing

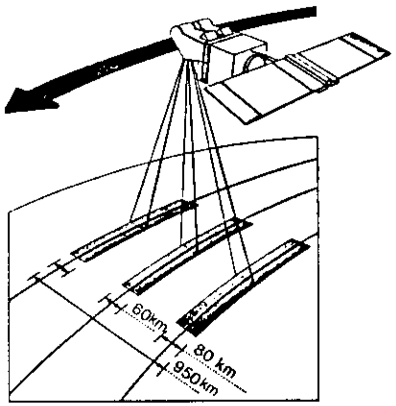
The two HRV instruments can be pointed so as to cover adjacent fields. In this configuration the total swath width is 117 km (nadir) and the two fields overlap by 3 km. Since the distance between adjacent ground tracks at the equator is approximately 108 km, complete Earth coverage can be obtained with this fixed setting of instrument fields.



The angle between the sun direction and the vertical at the sub-satellite point varies with the seasons. This variation is illustrated opposite as a function of latitude and time of year (in months).



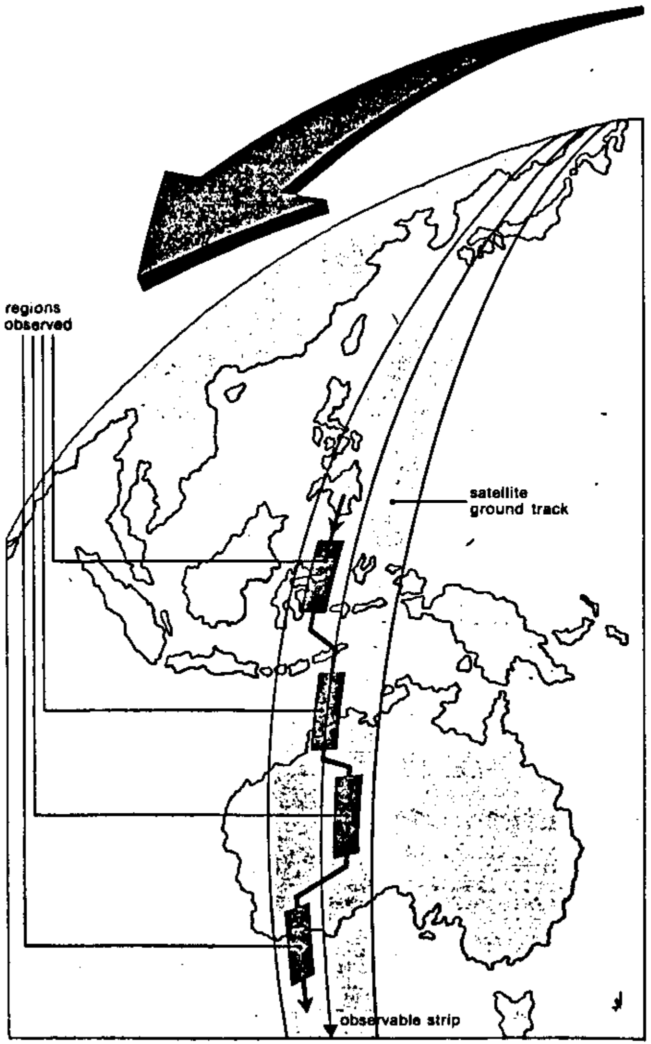
off-nadir viewing



By appropriately selecting the orientation of the pointing mirror, which is controlled from the ground it is possible to observe any region of interest within a 950-km-wide strip centered on the satellite ground track, i.e. the observed region needs not necessarily be centered on the ground track.

The width of the swath actually observed varies between 60 km for nadir viewing and 80 km for extreme off-nadir viewing.

The program of observations to be made is controlled by the satellite's onboard computer. A sequence of recorded images may include both modes of instrument operation (multispectral or panchromatic mode) and changes in each instrument's viewing directions.



the HRV instrument

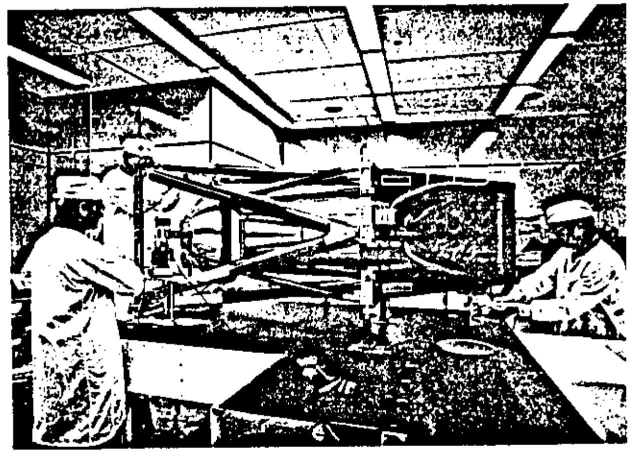
The HRV instrument is designed to operate in either of two modes, in the visible and infrared portions of the spectrum :

- a panchromatic (black and white) mode corresponding to observation over a broad spectral band, and;
- a multispectral (color) mode corresponding to observation in three narrower spectral bands.

The instrument's sampling mesh corresponds to a ground element (pixel) that is 10 m × 10 m in the first case and 20 m × 20 m in the second, for nadir viewing. This basic design decision was dictated by the small-scale subdivision of much of the agricultural land in many parts of the world and was also required for cartographic applications.

Light from the scene being viewed enters the HRV instrument via a plane mirror that is steerable by ground control. The viewing axis can thus be oriented as required in the plane perpendicular to the orbit. This off-nadir viewing capability covers a range of ± 27° relative to the vertical (in 45 steps of 0.6° each). This allows the instrument to image any point within a strip extending 475 km to either side of the satellite ground track. Because of the earth's curvature, the maximum viewing angle at the ground is 33° from the vertical.

This off-nadir viewing capability, along with the high resolution, are two of the most innovative features of the satellite. The possibilities offered by these design features are described on pages 9 to 11.



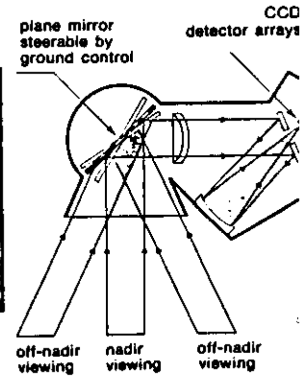
Engineering model of the HRV instrument

Characteristics of the HRV instrument	Multispectral mode	Panchromat mode
Spectral bands	0,50-0,59 µm	0,51-0,73 µ
....	0,61-0,68 µm	
....	0,79-0,89 µm	
Instrument field of view	4,13°	4,13°
Ground sampling interval (nadir viewing)	20 m × 20 m	10 m × 10
Number of pixels per line	3000	6000
Ground swath width (nadir viewing) ...	60 km	60 km
Pixel coding format	3 × 8 bits	6 bits DPCM
Image data bit rate	25 M bits/s	25 M bits/

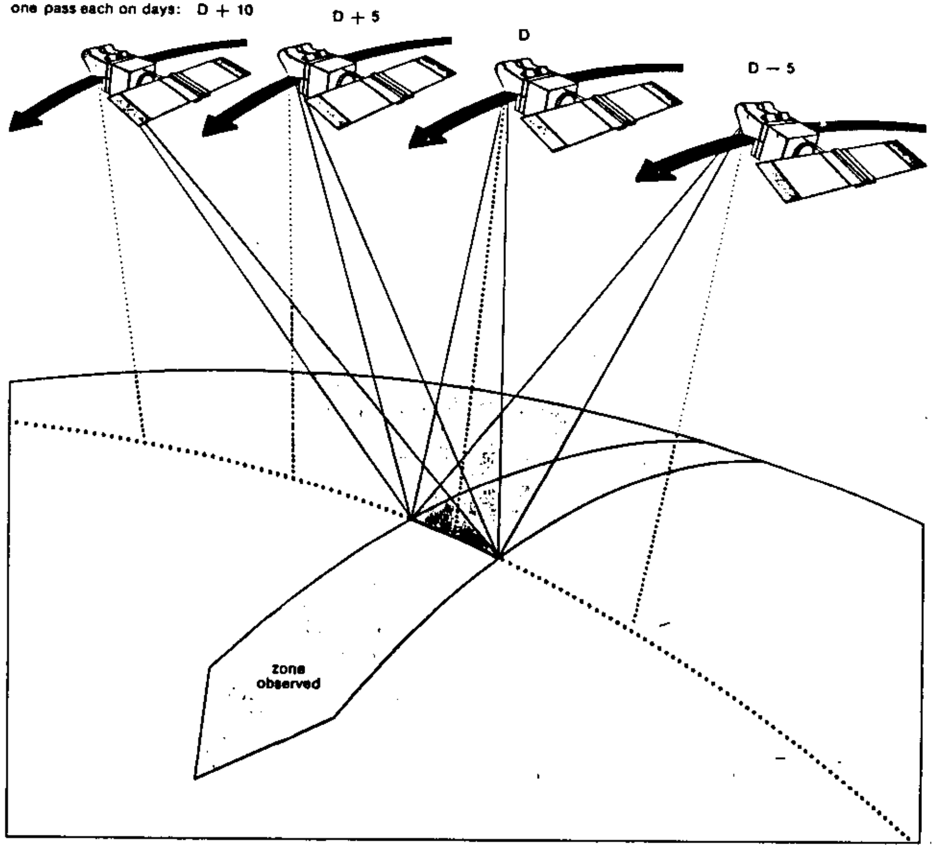
(1) DPCM (digital pulse code modulation) is a mode of data compression that does degrade the radiometric accuracy of the image data (256 grey levels).

Basic detector array (Charge Coupled Device, 1728 elements)

(2) The detectors are of the CCD (charge-coupled device) type. Each array consists of 6000 detectors arranged linearly. This forms what is known as a " push-broom " scanner since it images a complete line of the ground scene in the cross-track direction in one " look " without any mechanical scanning.



revisit capabilities



Were the satellite instruments only capable of nadir viewing, the revisit frequency for any given region would be 26 days.

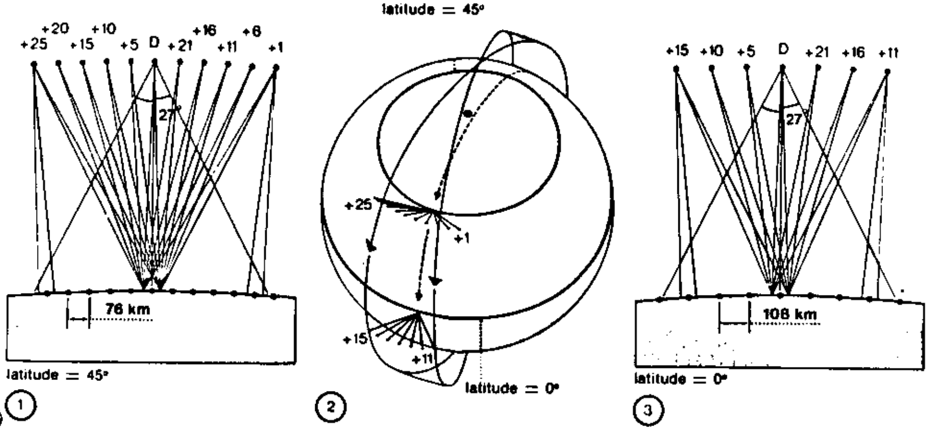
This interval is unacceptable for the observation of phenomena evolving on timescales ranging from several days to a few weeks, especially where the cloud cover hinders the acquisition of usable data.

However, with SPOT, the capability for off-nadir viewing during satellite passes in the vicinity of a region of interest considerably increases the revisit possibilities.

What, precisely, are the revisit frequencies that can be achieved ?

During the 26-day period separating two successive satellite passes over a given point on the Earth's surface, and taking into account the steering capability of the instruments, the point in question could be observed on 7 different passes if it were on the equator and on 11 if at a latitude of 45°. More specifically, if the day on which the satellite first passes vertically over the point of interest is represented by D, then the other days on which this same point can be observed are as shown at the top of the following page (1, 2, 3).

It can be seen from the above that a given region can be revisited on dates separated alternately by one and four (or occasionally five) days. The possibility of obtaining image pairs on successive days is of interest because of the relative short-term stability (48 hours) of weather patterns.

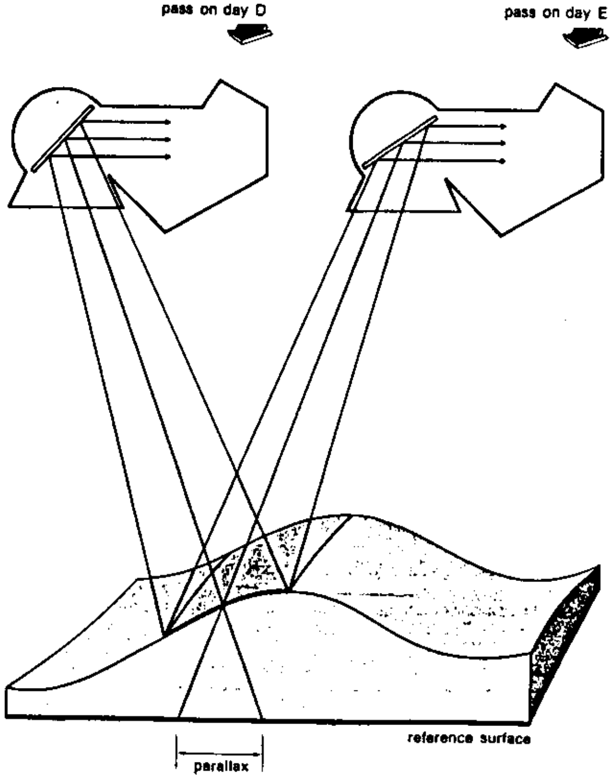


stereoscopic viewing capabilities

Another important possibility offered by the HRV instruments' off-nadir viewing capability is that of recording stereoscopic pairs of images of a given scene (i.e. images recorded at different viewing angles during successive satellite passes in the vicinity of the scene concerned).

At the top of the page we saw that two observations can be made on successive days such that the two images correspond to pointing angles on either side of the vertical. In such cases, the ratio between the observation base (or distance between the two satellite positions) and the height (or satellite altitude) is approximately 0.75 at the equator and 0.50 at a latitude of 45°.

The main applications for stereoscopic imagery are in photogrammetry and photo-interpretation (morphogeology, hydrographic studies, etc.).



SPOT 1 IN ORBIT PERFORMANCES (2)

IMAGE QUALITY

→ *GEOMETRY*

	SPECIFICATION	MEASURED OR EVALUATED
LOCALISATION	*1500m RMS*	*260 - 910m / 570m RMS*
DISTANCES ALTERATION	*10^{-2}*	*10^{-3}*
MULTISPECTRAL REGIST.	*.3*	*.15*
ALTITUDE RESTITUTION	*10m*	*3.5m(B/H : 1,1)*

→ *RADIOMETRY*

SIGNAL TO NOISE RATIO .... OK SOME STRUCTURED NOISE

DETECTOR EGALISATION .... GENERALLY OK SOME PROBLEMS OVER SPECIFIC AREAS

ABSOLUTE CALIBRATION ....OK

MTF ....OK EXCEPT ONE CCD OF HRV 2

EVOLUTION OF HRVIR PRODUCTS

SPOT 1 - 2 - 3		SPOT 4 - 5
LEVEL 0	PIXELS GEOGRAPHICALLY ARRANGED - EXCHANGE LEVEL	
LEVEL 1 A	RADIOMETRIC CORRECTION	LOCALIZATION ACCURACY 1500 m RMS
• 1 B	GEOMETRIC CORRECTION	LOCALIZATION ACCURACY 1500 m RMS
	Scenes are centered on node of a reference grid	Scenes can be mosaïqued along the track and centered on any point along the track
LEVEL 2	MAPPING TO DIFFERENT PROJECTIONS	
	LOC. ACC 50 m RMS	2 A LOC. ACC 1500 m RMS 2 B LOC. ACC 10/20 m RMS
LEVEL S — REGISTRATION WITH LEVEL 1 OR 2 SCENES — REGISTRATION ACC. 0.5 PIXEL FOR SAME VIEWING ANGLE		LEVEL 3 MAPPING TO DIFFERENT PROJECTIONS WITH ALTITUDE / VIEWING ANGLE CORRECTION 3 A LOC. ACC 1500 RMS 3 B LOC. ACC 10/20 m RMS PRODUCTS CAN BE RESAMPLED/MOSAÏQUED
		D.T.M. - Digital Terrain Model altitude accuracy 10 m RMS

HRVIR PAYLOAD

		MULTISPECTRAL			MONOSPECTRAL	
PIXEL (m)		20			10	
SPECTRAL BAND (µm)		B1 0.50 - 0.59 B2 0.61 - 0.68 B3 0.79 - 0.89 MIR 1.55 - 1.75			0.61 - 0.68	
GROUND REFLECTANCE	Ne Δρ ρ MIN ρ MAX	B1 0.005 0.02 0.5	B2 0.005 0.01 0.5	B3 0.005 0 0.7	MIR 0.005 0 0.6	B2 (10m) 0.007 0.001 0.5
CODING (SPOT 4 FORMAT)		6 BITS D.P.C.M. (8 - 5 - 5 - 8)			6 BITS D.P.C.M. (8 - 5 - 5 - 8)	
CODING (SPOT 1 FORMAT)		8 BITS LINEAIRES B1, B2, B3			6 BITS D.P.C.M. B2 10 m (8 - 5 - 5 -8)	
BIT RATE		25 Mb/s			25 Mb/s	
ABSOLUTE CALIBRATION BAND TO BAND CAL. MULTI-TEMPORAL CAL.		10 % 3 % 10 %				
SWATH WIDTH (km) LATERAL POINTING		60 (NADIR) ± 27°(460 km , ± 45 steps 0.6°)				
ON BOARD REGISTRATION		6 m				

	SPOT 1 / 2/ 3	SPOT 4 / 5
HRV PAYLOAD	*3 SPECTRAL BANDS, 20m, REGISTERED* *1 PANCHRO BAND 10m* *22mn RECORD TIME PER RECORDER*	*ADDITION OF A MIR 20m BAND, (1.5-1.7µm)* *ALL SPECTRAL BANDS 10m AND 20m REGISTERED* *40mn RECORD TIME* *SAME IMAGE TELEMETRY BIT RATE* *SPOT 1 AND SPOT 4 DIRECT TRANSMISSION MODES AVAILABLE*
VEGETATION PAYLOAD		*SAME SPECTRAL BANDS AS HRV PLUS ONE BAND (.43-.52µm)* *1,2 km GROUND RESOLUTION* *2200 km FIELD OF VIEW* *SEPARATE TELEMETRY AND PROGRAMMING*
PASTEL EXPERIMENTAL PAYLOAD		*EXPERIMENTAL IMAGES TRANSMISSION VIA OPTICAL LINK AND DATA RELAY SPACECRAFT*

DORIS : PRECISE ORBIT DETERMINATION EXPERIMENT (10cm) WILL BE IMPLEMENTED ON SPOT AFTER SPOT 1

Table 4 : Selected sensors characteristics of past missions available to Europeans (prior to 1987).

SATELLITE MISSION	SENSOR	SCANNING METHOD (number of detectors per band)	SUMMARY WAVEBAND CHARACTERISTICS			WAVEBANDS (µm)	IFOV pixel size at nadir in m	SWATH WIDTH in km	RADIOMETRIC RESOLUTION quantization levels
			TYPE (1)	NUMBER	AVERAGE BANDWIDTH OR FREQUENCY				
HCMM	HCMR	scanning mirror	VIS RIR	1	0.55 µm	0.55-1.1	500	716	
			TIR	1	2.0 µm	10.5-12.5	600 at edges of swath image		
NIMBUS-7	CZCS	scanning mirror	VIS	4	0.02 µm	0.43-0.45 0.51-0.53 0.54-0.56 0.66-0.68	825	1566	8-bit
			RIR	1	0.1 µm	0.70-0.80			
			TIR	1	2.0 µm	10.5-12.5			

Table 3 : Selected sensors' characteristics from operational and planned missions (1987-1991)

SATELLITE MISSION	SENSOR	SCANNING METHOD (number of detectors per band)	SUMMARY WAVEBAND CHARACTERISTICS: TYPE (1)	NUMBER	AVERAGE BANDWIDTH OR FREQUENCY	WAVEBANDS	IFOV pixel size at nadir in m	SWATH WIDTH in km	RADIOMETRIC RESOLUTION quantization levels
Landsat-5	MSS	mechanical (6) rotating mirror	VIS	3	0.10 µm	0.5-0.6 0.6-0.7 0.7-0.8	82	185	6-bit
			RIR	1	0.3 µm	0.8-1.1			
	TM		VIS	3	0.07 µm	0.45-0.52 0.52-0.60 0.63-0.69	30	185	8-bit
			RIR	3	0.20 µm	0.76-0.90 1.55-1.75 2.08-2.35	30		
			TIR	1	2.10 µm	10.40-12.50	120		
SPOT-1, -2	HRV/MS	CCD pushbroom (3000)	VIS	2	0.09 µm	0.50-0.59 0.61-0.68	20	60 each tot: 116	8-bit
			RIR	1	0.1 µm	0.79-0.89			
	HRV/P		VIS	1	0.10 µm	0.51-0.73	10		6-bit
MOS-1	MESSR	CCD pushbroom (2048)	VIS	2	0.08 µm	0.51-0.59 0.61-0.69	50	100 each Tot: 185	6-bit
			RIR	2	0.19 µm	0.72-0.80 0.8-1.1			
	VTIR	mechanical rotating mirror	VIS	1	0.20 µm	0.5-0.7	900	1,500	8-bit
			WVIR TIR	1 2	1.0 µm 1.0 µm	6.0-7.0 10.5-11.5 11.5-12.5	2,700		
	MSR	mechanical conical scan	PMW	2	- -	23.8 GHz 31.4 GHz	32,000 23,000	320	10-bit
NOAA-9, -10	AVHRR	mechanical	VIS	1	0.10 µm	0.58-0.68	1,100	3,000	10-bit
			RIR	2	0.38 µm	0.725-1.1 3.55-3.93			
			TIR	2	1.0 µm	10.3-11.3 11.5-12.5			
Meteosat	Meteosat radiom.	electro-optical	VIS+ RIR	1	0.4 µm	0.5-0.9	2,500* 4,000		
			FIR	1	1.4 µm	5.7-7.1	5,000* 8,000		
			TIR	1	2.0 µm	10.5-12.5			
ERS-1	ATSR	mechanical conical scanning	VIS RIR/TIR TIR	1 1 2	- - -	1.6 3.7 11 12	1,000	500	
	MV		PMW	2	- -	23.8 GHz 36.4 GHz	22,000		

* 2,500 and 5,000 km at 0°lat.; 4,000 and 8,000 km at mid-lat.

(1) VIS: Visible (0.4-0.7 µm); RIR: Reflected Infrared (near- and middle- 0.7-3 µm); TIT: Thermal (far 3-5 and 8-14 µm); WVIR Water Vapor Infrared (5-7 µm); PMW: Passive Microwave (1cm-3m or 30 GHz-0.1 GHz).

Table 3.: Selected sensors' characteristics from operational and planned missions (1987-1991)

SATELLITE MISSION	SENSOR	SCANNING METHOD (number of detectors per band	SUMMARY WAVEBAND CHARACTERISTICS: TYPE (1)	NUMBER	AVERAGE BANDWIDTH OR FREQUENCY	WAVEBANDS	IFOV pixel size at nadir in m	SWATH WIDTH in km	RADIOMETRIC RESOLUTION quantization levels
Landsat-5	MSS	mechanical (6) rotating mirror	VIS	3	0.10 µm	0.5-0.6 0.6-0.7 0.7-0.8	82	185	6-bit
			RIR	1	0.3 µm	0.8-1.1			
	TM		VIS	3	0.07 µm	0.45-0.52 0.52-0.60 0.63-0.69	30	185	8-bit
			RIR	3	0.20 µm	0.76-0.90 1.55-1.75 2.08-2.35	30		
			TIR	1	2.10 µm	10.40-12.50	120		
SPOT-1, -2	HRV/MS	CCD pushbroom (3000)	VIS	2	0.09 µm	0.50-0.59 0.61-0.68	20	60 each tot: 116	8-bit
			RIR	1	0.1 µm	0.79-0.89			
	HRV/P		VIS	1	0.10 µm	0.51-0.73	10		6-bit
MOS-1	MESSR	CCD pushbroom (2048)	VIS	2	0.08 µm	0.51-0.59 0.61-0.69	50	100 each Tot: 185	6-bit
			RIR	2	0.19 µm	0.72-0.80 0.8-1.1			
	VTIR	mechanical rotating mirror	VIS	1	0.20 µm	0.5-0.7	900	1,500	8-bit
			WVIR TIR	1 2	1.0 µm 1.0 µm	6.0-7.0 10.5-11.5 11.5-12.5	2,700		
	MSR	mechanical conical scan	PMW	2	- -	23.8 GHz 31.4 GHz	32,000 23,000	320	10-bit
NOAA-9, -10	AVHRR	mechanical	VIS	1	0.10 µm	0.58-0.68	1,100	3,000	10-bit
			RIR	2	0.38 µm	0.725-1.1 3.55-3.93			
			TIR	2	1.0 µm	10.3-11.3 11.5-12.5			
Meteosat	Meteosat radiom.	electro-optical	VIS+ RIR	1	0.4 µm	0.5-0.9	2,500[*] 4,000		
			FIR	1	1.4 µm	5.7-7.1	5,000[*] 8,000		
			TIR	1	2.0 µm	10.5-12.5			
ERS-1	ATSR	mechanical conical scanning	VIS RIR/TIR TIR	1 1 2	- - -	1.6 3.7 11 12	1,000	500	
	MV		PMW	2	- -	23.8 GHz 36.4 GHz	22,000		

[*] 2,500 and 5,000 km at 0°lat.; 4,000 and 8,000 km at mid-lat.

(1) VIS: Visible (0.4-0.7 µm); RIR: Reflected Infrared (near- and middle- 0.7-3 µm); TIT: Thermal (far 3-5 and 8-14 µm); WVIR Water Vapor Infrared (5-7 µm); PMW: Passive Microwave (1cm-3m or 30 GHz-0.1 GHz).