A Study of Infra-Red Imaging Sensors and Instruments on Geo-Stationary Satellites

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***Abstract:*-Infrared (IR) imaging by satellites is an advanced field of space research which deals with providing day and night coverage of the earth, by capturing the emitted infrared radiation with the help of IR sensors thereby generating images. The imaging module consists of the detector array, cryogenic coolers, and data processing unit. With advances in this field, it is now possible to exploit this technology for different applications like weather predictions, global climate pattern study, forest cover and ocean currents. The paper investigates different imaging sensors used in geo-stationery satellites. Next, scanning systems, cryogenic coolers and its types, data processing, and data transmission system have been delved into, which forms a complete module that is mounted on a satellite. Further, the detector assembly for sensors like Visible Infrared Imaging Radiometer and Thermal Infrared Sensor have also been conferred. Lastly, the criteria for sensor design is also briefly dealt with. The above topics have been explained using examples of Kalpana and INSAT-3D (ISRO, India) and GOES series (NOAA, USA).**

Keywords – Data processing, Geo Stationary, Infrared Sensors, Infrared Imaging, Instruments, Satellites.

I. INTRODUCTION

Infrared (IR) Imaging from Satellites is an advanced field of space science and technology. The first satellite with thermal imaging capability was by NOAA/NASA in 1970's (civilian). Satellite IR imaging sensors provide day and night coverage, as images are generated by emitted IR radiation from the Earth surface, unlike visible imaging which is based upon reflected sunlight. Imaging in the 2um to 18um Electromagnetic (EM) radiation wavelengths is considered as 'Infrared Imaging'. The advent of satellite IR Imaging has been made possible due advances in technology like sensitive IR detectors and detector arrays, stabilized satellites, special cryogenic coolers, high data rate digital transmission, and advances in electronic devices and circuits. Satellite Thermal imaging systems exploit MWIR (3-5um) and LWIR (8-14um) atmospheric windows where the atmosphere is transparent enough to permit emitted radiation to reach satellite sensors for passive imaging (fig 1). Satellite IR imaging has proved to be a boon for scientific applications like Weather Prediction, Global climate studies, Cyclone monitoring and warning, Earth resource studies, detection of forest fires, and many more applications which are directly of benefit to the society. Here we attempt to bring out the state-of-art technology and likely future trends in Geostationary Satellite IR imaging and radiometers.

II. GEOSTATIONARY SATELLITES (GEO-S) FOR IR IMAGING

A geostationary satellite is placed in geostationary Earth orbit or geosynchronous equatorial orbit (GEO) circular orbit 35,786 kilometers above the Earth's equator and following the direction of the Earth's rotation. Such satellites are three-axis stabilized or spin stabilized (earlier generation). 3-axis stabilized satellites provide the sensors full temporal imaging period, but need image scanning systems, to generate 2-D images. Spinning satellites provide only 4.73% time period for earth view in each spin, but they need much simpler methods for generating the image scan. However, as the actual imaging period is much less per scan period, much larger imaging systems are required for the same quality of imaging. GEO-S Imaging sensors can see 1/3 of the earth sphere only, centered with the satellite location. Such sensors can take images continuously of the same area of theearth, as the satellite 'stares' at the same point on earth always. Actual GEO-Sat IR sensors provide 48 or fuller earth disc, and several hundred area-specific images (e.g. Cyclone) per day. Currently, USA, Europe, India, Japan, China have deployed operational GEO-S for earth imaging, mainly for meteorological applications, detailed in tableI.

Table. I. Description of satellites of different countries

Country/Org	Satellite	Sensor	Ground-resolution
USA (NOAA)	GOES-SERIES	IMAGER, SOUNDER	<1km, 4km
INDIA (ISRO)	INSAT-3D	IMAGER, SOUNDER	4km,10km
INDIA (ISRO)	KALPANA	VHRR (VIS/IR)	2km, 8km
EUROPE (ESA)	METEOSAT	SEVIRI	1km, 4.8km

The GEO satellites being much distant, imaging sensors require very large radiation collecting optics compared to Low earth orbiting satellites, which are generally at orbits of 500-900km.

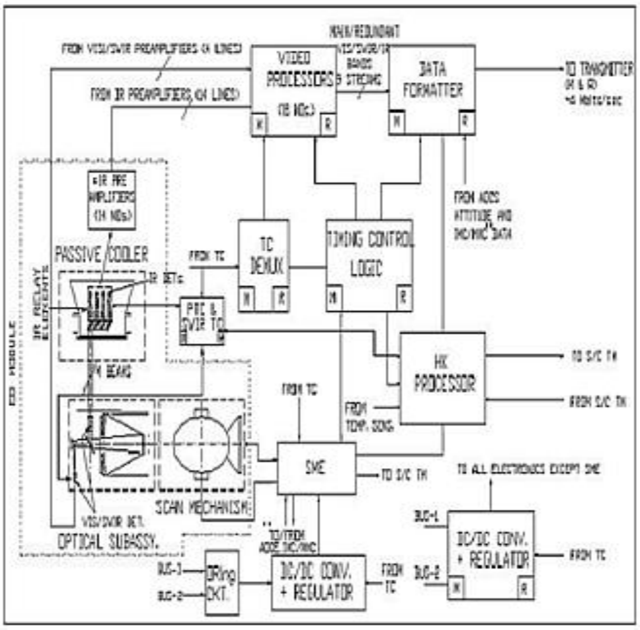

Fig.1.Block diagram of INSAT-3D IMAGER *(credit: ISRO)*

III.GEO-SATELLITE IR IMAGING SENSOR TYPES

A. Imager/Radiometer

Imagers provide images for the entire Earth disc or a part of it. They have much wider bands, and fewer imaging channels (3/6/9+). From a GEO orbit resolutions are 500mts-2.5km. Imaging intervals can be 1min, for a small part of the earth, to about 20 min. for the full earth disc. Generally, 48 or more earth images can be generated and transmitted per day.

B. Sounder

Atmospheric "Sounder" is a special type of multi-band IR sensor, which provides the information about different "layers" of the atmosphere from the Sea-level to about 10kms. The Sounder instrument is designed for imaging the earth in several narrow IR bands which are physically related with emission or absorption of EM/IR radiation of atmospheric gasses (at different temperature and pressure),water vapor in the atmosphere and gasses like CO2,Ozone. Sounder instruments have resolutions of 4-10km, and may provide up to 6-8 images per day.

IV.CONSTITUENTS OF A SATELLITE IR IMAGING SENSOR

A. Telescope and Scanning systems

Reflective optical systems are generally used for the GEOS, with apertures of 8" (Kalpana-VHRR),12" (GOES, INSAT-3D). The telescope configuration generally Cassegrain or RC type, with a suitable focal length that covers the Earth disc and its surrounding space (approx. 20^0 x 20^0). Such optics has the advantage that special glass is not required for the wide band (2.5 um – 14 um) IR sensing and the weight of the telescope is limited, as the primary mirror can be "scooped" to make it light-weighted. GEOS being stationary, to create the image of the Earth disc or any part of it, a "Scan Mirror" is required to be placed before the telescope. The Scanner consists of Scan-mirror, precision servo motors for thehorizontal and vertical scan, servo control electronics.

Spinning satellites like MeteoSat, require only one axis scan for the mirror. The size of the mirror is similar to the telescope.

The scanned systems have interlinked electronic systems, such that the electronic sampling of the IR detectors is synchronized with the movement of the Scan-mirror. A typical such instrument block diagram is shown in figure.2.

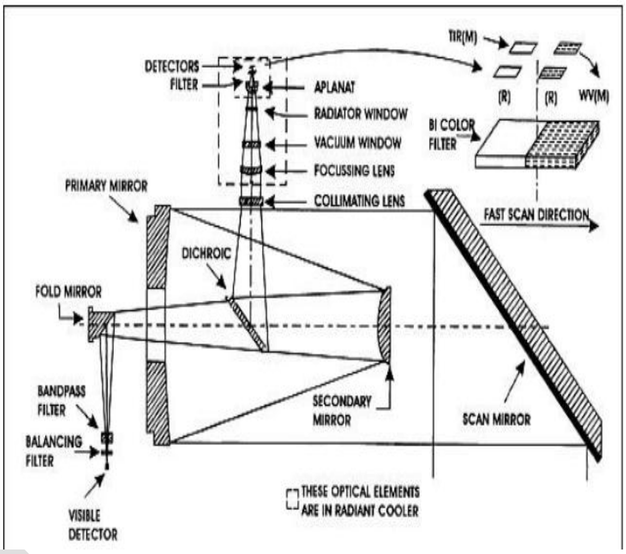

Fig.2. Band VHRR- Kalpana-1 *(credit: ISRO)*

B. Pre – detector optical system

There is only one telescope for an Instrument like IMAGER or VHRR, but several IR imaging detectors are required to cover the different IR bands, to provide the images of features on Earth. Hence following the telescope, "beam splitters" are placed, with physical properties as required to only transmit that part of the IR radiation required for a specific detector, e.g. Gold di-chorics are used with different thickness to split 8-14um bands where it is required to split the beam into different directions(INSAT-VHRR, GOES-IMAGER), glass filters are also used for 2.5-14 um radiation bands, especially in Atmospheric Sounder instruments (GOES/INSAT-3D) Sounder, where large number of narrow bands(18+) are required. If the instrument is required to have more and more narrow bands, for finer spectral differentiation, gratings are placed in the optical path (IR Hyper Spectral sensors).

C. Electronic IR Detectors and Cryogenic coolers

There are two basic types of photon (radiative energy) detectors; themajority (electron) and the minority (hole) carrier. If the dominant mode is majority carrier-based the detector is 'photoconductive' while it may be both photoconductive and photovoltaic for minority carrier mode. Most GEO satellites with IR imaging use cryogenic cooled HgCdTe (photoconductive) detector arrays. Mercury-Cadmium-Telluride (HgCdTe) is a detector semiconductor alloy in which it is possible to adjust the constituents of the alloy such that “tunable electronic band gaps” can be created. Such detectors can be made to respond to IR wavelengths from 1-20um [z], and can be more easily fabricated for large linear and area arrays. Such detector arrays are mounted on Si substrate, and electric connection metal tracks are brought out. The complete detector is encapsulated in a hermetically sealed ceramic package, like an Integrated circuit device. The detectors may be covered with IR transparent glass filters or can be ‘bare’.

Other detectors materials include Indium Antimonide (InSb) which has a peak sensitivity of approximately 5 µm, Mercury-Doped Germanium (GdHg) having a peak sensitivity around 10 µm.
The IR detectors being photoconductive, the performance is governed by Planck’s radiation law, Stephan-Boltzmann black body law, and Electronic Work Function law.

The Planck’s law is expressed as:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{kT\lambda}} - 1}$$

Where, $h=6.62\times10^{-34}$ Js (Planck’s constant)
The Stefan-Boltzmann law is expressed as:
$M_b = \sigma T4$

Where, $\sigma = 5.6697 \times 10^{-8}$ W m^{-2} K^{-4} (Stefan-Boltzmann constant), and T is thetemperature in degrees Kelvin.

Electronic Work Function is expressed as:
$W= - e - \phi E_F$

Where −e is acharge of an electron, ϕ is the electrostatic potential in the vacuum nearby the surface, and E_F is the Fermi level.

Energy transfer by EM radiation is of chief interest since it happens to be the sole form of energy transfer that transpires in avacuum like a region between the Earth and the Sun. EM radiation escaping from a body is known as radiant flux, and the amount of this flux radiated from the body is positively related to the true kinetic temperature of an object. Hence, radiometers can be positioned at a distance from the body for measuring its radiant temperature by which the body’s true kinetic temperature can be correlated. This forms the basis of thermal IR remote sensing. However, this relationship is not impeccable, as ameasurement of radiant temperature from a distance, leads to recording a value slightly less than the actual value of thetrue kinetic temperature of the object. This is caused due to emissivity. Two ways of collecting thermal IR remote sensor data is: a.) Across-track thermal scanner, and b.) Push-broom linear and area array charge-coupled device (CCD) detectors.

To sense and measure the received radiant energy of IR wavelengths (lower energy) from the object being imaged, the detector elements have to be operated at the lowest possible cryogenic temperatures to obtain ameaningful electronic signal. The received signal from the object can be sensed only if the detector temperature and the ‘background’ temperature are well below the object temperature. Thus, these type of HgCdTe detectors are called ‘background limited’ detection sensors. The detector array, along with precision front-end electronic low noise amplifiers is mounted on a highly conductive small thermal plate (called ‘patch’), which is cooled to low temperature. The cooling mechanism in GEO satellites can be passive, using radiant cooler looking away from the earth towards deep space, or active, using cryogenic electro-mechanical coolers (sterling cycle).

To keep the components of spacecraft in appropriate temperature limits, a Thermal Control System (TCS) is utilized. This system is cardinal to achieve optimum performance and it ensures efficient equipment (sensors, atomic clocks etc.) operation. The generated heat is transferred by TCS from the spacecraft or space station to space. If the external temperature is very cold, heat is released from internal sources or is absorbed from some other external sources. The TCS system has two subsystems – a Passive Thermal Control System (PTCS) and an Active Thermal Control System (ATCS) [3]. When insulation, surface coatings, heat pipes that comprise the passive system are not adequate to maintain the temperature, the Active system takes over. A comparison between different cooling technologies is made in table no. II [4],where Rev. Brayton is Reverse Brayton cycle coolers and ADR is adiabatic demagnetization.

Active coolers require a large amount of energy (>100 W), and have a limited operational life, but they can operate the Patch at even < 40K.They also require special powering and electronic control circuits to operate in the satellite. Also, the active cooler and detector are assembled as a coupled structure with a Dewar cylinder and require special mounting mechanisms. Active coolers are used in such satellites, wherein the passive detector cooler may not be able to look at deep space during the operations. The heat from the active cooler is removed using secondary passive radiative coolers.

Passive coolers are developed to take advantage of the fact that, in deep space any object can be cooled by exposing it to look at “cold space” i.e. away from any large body like earth, ormoon. Thus, a part of the satellite body is built with metal that does not require any protection blanket, and the ‘patch’ to be cooled is placed as near to it as possible. The cooler is actually a large open metal hood, which radiates the heat away from the satellite. The design of such radiant coolers and their placement on the satellite requires that the solar heat should not prevent its normal operation.
IR sensors on Orbiting satellites and some planetary exploration satellites use active coolers. GEOS like, INSAT, MTG GOES, make use of HgCdTe linear arrays operating at temperatures of 70K-100Kwith passive coolers and scanning mechanisms to generate IR Earth imagery.

V. DATA PROCESSING TOOLS AND DATA TRANSMISSION

The analog signal from the IR imaging sensor is received by the pre-processing electronic circuits consisting of very low noise instrumentation amplifiers, which is followed by Analog to Digital converters (10 to 14 bit). Background signal (IR background signal) called "space data", is subtracted as an "offset" from the total signal, using a complex feedback system, after which the final digitized signal, is formatted, along with the health data like detector temperatures, scan mirror rates, voltages, currents in the instrument. The formatted digital data is converted to aserial stream, processed further by the data transmission electronics, modulated as per the satellite transmission requirements and transmitted to earth stations.

Table. II. Comparison of different cooler technologies [4]

Cooler	Typical temperature	Typical heat lift	Advantages	Disadvantages
Radiator	80 K	0.5 W	Reliable, low vibration, long lifetime	Complicates orbit
Cryogen	4 K	0.05 W	Stable, low vibration	Short lifetime, out-gassing, massive, complex
Stirling 1 stage	80 K	0.8 W	Efficient, heritage	Vibrations
Stirling 2 stage	20 K	0.06 W	Intermediate temp	Under development
Pulse tube	80 K	0.8 W	Lower vibrations	Lower efficiency than Stirling
Peltier	170 K	1 W	Lightweight	High temp, low efficiency
Joule-Thompson	4 K	0.01 W	Low vibrations	Requires hybrid design
Sorption	10 K	0.1 W	Low vibrations	Under development
Rev. Brayton	65 K	8 W	High capacity	Complex
ADR	0.05 K	0.01 mW	Only way to reach these temps.	Large magnetic field

TeraScan from SeaSpace is a software which provides complete solutions for receiving, distributing, processing and archiving of satellite data [5]. TeraScan has a range of different add on and products which offer a comprehensive remote sensing solution. Different products provide services such as data acquisition, sensor conversion, visualization, algorithm generation, data export, environmental monitoring, data cataloging, etc. TeraScan has been used for Suomi NPP to facilitate end to end environmental data processing and processing EOS datasets to level 2 from theraw state on its own. It has been processing data from the VIIRS, ATMS, and CrIS sensors.

Some other similar solutions which provide geospatial image processing and data processing are Geomatica by PCI Geomatics [6], Idrisi by Clark Laboratories [7], GRASS GIS (Geographic Resources Analysis Support System) (Geographic Information System) (free and open source) [8].

Satellite communication involves the uplink station on theground to transmit the signal to the satellite. This signal at the satellite is processed along with changing its frequency and amplifying it. Then the modified signal is again sent back to the downlink station on theground.The ground equipment receives it and processes it. However, such communication necessitates a clear line of sight.

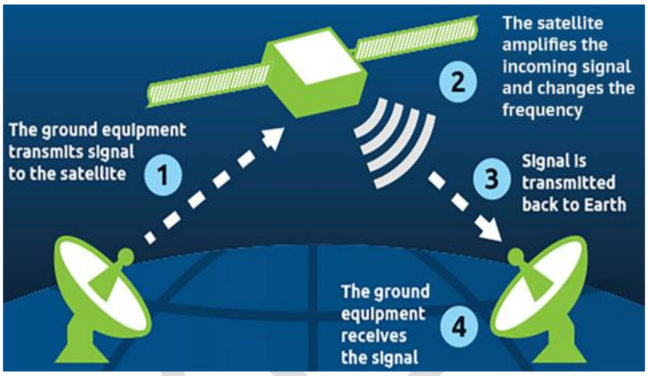

Fig. 3. Satellite Communication (*source: www.intelsatgeneral.com*)

VI.SENSOR DETECTOR ASSEMBLY OF SOME SENSORS

A. VIIRS [9][10]

Visible Infrared Imaging Radiometer Suite (VIIRS) by Raytheon, is an inspecting radiometer that accumulates visible, IR imagery and radiometric measurements of land, atmosphere, oceans and, cryosphere. It is used in Suomi National Polar-Orbiting Partnership (NPP) for monitoring global weather patterns, land surface parameters (e.g. snow cover, vegetation), ocean parameters (e.g. phytoplankton production, surface winds), solar parameters (e.g. total solar irradiance) and other predictive information. VIIRS was also used in National Polar-orbiting Environmental Satellite System (NPOESS) for Environmental Data Record (EDR). Further VIIRS is also scheduled for NOAA's Joint Polar Satellite System next - generation weather satellite program.

It is a 22 band optomechanical radiometer which uses a cross track rotating telescope fore-optics design allowing it to cover a greater swath. VIIRS has 22 imaging and radiometric bands having a spectral range from 0.41 to 12.5 microns. The observation scene is imaged onto 3 focal planes, splitting the VNIR, SWIR, MWIR, and TIR energy.

Instrument Specifications (credit: Raytheon [11])

Spectral Bands
Visible/Near-IR: 9 plus day/night pan band
Mid-Wave IR: 8
Long-Wave IR: 4
Imaging Optics: 19.1 cm aperture, 114 cm focal length
Orbit Average Power: 200 Watts
Weight: 275 kg
Data Acquisition Parameters:
Scanned Swath: ±56°, 3000 km
Horizontal Sample Interval on Ground: <1.6 km @ end of scan

Data Quantization: 12 bit –14 bit A/D converters for lower noise
Data Rate: 10.5 Mbps (max.)

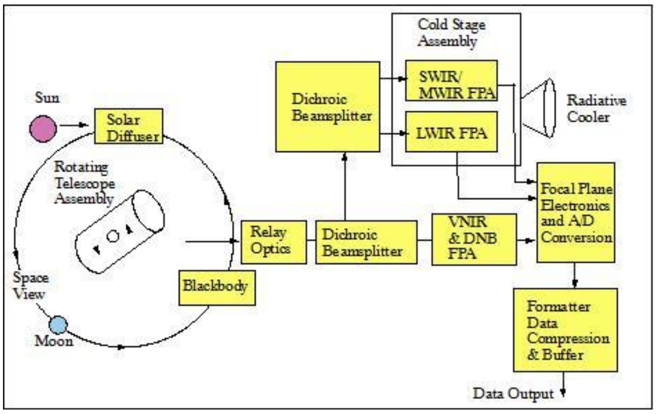

Fig.4. Major subsystems/components of VIIRS (functional block diagram)(*credits: Raytheon*)

B. TIRS

Another Mission by NASA is Landsat 8 (formerly known as Landsat Data Continuity Mission [LDCM]) [12] which monitors environmental changes and aims at managing reserves and supplies such as water, forest, crops for human sustainment. This satellite observatory is in the low- Earth orbit, carting two sensors – Thermal Infrared Sensor (TIRS) and Operational Land Imager (OLI). TRIS collects image data over an 185 km swath for two narrow spectral thermal bands with 100 meters resolution. This resolution is considered adequate for gauging consumption of water over irrigated fields [13].

Table III: Spatial resolution and Spectral bandsfor TIRS [source: 14]

Band #	Center wavelength (µm)	Minimum lower band edge (µm)	Maximum upper band edge (µm)	Spatial resolution (m)
10	10.9	10.6	11.2	100
11	12.0	11.5	12.5	100

Table III: Saturation Radiance and Noise-Equivalent-Change-in-Temperature (NEΔT) specifications for TIRS [source: 14]

Band #	Saturation temperature	Saturation radiance	NEΔT at 240 K	NEΔT at 300 K	NEΔT at 360 K
10	360 K	20.5 W/m2 sr µm	0.80 K	0.4 K	0.27 K
11	360 K	17.8 W/m2 sr µm	0.71 K	0.4 K	0.29 K

Using a focal plane with long arrays of photosensitive detectors, TIRS is a push broom sensor. It is a refractive telescope having four elements and focuses a f/1.6 beam of thermal radiation onto a cooled focal plane. Three modules with Quantum Well Infrared Photodetector (QWIP) arrays are positioned in an alternating configuration with the centerline of the focal plane. A 2-statecryocooler is employed to let the QWIP detectors function at the required temperature of 43K. The design life of TIRS is only three years and this becomes a chief differentiating factor between OLI and TIRS.

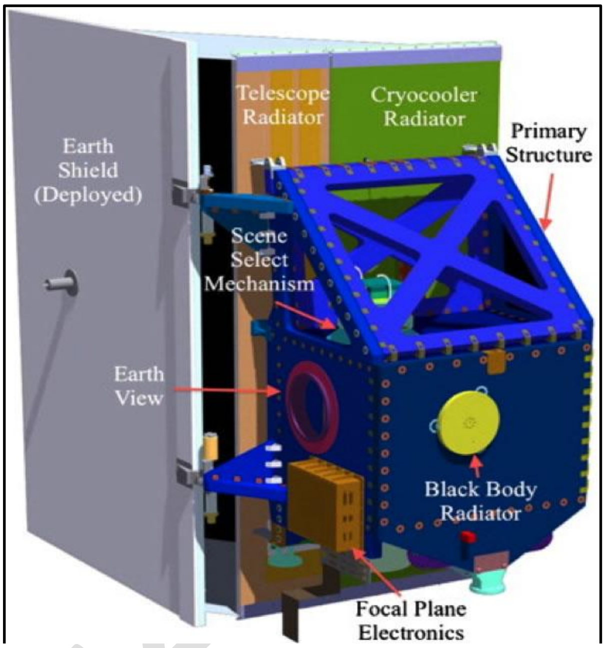

Fig. 5.Drawing of the Thermal Infrared Sensor (TIRS) [15]*(source:http://landsat.gsfc.nasa.gov/?p=5692)*

VII. SENSOR DESIGN

Designing a sensor which can perform appropriately in space can be intimidating. Myriad parameters have to be taken into consideration. At times, the parameters may be interdependent and so adjustments have to be made for balancing other criteria as well. Based on our survey (from [16]) we have made an attempt to list down the building blocks of the design criterion such as phenomenology, FPA characteristics, Design operation range performance etc. (see Fig. 6). Aspects that crucially influence the design and performance requirements comprisedensity of object being studied, tasks to be achieved, sensor location, and positioning of the object.

VIII.CONCLUSIONS

The thermal imaging module in a geo-stationary satellite consists of detector arrays, telescope and scanning assembly, cooling system, data processors, and atransmission module. The detector arrays consist of IR sensors that capture the infrared radiations emitted by the earth in different regions. The scanning system determines the region of the earth for imaging. Most detector arrays are cryogenically cooled by passive coolers. The data processing unit consists of instrumentation amplifiers, analog to digital converters

and feedback systems. The digital data is transmitted to the ground centers using transmitters. Softwares are available that can efficiently process the received data from satellites and extract the required information for getting the final image. Advancement in detector assemblies, data processing, and transmission systems have made it possible to get high-resolution images, with less noise. Such developmentshave helped in improving weather predictions, tracking climate change, ocean current and cloud formation patterns, forest covers, etc. This, in turn,has played an instrumental role in thefield of agriculture, disaster management, study of global warming and climate change, and marine life study.

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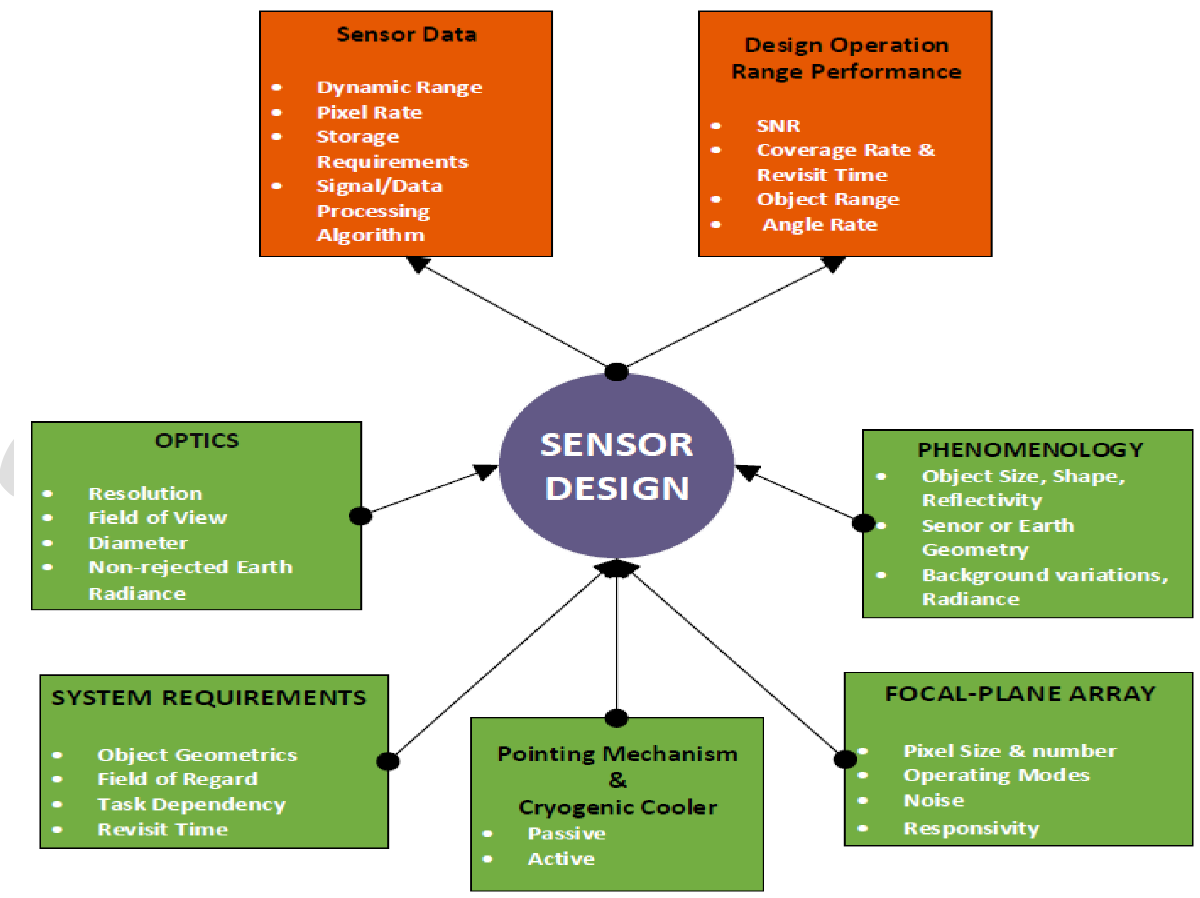

Fig. 6.Sensor Design Criterion