Chapter 2 Sensors

2.1 Types of Sensor

Figure 2.1.1 summarizes the types of **sensors** now used or being developed in remote sensing. It is expected that some new types of sensors will be developed in the future. **Passive sensors** detect the reflected or emitted electro-magnetic radiation from natural sources, while **active sensors** detect reflected responses from objects which are irradiated from artificially generated energy sources, such as radar.. Each is divided further in to **non-scanning** and **scanning systems**.

A sensor classified as a combination of passive, non-scanning and **non-imaging method** is a type of profile recorder, for example a microwave radiometer. A sensor classified as passive, non-scanning and **imaging method,** is a camera, such as an aerial survey camera or a space camera, for example on board the Russian COSMOS satellite.

Sensors classified as a combination of passive, scanning and imaging are classified further into **image plane scanning sensors,** such as TV cameras and solid state scanners, and **object plane scanning sensors,** such as multispectral scanners (optical-mechanical scanner) and scanning microwave radiometers.

An example of an active, non-scanning and non-imaging sensor is a profile recorder such as a laser spectrometer and laser altimeter. An active, scanning and imaging sensor is a radar, for example synthetic aperture radar (SAR), which can produce high resolution, imagery, day or night, even under cloud cover.

The most popular sensors used in remote sensing are the camera, solid state scanner, such as the CCD (charge coupled device) images, the multi-spectral scanner and in the future the passive synthetic aperture radar.

Laser sensors have recently begun to be used more frequently for monitoring air pollution by laser spectrometers and for measurement of distance by laser altimeters.

Figure 2.1.1 shows the most common sensors and their spectral bands.

Those sensors which use lenses in the visible and reflective infrared region, are called optical sensors.

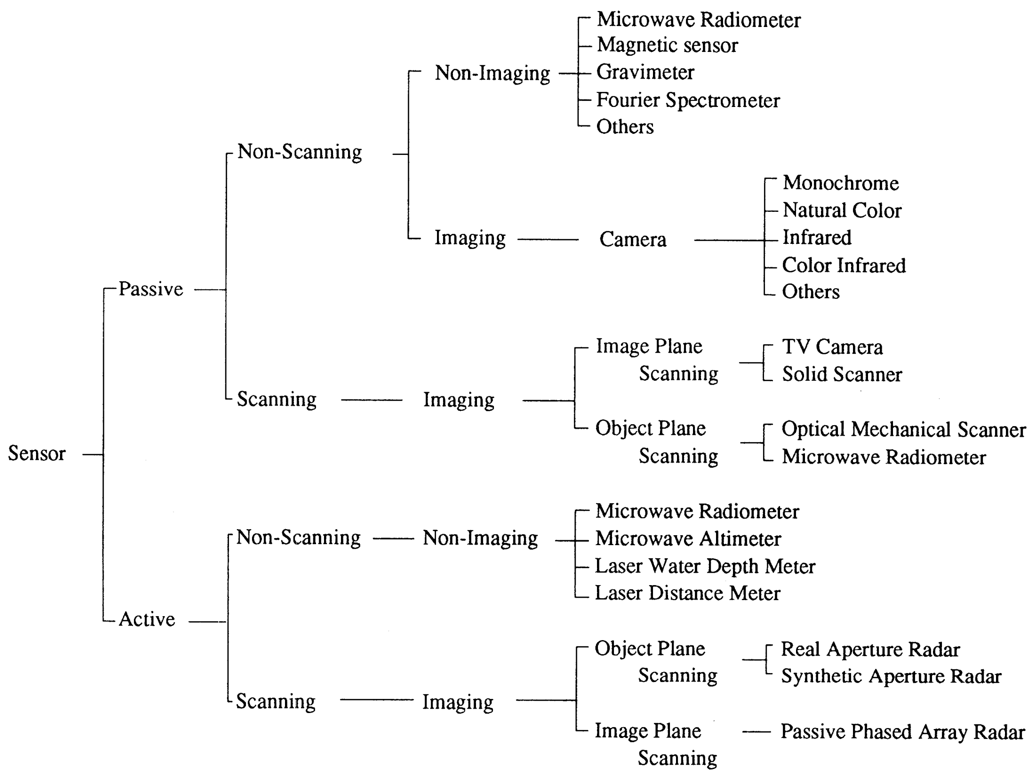


Figure 2.1.1 Classification of Sensor

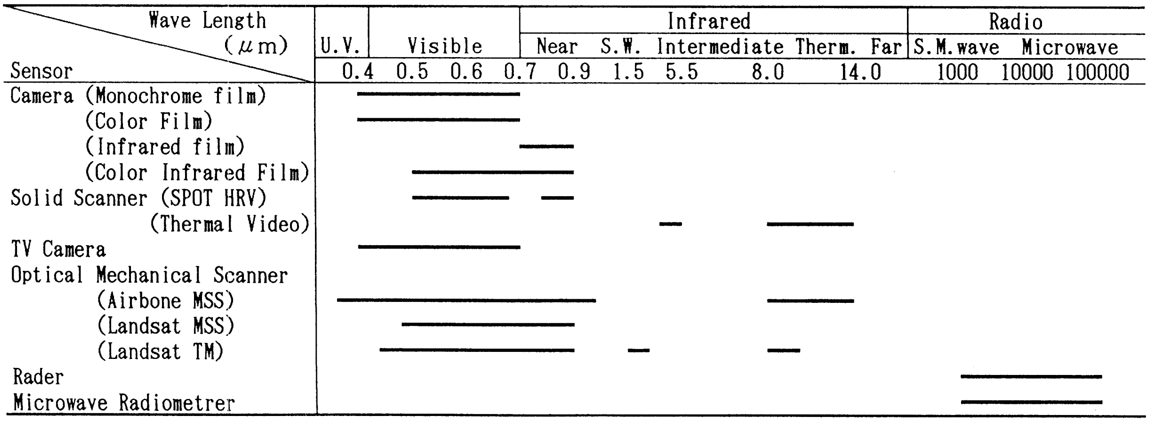


Figure 2.1.2 Wave Length Band of Principal Sensor

2.2 Characteristics of Optical Sensors

Optical sensors are characterized specified by spectral, radiometric and geometric performance. Figure 2.2.1 summarizes the related elements for the three characteristics of optical sensor. Table 2.2.1 presents the definitions of these elements.

The **spectral characteristics** are spectral band and band width, the central wavelength, response sensitivity at the edges of band, spectral sensitivity at outer wavelengths and sensitivity of polarization.

Sensors using film are characterized by the sensitivity of film and the transmittance of the filter, and nature of the lens. Scanner type sensors are specified by the spectral characteristics of the detector and the spectral splitter. In addition, chromatic aberration is an influential factor. The **radiometric characteristics** of optical sensors are specified by the change of electro-magnetic radiation which passes through an optical system. They are radiometry of the sensor, sensitivity in **noise equivalent power**, **dynamic range**, signal to noise ratio (**S/N ratio**) and other noises, including quantification noise.

The geometric characteristics are specified by those geometric factors such as field of view (**FOV**), instantaneous field of news (**IFOV**), band to band registration, MTF (see 2.3), geometric distortion and alignment of optical elements.

IFOV is defined as the angle contained by the minimum area that can be detected by a scanner type sensor. For example in the case of an IFOV of 2.5 milli radians, the detected area on the ground will be 2.5 meters x 2.5 meters,if the altitude of sensor is 1,000 m above ground.

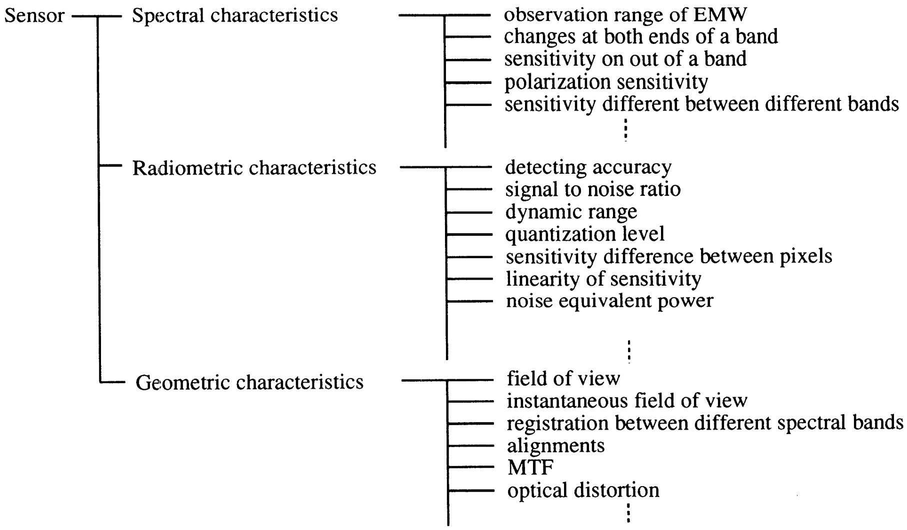


Figure 2.2.1 Elements of optical sensor's characteristics

Table 2.2.1 Definition of optical sensor's characteristics

items	definition
band range of EMW	observation width of EMW(Electro magnetic waves) on a band
center wavelength	center wave length on a band
band responsibility at both ends of a band	characteristics curve at both ends of a band
band sensitivity	sensitivity on a band
out of band sensitivity	sensitivity on spectral ranges of outside of the band
sensitivity difference between different bands	ratio of sensitivity between different bands
S/N ratio	signal to noise ratio
dynamic range	range of sensor's sensitivity in terms of the difference maximum and minimum radiance ratio
sensitivity difference between pixels	ratio of maximum output level to minimum output levels
linearity of sensor's input-output characteristics	input level to output level in higher input power level
noise equivalent power	input signal power giving output equivalent with noise power
field of view	covered area by a remote sensor, picture (angular field of camera, scanning width by scanner
instantaneous field of view (IFOV)	field of angle detected by one detector
registration between different spectral bands	geometric distortion between one standard band and other bands
MTF	modulation transfer function of a sensor, determining it's IFOV
optical distortion	image distortion due to optical components of a sensor. e.g. lens aberration
angle of stereoscopic observation	difference of viewing angle of stereoscopic sensors
imaging frequency	time of scanning one line

2.3 Resolving Power

Resolving power is an index used to represent the limit of spatial observation. In optics, the minimum detectable distance between two image points is called resolving limit, and the reverse is defined as the resolving power.

There are several methods to measure the resolving limit or resolving power. Two such methods, (1) resolving power by refraction and (2) MTF, are introduced below.

(1) Resolving limit by refraction

Theoretically an object point will be projected as a point on an image plane if the optical system has no aberration. However, because of diffraction the image of a point will be a circle with a radius of about one wavelength of light, which in called **the Airy pattern,** as shown in Figure 2.3.1. Therefore there exists a limit to resolve the distance between two points even though there is no aberration.

The resolving limit depends on how the minimum distance between two Airy images is defined. There are two definitions, as follows.

a. **Rayleigh's resolving power**: the distance between the left Airy peak and the right Airy peak when it coincides with the zero point of the left peak, that is 1.22u in Figure 2.3.2.
b. **Sparrow's resolving limit**: the distance between the two peaks when the central gap fades away, that is 1.08u in Figure 2.3.3.

(2) **MTF** (modular transfer function)

The resolving power measured on a resolving test chart by human eyes, depends on individual ability and the shape or contrast of the chart. On the other hand, MTF has no such problems because MTF comes from a scientific definition in which the response of spatial frequency, with respect to the amplitude, considers the optical imaging system as a spatial frequency filter.

As the spatial frequency is defined as the frequency of a sine wave, MTF shows how much the ratio of the amplitude decreases before and after an optical imaging system with respect to the spatial frequency as shown in Figure 2.3.4.

MTF coincides with the power spectrum which is obtained by Fourier transformation of a point image. Generally speaking, an optical imaging system will give a low pass filter as shown in Figure 2.3.5.

Modulation (M), contrast (K) and density (D) have the following relations.

$$\kappa=\frac{\tau\mathrm{max}}{\tau\mathrm{min}}\ ,\ D=\log\left(\frac{\tau\mathrm{max}}{\tau\mathrm{min}}\right)\ ,\ M=\frac{(\tau\mathrm{max}-\tau\mathrm{min})}{(\tau\mathrm{max}+\tau\mathrm{min})}=\frac{\kappa-1}{\kappa+1}$$

$$\kappa'=\frac{\tau'\mathrm{max}}{\tau'\mathrm{min}}\ ,\ D'=\log\left(\frac{\tau'\mathrm{max}}{\tau\mathrm{min}}\right)\ ,\ M=\frac{(\tau'\mathrm{max}-\tau'\mathrm{min})}{(\tau'\mathrm{max}+\tau\mathrm{min})}=\frac{\kappa'-1}{\kappa'+1}$$

The resolving power (or spatial frequency) is obtained from the MTF curve with a given contrast, which can be converted to the modulation.

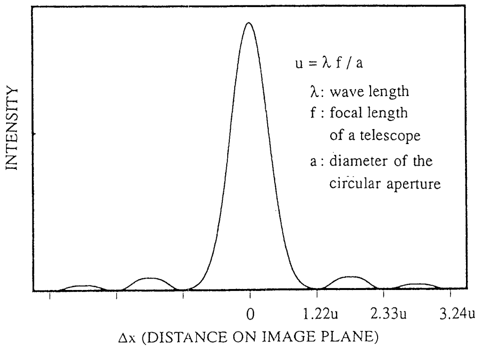


Figure 2.3.1 Airy pattern (point image by an aplanatic; no aberration, optical system having a circular aperture)

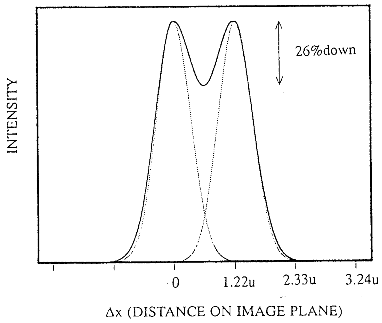


Figure 2.3.2 Rayleigh's resolving limit

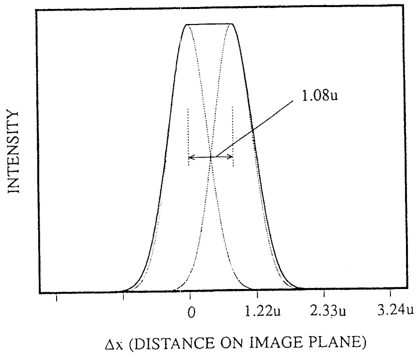


Figure 2.3.3 Sparraw's resolving limit

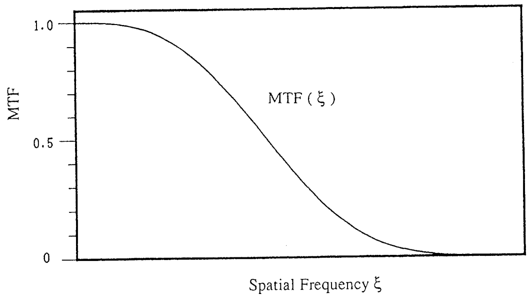


Figure 2.3.5 Typical MTF of a optical imaging system

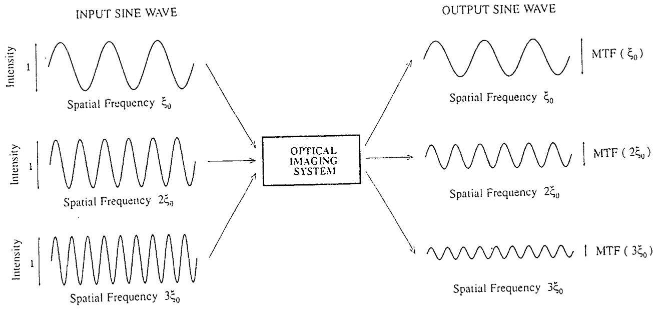


Figure 2.3.4 Optical imaging system as a spatial frequency filter

2.4 Dispersing Element

An array of light arranged by order of wavelength is called a **spectrum**. **Spectroscopy** is defined as the study of the dispersion of light into its spectrum. There are two types of dispersing elements, the prism and the diffraction grating.

Figure 2.4.1 shows the types of dispersing elements. The optical mechanism of prisms and diffraction gratings are shown in Figure 2.4.2 and Figure 2.4.3 respectively.

(1) Prism

A prism designed for spectroscopy is called a dispersing prism, which is based on the theory that refractive index is different depending on the wavelength, as shown in Figure 2.4.4. The spectral resolution of a prism is much lower than that of a diffraction grating. If higher spectral resolution is required, a layer prism should be produced. This can be a problem, because it is rather difficult to prepare homogeneous material and to keep the weight low.

(2) Diffraction grating

A diffraction grating is a diffraction element which utilizes the theory that incident light to a grating is dispersed in multiple different directions depending on the difference of light path length or phase difference between two neighboring gratings. Multiple spectra are generated in integer order direction in which multiplication by the wavelength corresponds to the light path difference as shown in Figure 2.4.5. Most diffraction gratings are reflection type rather than transparency type. Though the specular diffraction gives the maximum intensity as 0 order diffraction, it cannot be utilized because 0 order diffraction does not produce a spectrum. Therefore a reflecting plane is adjusted to have a proper angle to obtain a strong enough spectrum at a certain order. Such an adjusted grating is called a blazed grating.

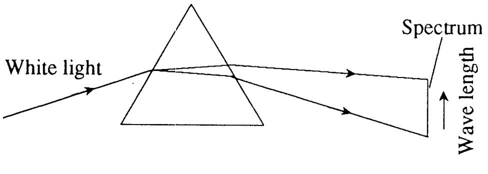


Figure 2.4.2 Dispersion by a prism

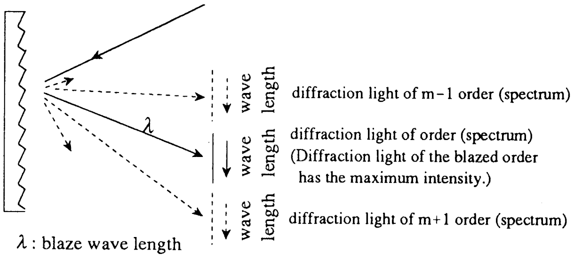


Figure 2.4.3 Dispersion by a diffraction grating;case of echelette (blazed) grating

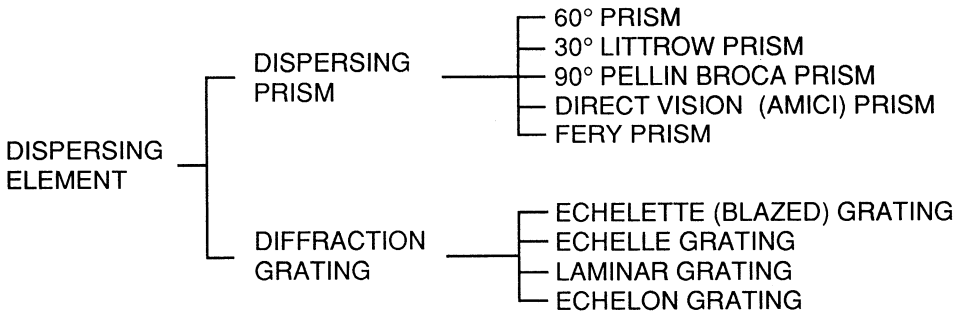
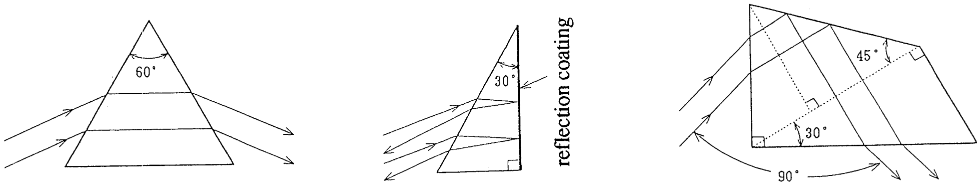
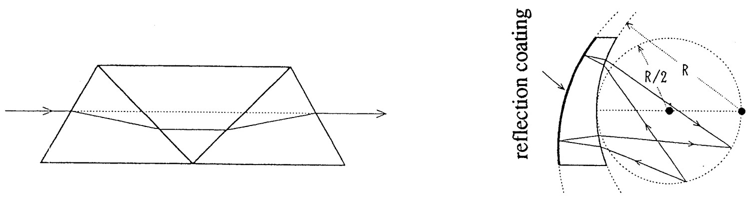


Figure 2.4.1 Dispersing elements

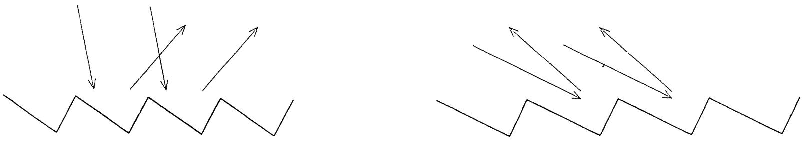


(a) 60° prism (b) 30° littrow prism (c) 90° Pellin Broca prism



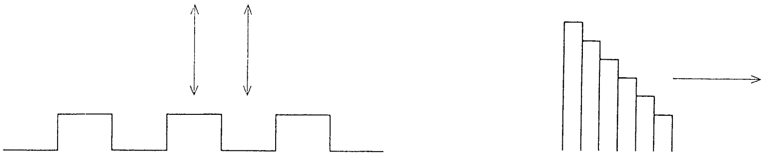
(d) direct vision (Amici) prism (e) Fery prism

Figure 2.4.4 Dispersing prizm



(a) echelette grating
(Easy slopes are used)

(b) echelle grating
(Steep slopes are used)



(c) laminar grating

(d) echelon grating
(It is used as a reflaction type
or a transmission type)

Figure 2.4.5 Diffraction grating

2.5 Spectroscopic Filter

A **filter** can transmit or reflect a specified range of wavelength. A filter designed for spectroscopy is called a spectroscopic filter.

Filters are classified into three types - **long wave pass filters, short wave pass filters** and **band pass filters** from the viewpoint of function, as shown in Figure 2.5.1. A cold mirror which transmits thermal infrared and reflects visible light is a long wave pass filter, while a hot mirror which reflects thermal infrared and transmits visible light is a short wave filter.

Figure 2.5.2 shows the types of filter from the viewpoint of function.

(1) **Absorption filter** :
a filter which absorbs a specific range of wavelengths, for examples, **colored filter glass** and **gelatin filter**.

(2) **Interference filter** :
a filter which transmits a specific range of wavelengths by utilizing the interference effect of a thin film. When light is incident on a thin film, only a specific range of wavelengths will pass due to the interference by multiple reflection in a thin film as shown in Figure 2.5.3 and 2.5.4. The higher the reflectance of the thin film, the narrower the width of the spectral band becomes. If two of these films, with different refractive indexes, are combined, the reflectance becomes very high which results in a narrow spectral band, for example of the order of several nanometers. In order to obtain a band pass filter which transmits a single spectral band, a short wave pass filter and long wave pass filter should be combined. A dichroic mirror ,which is used for three primary color separation, is a kind of multiple layer interference filter, as shown in Figure 2.5.2 and 2.5.3. It utilizes both functions of transparency and reflection.

(3) **Diffraction grating filter** :
a reflective long wave pass filter utilizing the diffraction effect of a grating, which reflects all light of wavelengths longer than the wavelength determined by the grating interval and the oblique angle of the incident radiation.

(4) **Polarizing interference filter** :
a filter with birefringent crystallinity plate between two polarizing plates, which pass a very narrow spectral band, for example less than 0.1 mm. This utilizes the interference by two rays of light ; a light following Snell's law and the other not following Snell's law, which pass a light with a narrow band of wavelength determined by the thickness of the birefringent crystallinity plate .

SPECTROSCOPIC FILTER
- LONG WAVE PASS FILTER
- SHORT WAVE FILTER
- BAND PASS FILTER

Figure 2.5.1 Spectroscopic filters from a view point of function

SPECTROSCOPIC FILTER
- ABSORPTION FILTER
- INTERFERENCE FILTER
- DIFFRACTION GRATING FILTER
- POLARIZATION INTERFERENCE FILTER

Figure 2.5.2 Spectroscopic filters from a view point of method

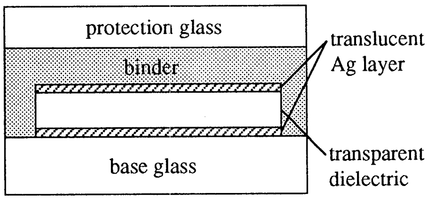


Figure 2.5.3 Structure of 3 layer Ag interference filter

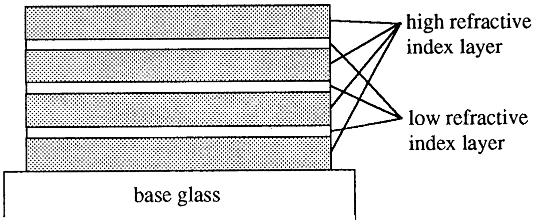


Figure 2.5.5 Structure of a dichroic mirror (filter)

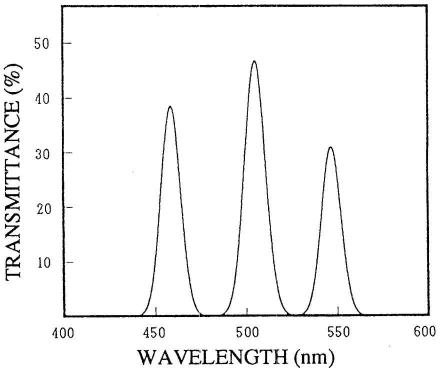


Figure 2.5.4 Spectral transmittance of three layer Ag interference filter

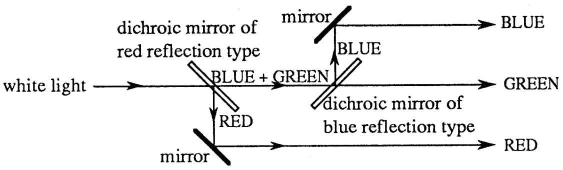


Figure 2.5.6 A example of three color splitting using dichroic mirrors

2.6 Spectrometer

There are many kinds of spectral measurement devices ,for example, **spectroscopes** for human eye observation of the spectrum, **spectrometer** to record spectral reflectance, **monochro meter** to read a single narrow band, **spectro photometer** for photometry, **spectro radiometer** for measurement of spectral radiation etc. However, in this section only optical spectrometers are of interest.

Figure 2.6.1 shows a classification of spectrometers, which are divided mainly into **dispersing spectrometers** and **interference spectrometers**. The former utilizes prisms or diffraction gratings, while the latter the interference of light.

(1) Dispersing spectrometer

A spectrum is obtained at the focal plane after a light ray passes through a slit and dispersing element as shown in Figure 2.6.2. Figure 2.6.3 and Figure 2.6.4 are typical dispersing spectrometers ; Littnow spectrometer and Czerny - Turner spectrometer respectively.

(2) Twin beam interference spectrometer

A distribution of the spectrum is obtained by cosine Fourier transformation of the interferogram which is produced by the inference between two split rays. Figure 2.6.5 shows Michelson interferometer which utilizes a beam splitter.

(3) Multi-beam interference spectrometer

The interference of light will occur if oblique light is incident on two parallel semi-transparent plane mirrors as shown in Figure 2.6.6. A different spectrum is obtained depending on incident angle, interval of the two mirrors and the refraction coefficient.

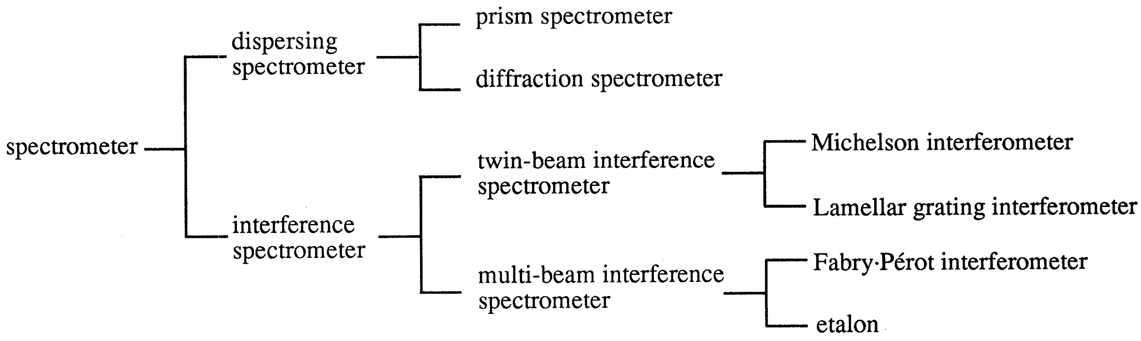


Figure 2.6.1 Spectrometers

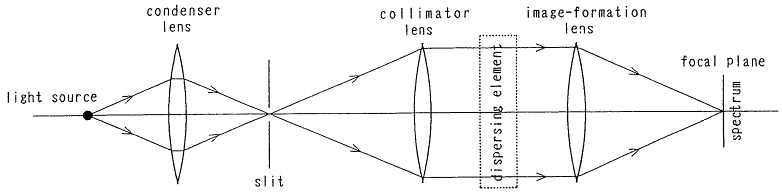


Figure 2.6.2 Conseputual structure of dispersing spectrometers

(Lenses are exchangeable by spherical mirrors and/or parabolic mirrors)

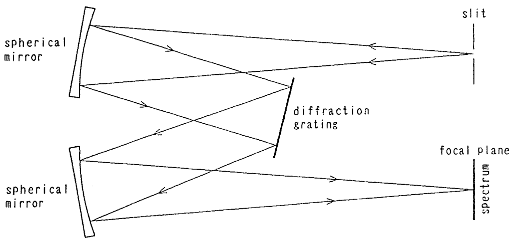


Figure 2.6.3 Czerny·Turnerspectrometer using a diffraction grating

(The diffraction grating is exchanged by a prism)

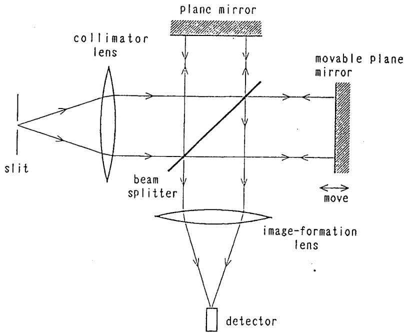


Figure 2.6.4 Michelson interferometer

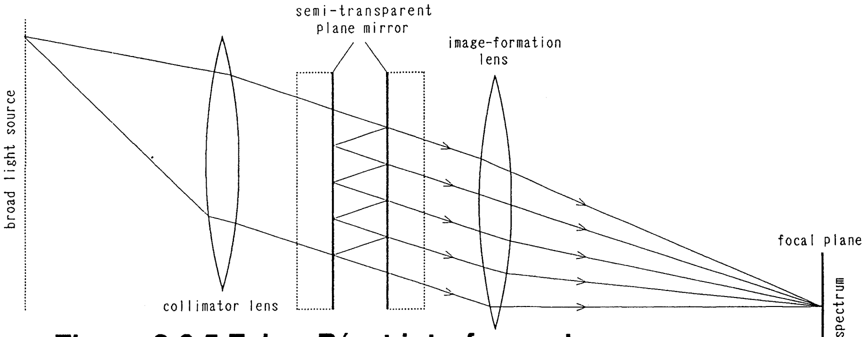


Figure 2.6.5 Fabry·Pérot interferometer

(That in which, space between mirrors is fixed, is called as a etalon)

2.7 Characteristics of Optical Detectors

An element which converts the electro-magnetic energy to an electric signal is called a detector. There are various types of detectors with respect to the detecting wavelength.

Figure 2.7.1 shows three types of detectors; photo emission type, optical excitation type and thermal effect type. **Photo tube** and **photo multiplier tubes** are the examples of the photo emission type which has sensitivity in the region from ultra violet to visible light. Figure 2.7.2 shows the response sensitivity of several photo tubes.

Photodiode, phototransistor, photo conductive detectors and linear array sensors (see 2.11), are examples of optical excitation types, which have sensitivity in the infrared region. Photo diode detectors utilize electric voltage from the excitation of electrons, while photo transistor and photo conductive detector utilize **electric current**. Table 2.7.1 shows the characteristics of these optical detectors with respect to type, temperature, range of wavelength, peak wavelength, sensitivity in term of D^* and response time.

Thermocouple barometers and **pyroelectric barometers** are examples of the thermal effect type, which has sensitivity from near infrared to far infrared regions. However the response is not very high because of the thermal effect. Figure 2.7.3 shows the detectivity of the pyroelectric barometer.

Detectivity denoted as D^* (termed D star) is usually related to the sensitivity, expressed as **NEP** (noise equivalent power). D^* is used for comparison between different detectors. NEP is defined as the signal input identical to the noise output. NEP depends on the type of detector, surface of detector or band of frequency. D^* is inversely proportional to NEP, and is given as follows.

D^* : $(Ad\ \Delta f)^{1/2} / NEP$
D^* : detectivity ($cm\ Hz^2 / W$)
NEP : noise equivalent power (W)
Ad : surface area of detector (cm^2)
Δf : band of frequency (Hz)

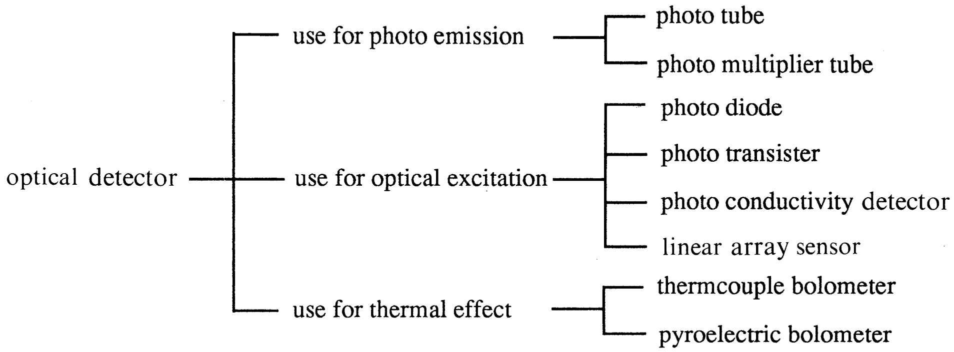


Figure 2.7.1 Classification of optical detector

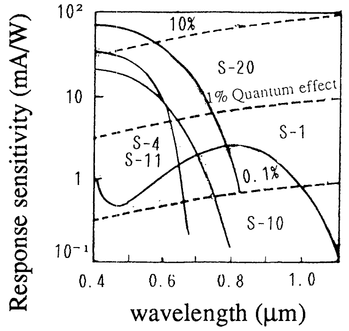


Figure 2.7.2 Response sensitivity of photo tube

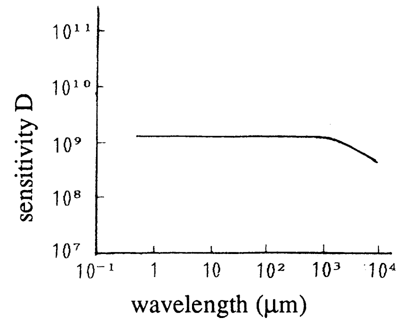


Figure 2.7.3 Sensitivity of pyroelectric detector

Table 2.7.1 Characteristics of optical detecter

detector	types *1	wave range (λm)	detectivity D *2	cut off freqency (Hz)	operating temperature (K)
Pt-S	PV	0.35 - 0.6	30	10^8	295.0
Si p-n PD	PV	0.4 - 1.0	50	10^7	295.0
Si p-i-n PD	PV	0.4 - 1.1	80	10^8	295.0
Si APD	PV	0.4 - 0.8	80	10^{10}	295.0
Ge p-n PD	PV	0.6 - 1.8	50	10^7	295.0
InSb p-n PD	PV	3.0 - 6.2	8	$5x10^2$	77.0
PbSnTe p-n PD	PV	5.0 - 11.4	>15-60V/W	10^7	77.0
PbS	PC	0.5 - 3.8	15.00	300	196.0
PbSe	PC	0.8 - 4.6	3.00	$3x10^3$	196.0
PbTe	PC	0.8 - 5.5	0.16	$3x10^3$	196.0
p - InSb	PC	2.0 - 6.7	2.00	$2x10^5$	77.0
n - InSb	PC	1.0 - 3.6	30.00	$2x10^6$	195.0
PbSnTe	PC	5.0 - 11.0	1.70	$8x10^5$	4.2
CdHgTe	PC	5.0 - 16.0	3.00	10^4	4.2
Ge:Au	PC	2.0 - 9.5	0.02	10^4	77.0
Ge:Zn,Au	PC	5.0 - 40.0	1.00	10^3	4.2
Ge:Cu	PC	5.0 - 30.0	3.00	10^3	4.2
Si:Al	PC	2.0 - 16.0	1.00	10^4	27.0
Si:Sb	PC	2.0 - 31.5	1.80	10^4	4.0
ATGS	TC	1 - 1000	0.030	10	295.0
(Ba,Sr)TiO3	TC	1 - 1000	0.011	400	295.0

*1 PV:photo transistor type PC:photo conductive detector type TC:pyroelectric detector type
*2 (10^{10}cm·$Hz^{1/2}$ ·W^1)

2.8 Cameras for Remote Sensing

Aerial survey cameras, multispectral cameras, panoramic cameras etc. are used for remote sensing.

Aerial survey cameras, sometimes called metric cameras are usually used on board aircraft or space craft for topographic mapping by taking stereo photographs with overlap. A typical aerial survey camera is RMK made by Carl Zeiss or RC series made by Leica company. Figure 2.8.1 shows the mechanics of the Zeiss RMK aerial survey camera.

Typical well known, examples of space cameras, are the **Metric Camera** on board the Space Shuttle by ESA, the **Large Format Camera** also on board the Space Shuttle by NASA, and the **KFA 1000** on board COSMOS by Russia. Figure 2.8.2 shows the LFC system and its film size. Figure 2.8.3 shows a comparison of photographic coverage on the ground between LFC (173 km x 173 km) and KFA (75 km x 75 km).

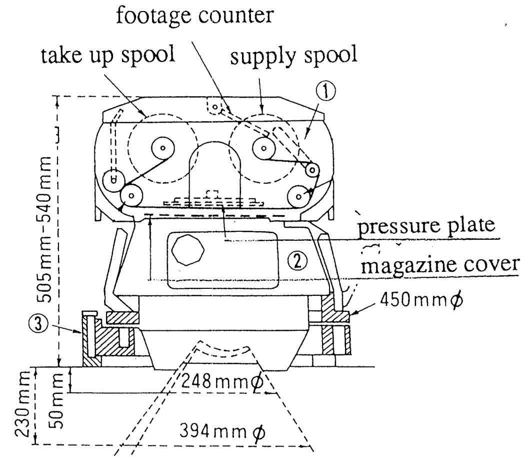
As the metric camera is designed for very accurate measurement of topography, the following requirements in optics as well as geometry should be specified and fulfilled.

(1) Lens distortion should be minimal
(2) Lens resolution should be high and the image should be very sharp even in the corners
(3) Geometric relation between the frame and the optical axis should be established, which is usually achieved by fiducial marks or reseau marks
(4) Lens axes and film plane should be vertical to each other.
(5) Film flatness should be maintained by a vacuum pressure plate
(6) Focal length should be measured and calibrated accurately
(7) Successive photographs should be mode with high speed shutter and film winding system
(8) Forward Motion Compensation (**FMC**) to prevent the image motion of high speed moving objects during shutter time, should be used, particularly in the case of space cameras

Multispectral cameras with several separate film scenes in the visible and reflective IR, are mainly used for photo-interpretation of land surface covers.

Figure 2.8.4 shows a picture taken by the MKF-6, with 6 bands, on board the Russian Soyuz 22.

Panoramic cameras are used for reconnaissance surveys, surveillance of electric transmission lines, supplementary photography with thermal imagery, etc., because the field of view is so wide.



① Film magazine
② Camera body
③ Suspension mount

Figure 2.8.1 Zeiss RMK camera system

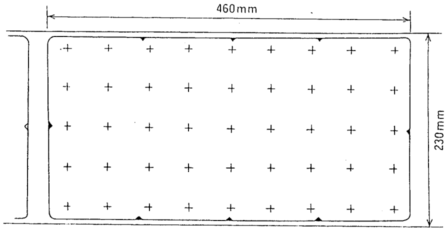


Figure 2.8.2 picture field size of LFC

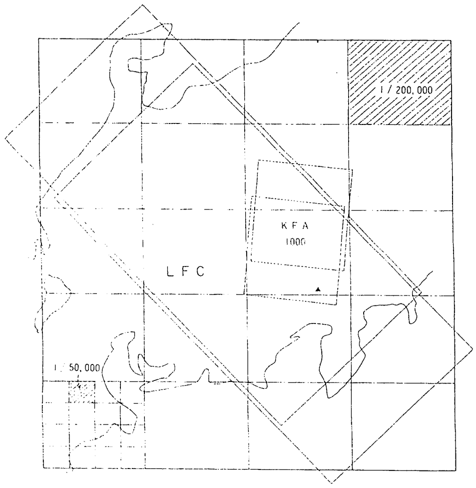


Figure 2.8.3 comparison with cover area for photographed by KAF & LFC

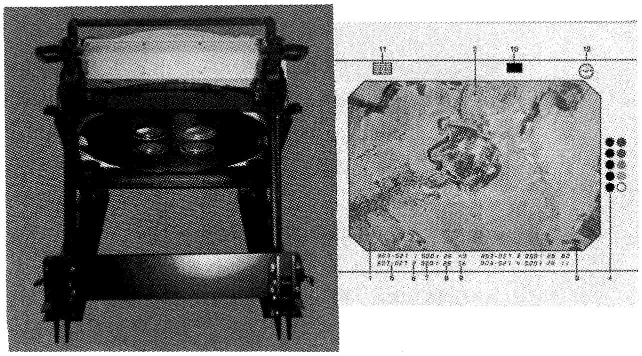


Figure 2.8.4 4 bands multispectral camera (MSK-4) and it's photo

2.9 Film for Remote Sensing

Various type of films are used in cameras for remote sensing. Film can record the electromagnetic energy reflected from objects in the form of optical density in an **emulsion** placed on a **film base** of polyester. There are **panchromatic** (black and white film), **infrared film**, **color film**, **color infrared film**, etc.

The **spectral sensitivity of film** is different depending on the film type. Black and white infrared film has wider sensitivity up to near infrared as compared with panchromatic film. Color film has three different spectral sensitivities according to three layers of primary color emulsion (B,G, R). Color infrared film has sensitivity up to 900 nm. Kodak aerial color film SO-242 has high resolution and is specially ordered for high altitude photography.

Generally film is composed of a photographic emulsion which records various gray levels from white to black according to the reflectivity of objects.

A curve which shows the relationship between the exposure E (meter caudera second) and the photographic density is called the "**characteristic curve**". Usually the horizontal axis of the curve is log E, while the vertical axis is D (density) which is given as follow.

$D = \log (1 / T)$
where T : transparency of film

The characteristic curve is composed of three parts of toe, straight line and shoulder. γ Gamma is defined as the gradient of the straight line part, which is an index of contrast. If γ is given by $\Delta D / \Delta \log E$ which gives high contrast in the case of gamma larger than 1.0, and low contrast in the case of gamma smaller than 1.0.

The sensitivity of a photographic emulsion is defined as the minimum exposure to give the minimum recognizable density. In the definition of JIS (Japan Industrial Standard), the sensitivity is given as $\log (1 / E_A)$ under the conditions of exposure and development density as denoted (E_A, E_B) and (A, B) respectively,

where A : the gross fog + 0.1
E_B : $E_A + 1.5$
$0.75 < B - A < 0.9$

The spectral sensitivity of photographic emulsion ($S\lambda$) represents the sensitivity with respect to each wavelength, which is usually given in the form of a spectral sensitivity curve. In the spectral sensitivity curve $\log S\lambda$ is used instead of $S\lambda$ as the vertical axis, while sometimes **relative sensitivity** is used.

Figure 2.9.3 (a) - (d) show the spectral sensitivity curves corresponding to panchromatic, infrared,color and color infrared films respectively.

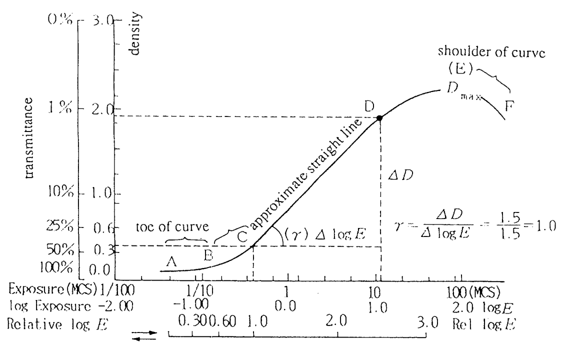


Figure 2.9.1 Characteristic curve for aerial film

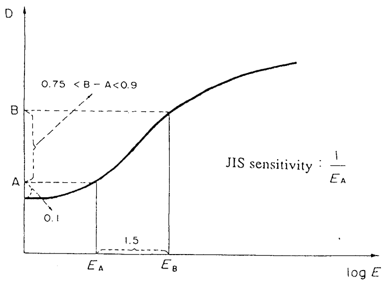
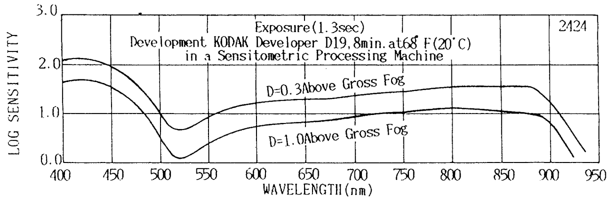
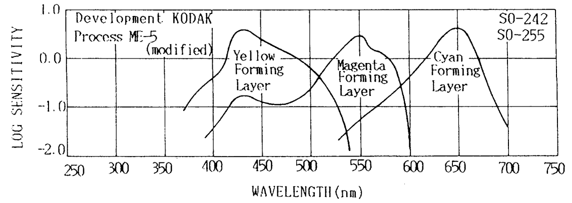


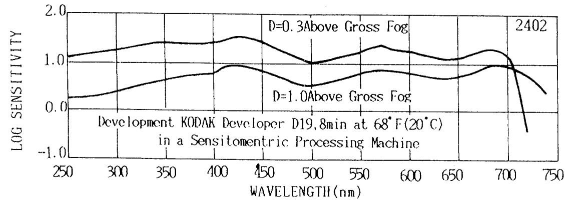
Figure 2.9.2 Definition of B/W film sensitivity in JIS

KODAK
infrared
aerographic 2424





KODAK
plus x
aerographic 2402



KODAK
aerial color
SO - 242

KODAK
Ektachrome
infrared

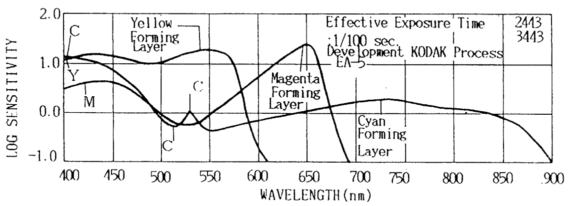


Figure 2.9.3 Characteristic curve for aerial films

2.10 Optical Mechanical Scanner

An **optical mechanical scanner** is a multispectral radiometer by which two dimensional imagery can be recorded using a combination of the motion of the platform and a rotating or oscillating mirror scanning perpendicular to the flight direction. Optical mechanical scanners are composed of an optical system, spectrographic system, scanning system, detector system and reference system.

Optical mechanical scanners can be carried on polar orbit satellites or aircraft. Multispectral scanner (**MSS**) and thematic mapper (**TM**) of LANDSAT, and Advanced Very High Resolution Radiometer (**AVHRR**) of NOAA are the examples of optical mechanical scanners. M^2S made by Daedalus Company is an example of an airborne type optical mechanical scanner.

Figure 2.10.1 shows the concept of optical mechanical scanners, while Figure 2.10.2 shows a schematic diagram of the optical process of an optical mechanical scanner.

The function of the elements of an optical mechanical scanner are as follows.

a. Optical system: Reflective telescope system such as Newton, Cassegrain or Ritchey-Chretien is used to avoid color aberration.

b. Spectrographic system: Dichroic mirror, grating, prism or filter are utilized.

c. Scanning system: rotating mirror or oscillating mirror is used for scanning perpendicular to the flight direction.

d. Detector system: Electro magnetic energy is converted to an electric signal by the optical electronic detectors. Photomultiplier detectors utilized in the near ultra violet and visible region, silicon diode in the visible and near infrared, cooled ingium antimony (InSb) in the short wave infrared, and thermal barometer or cooled Hq Cd Te in the thermal infrared.

e. Reference system: The converted electric signal is influenced by a change of sensitivity of the detector. Therefore light sources or thermal sources with constant intensity or temperature should be installed as a reference for calibration of the electric signal.

Compared to the pushbroom scanner, the optical mechanical scanner has certain advantages. For examples, the view angle of the optical system can be very narrow, band to band registration error is small and resolution is higher, while it has the disadvantage that signal to noise ratio (S/N) is rather less because the integration time at the optical detector cannot be very long due to the scanner motion.

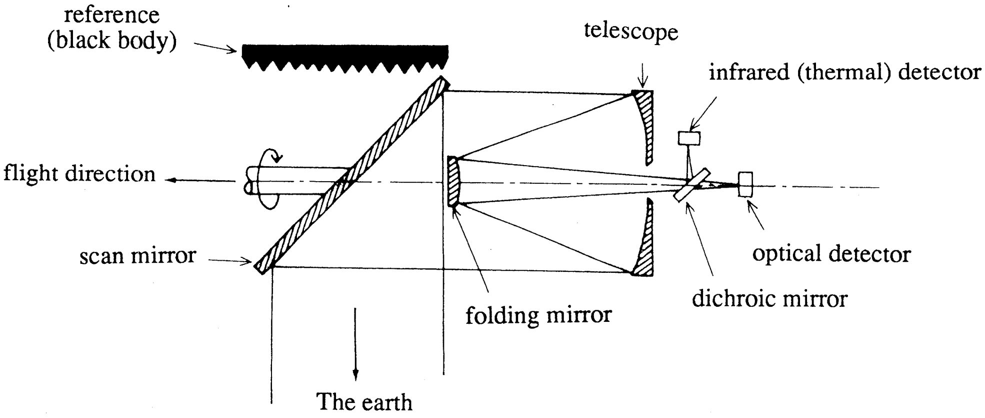


Figure 2.10.1 Structure of optical mechanical scanner

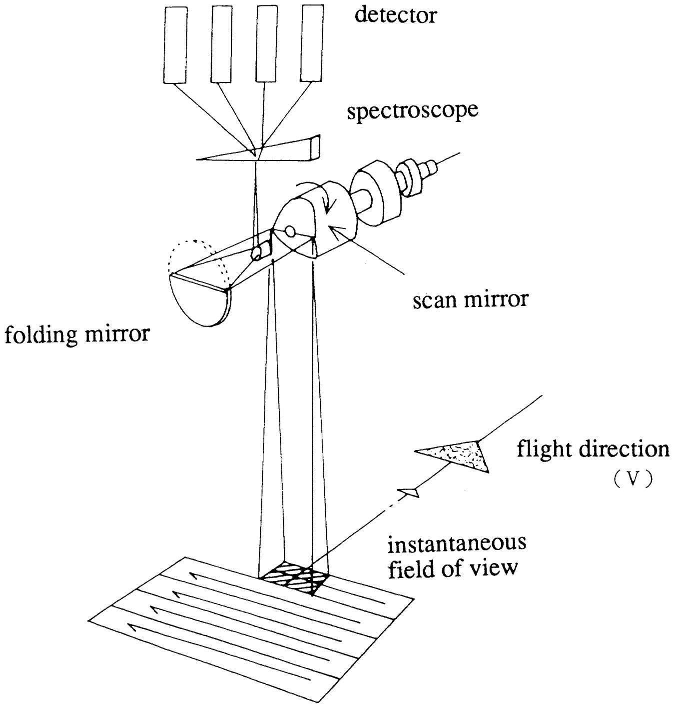


Figure 2.10.2 Schematic diagram of data acquisition by optical mechanical scanner

2.11 Pushbroom Scanner

The **pushbroom scanner** or linear array sensor is a scanner without any mechanical scanning mirror but with a **linear array** of solid semiconductive elements which enables it to record one line of an image simultaneously, as shown is Figure 2.11.1.

The pushbroom scanner has an optical lens through which a line image is detected simultaneously perpendicular to the flight direction. Though the optical mechanical scanner scans and records mechanically pixel by pixel, the pushbroom scanner scans and records electronically line by line.

Figure 2.11.2 shows an example of the electronic scanning scheme by switching method.

Because pushbroom scanners have no mechanical parts, their systematic reliability can be very high.

However, there will be some line noise because of sensitivity differences between the detecting elements.

Charge coupled devices, called **CCD,** are mostly adopted for linear array sensors. Therefore it is sometimes called a linear CCD sensor or CCD camera. HRV of SPOT, MESSR of MOS-1, and OPS of JERS-1 are examples of linear CCD sensors as is the Itres CASI airborne system. As an example, MESSR of MOS-1 has 2048 elements with an interval of 14 mm (Figure 2.11.3). However CCD with 5,000 - 10,000 detector elements have been developed and recently made available.

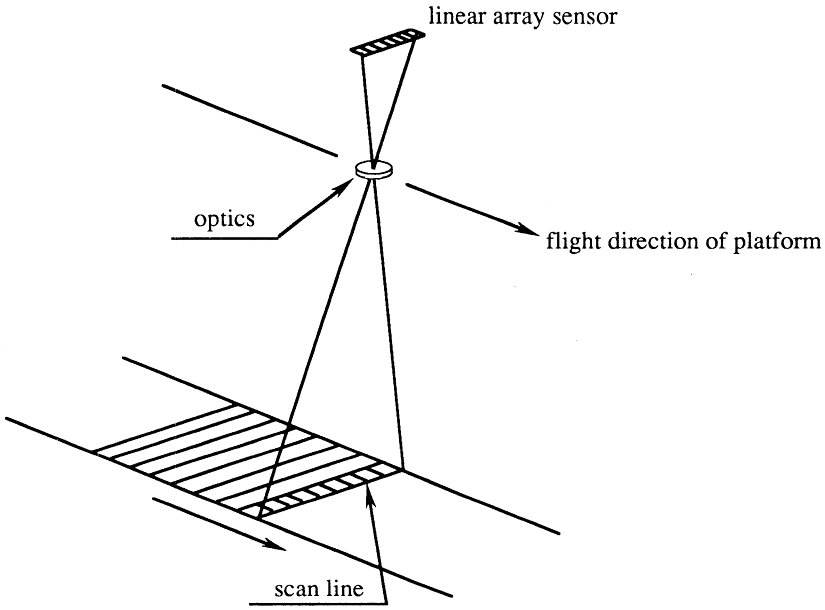


Figure 2.11.1 schematic diagram of data acquisition by push broom scanner

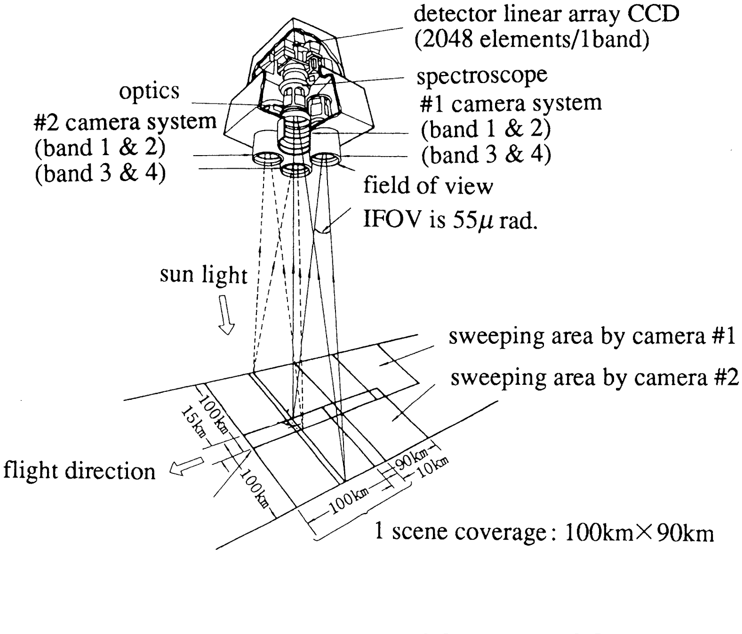


Figure 2.11.2 structure of MESSER in MOS-1

2.12 Imaging Spectrometer

Imaging spectrometers are characterized by a multispectral scanner with a very large number of channels (64-256 channels) with very narrow band widths, though the basic scheme is almost the same as an optical mechanical scanner or pushbroom scanner.

The optical system of imaging spectrometers are classified into three types; dioptic system, dio and catoptic system and catoptic system which are adopted depending on the scanning system. Figure 2.12.1 shows a comparison of the three types. In the case of object plane scanning, the catoptic system is best chosen because the linearity of the optical axis is very good due to the narrow view angle and the observation wave range is so wide. However in the case of image plane scanning, the dioptic system or dioptic and catoptic system is best suited because the view angle should be wider.

Figure 2.12.1 shows four different types of multispectral scanner. The left upper (multispectral imaging with discrete detectors) corresponds to the optical mechanical scanner on the using the object plane scanning method used in the LANDSAT. The right upper (multispectral imaging with line arrays) corresponds to pushbroom scanner using the image plane scanning method with a linear CCD array.

The left lower (imaging spectrometry with line arrays) shows a similar scheme to the right upper system but with an additional dispersing element (grating or prism) to increase the spectral resolution. The right lower (imaging spectrometry with area arrays) shows an imaging spectrometer with area arrays.

Figure 2.12.2 shows the optical scheme of the Moderate Resolution Imaging Spectrometer-Tilt (**MODIS-T**) which is scheduled to be carried on EOS-a (US Earth Observing Satellite). MODIS-T has an area array of 64 x 64 elements which enables 64 multispectral bands from 0.4 μm to 1.04 μm with a 64 km swath. The optical path is guided from scan mirror to Schmitt type off axis parabola of dio and catoptic system. The the light is then dispersed into 64 bands by a grating and is detected by an area CCD array of 64 x 64 elements.

As imaging spectrometer provides multiband imagery with a narrow wave length range, and is useful for rock type classification and ocean color analysis.

Table 2.12.1 Comparison with object plane scanning method and image plane scanning method

items	object plane scanning method	image plane scanning method
Scanning mechanism	mirror for rotating and/or tilting	non mechanism
Width of scanning	wide	narrow
Field of view (IFOV)	narrow	wide
Aperture of optics	large	small
Optical system	catoptic system	dio/catoptic system
Observation range	visible -- thermal	visible -- near infrared
Number of optical detector	few	many (area array)
Signal noise ratio	low	high
Size & weight	large & heavy	small & light

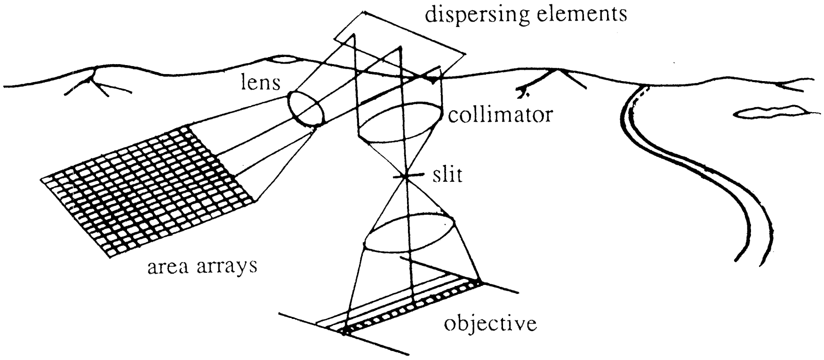


Figure 2.12.1 Imaging spectrometry with area array

Table 2.12.2 Comparison with dioptic system & catoptic system

items	dioptic system	dio & catoptics system	catoptics system
wide angle (>90°)	most suitable	suitable	unsuitable
temperature effect	no good	middle	good
stray light effect	no good	middle	good
observation range	narrow (color aberration)	middle	wide
aperture (>250mm)	unsuitable	suitable	most suitable
linearity of optical axis	bad	middle	good
size & weight	big & heavy	middle	small & light

2.13 Atmospheric Sensors

Atmospheric sensors are designed to provide measures of air temperature, vapor, atmospheric constituents, aerosols the etc. as well as wind and earth radiation budget. Table 2.13.1 shows the important atmospheric constituents for green house effect gases, ozone layer and acid rain.

As remote sensing techniques cannot meet the direct measurement of these physical magnitude, it is necessary to estimate them from spectral measurement of atmospheric scattering, absorptance or emission.

The spectral wave length range is very wide from the near ultraviolet to the millimeter radio wave depending on the objects to be measured, as shown in Table 2.13.2.

There are two types of atmospheric sensor, that is, active and passive . Because the active sensor is explained in section 2.15 "Laser Radar" or Lidar,only the passive type sensors will be introduced here.

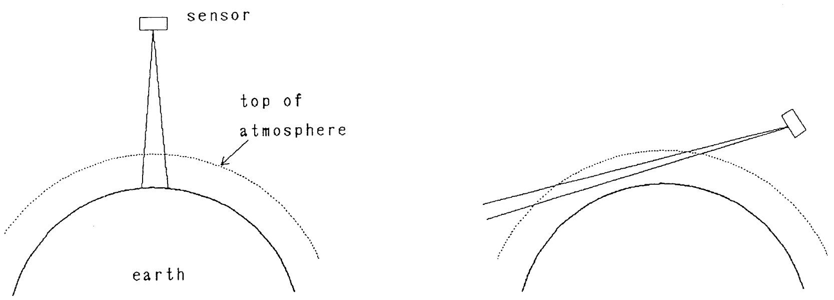
Two directions of atmospheric observation are usually adopted; one is nadir observation and the other is limb observation as shown in Figure 2.13.1. The nadir observation is superior in the horizontal resolution compared to vertical resolution. It is mainly useful in the troposphere but not in the stratosphere where the atmospheric density is very low.

The **limb observation method** is to measure the limb of the earth with an oblique angle. In this case, not only atmospheric emission but also atmospheric absorption of the light of the sun, the moon and the stars are measured, as shown in Figure 2.13.1. Compared with the nadir observation, the limb observation has higher vertical resolution and higher measurability in the stratosphere. The absorption type of limb observation has rather high S/N but observation direction or area is limited except for the stars.

There are two types of atmospheric sensors, that is, sensors with a fixed observation direction, called sounders and scanners.

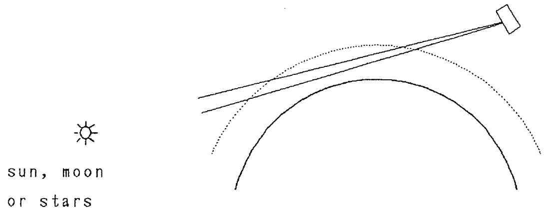
The main element of optical sensor is a spectrometer with a very high spectral resolution such as the **Michelson spectrometer, Fabry-Perot spectrometer** and other spectrometers with grating and prism.

Figure 2.13.2 shows the structure of Michelson spectrometer called IMG which will be borne on ADEOS (Advanced Earth Observing Satellite to be launched in 1995 by Japan).



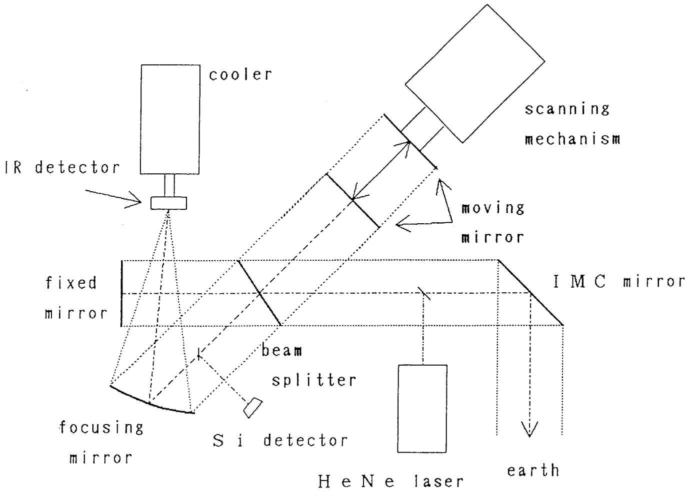
a) nadir observation

b) limb radiation observation



c) limb absorption observation

Figure 2.13.1 Direction of atmospheric observation



IMG : Michelson spectrometer on board ADEOS
nadir looking spectrometer, wavelength resolution 0.1cm
wavelength region 3.3 - 14 m
IMC : image motion compensation mirror
HeNe laser : laser measuring mirror displacement
Si detector : HeNe laser detection
beam : KBr + Ge
splitter : HgCdTe, InSb

Figure 2.13.2 Structure of IMG

2.14 Sonar

Sound waves or ultrasonic waves are used underwater to obtain imagery of geological features at the bottom of the sea or lakes because radio waves are not usable in water. Sound waves have many characteristics such as reflection, refraction, interference, diffraction etc. similar to radio waves, though it is an elastic wave different from the radio wave. Sound waves have a form of longitudinal wave in water along the direction of the wave. Generally, sound waves transmitting in water have a higher resolution according to higher frequency but also higher attenuation. The detectability depends on S/N ratio when receiving the sound signal after loss by noises in water.

The velocity of sound is approximately 1,500 meters/second which varies depending on temperature, water pressure, and salinity of the medium.

As shown in Figure 2.14.1, there are **side scan sonar** and **multi-beam echo sounder** by which the sea bottom is scanned and imaged. These sensors are kinds of active sensors which record the sound intensity reflected from the projected sound wave onto the bottom.

Because sonar is an active sensor, it generates image distortion from the effects of foreshortening, layover and shadow, with respect to incident angle at the bottom, in the same manners as radar.

As shown in Figure 2.14.2, a side scan wave is produced from a transducer borne on a towfish connected by tow cable to a tug boat. The incident sound wave on the sea bottom will produce sound pressure on the bottom materials causing back scattering to return to the receiver, after attenuation, according to the shape and density of the bottom. The sonar acquires the backscattering in the time sequence to a form of image.

Figure 2.14.3 shows a multi narrow beam sounder with a transmitting transducer and a receiving transducer in a T shape at the bottom of the boat. A receiving transduce has 20 to 60 elements which receive the sound signal reflected from the sea bottom, which is usually converted to an image as for the side scan sonar.

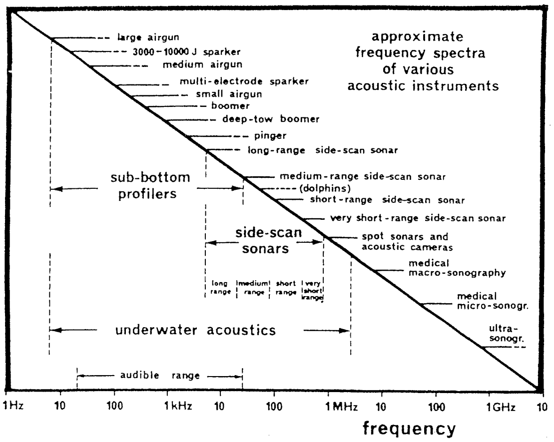


Figure 2.14.1 Approximate frequency spectra of Various acoustic instruments

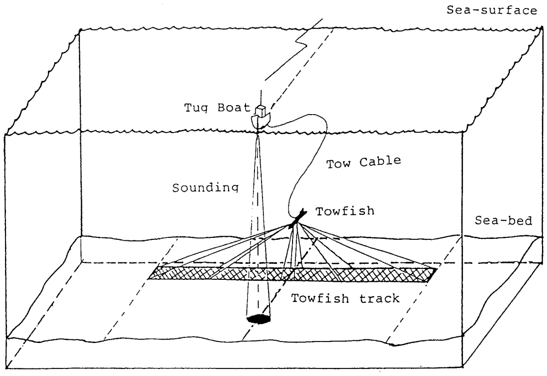


Figure 2.14.2 Method of data sampling by using side scan sonar

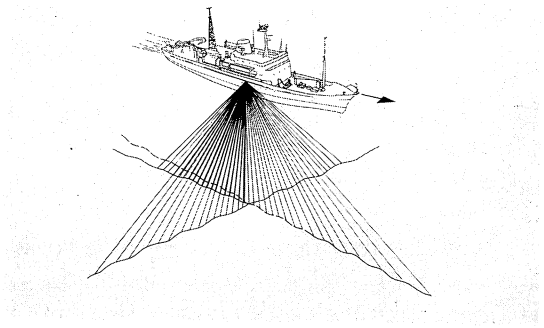


Figure 2.14.3 Method of data sampling by using multi beam echo sounder

2.15 Laser Radar

Devices which measures the physical characteristics such as distance, density, velocity, shape etc., using scattering, returned time, intensity, frequency and/or polarization of light are called optical sensors. However as the actual light used by the optical sensor is mostly laser, it is usually called **laser radar** or **lidar** (light detection and ranging).

Laser radar is an active sensor which is used to measure air pollution, physical characteristics of atmospheric constituents in the stratosphere and its spatial distribution. The theory of laser radar is also utilized to measure distance, so that for this application it is called laser distancemeter or laser altimeter.

The main measurement object is the atmosphere although laser radar is also used to measure water depth, thickness of oil film or vividness of chlorophyll in vegetation.

[Theory of Lidar]

Figure 2.15.1 shows a schematic diagram of a lidar system. The power of the received light $P_r(R)$ reflected from a distance of R can be expressed as follows.

$$P_r(R) = P_0 K A_r q\beta(R) T^2(R) Y(R) / R^2 + P_b$$

where P_0 : intensity of transmitted light

K : efficiency of optical system

A_r : aperture

q : half wavelength

$\beta(R)$: backscattering coefficient

$T(R)$: transmittance of atmosphere

$Y(R)$: geometric efficiency

P_b : light noises of background

Received light is converted to an electric signal which is displayed or recorded after A/D conversion. The effective distance of lidar depends on the relationship between the received light intensity and the noise level.

Lidar can be classified with respect to its physical characteristics, interactive effects, physical quantities etc., as shown in Table 2.15.1. In this table, Mie Lidar is the most established sensor,with a which signal intensity large enough to measure Mie scattering due to aerosols.

Fluorescence lidar, Roman lidar and differential absorption lidar are utilized for measurement of density of gaseous body, while Doppler lidar is used for measurement of velocity. Polarization effects of lidar is utilized for measurement of shape.

There are several display modes for example, a scope with horizontal axis of distance and with vertical axis of intensity, **PPI** (plane position indication) with gray level in polar coordinate system, **RHI** (range high indication) with a display of the vertical profile, **THI** (time height indication) with a horizontal axis of elapsed time and with a vertical axis of altitude.

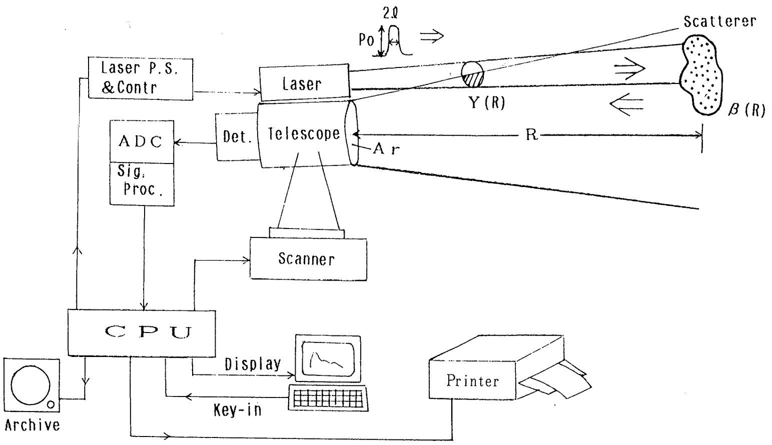


Figure 2.15.1 Schematic diagram of lidar system

Table 2.15.2 Classification of lidar based on interaction

items	interractive effects	physical quantities	lidar	effects
intensity	Mie scattering	aerosol	Mie lidar	S
	Rayleigh scattering	moleculer of atmospher	Rayleigh lidar	W
	fluorescence scattering	density of atmospheric constituents	fluorescence lidar	M
	Raman scattering	density of O2 & N2 in atmosphere	Raman lidar	S
	differential scattering	density of atmospheric constituents	differential lidar	M
wave number		speed	doppler lidar	s
polarization		shape	Mie lidar	-

note : S=Strong, M=Medium, W=Weak

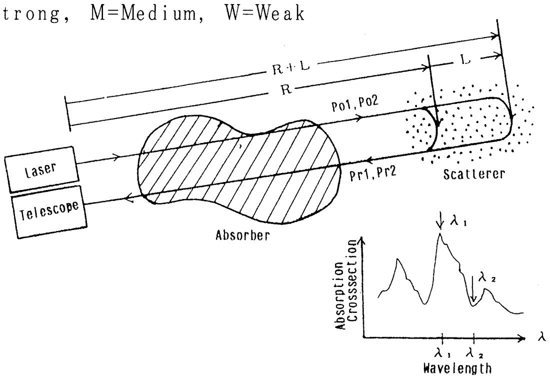


Figure 2.15.3 Principle of a differential absorption lidar (DIAL)