Spacecraft technology

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This paper presents a summary of the efforts at ISRO for the development of spacecraft technology over the past three decades and also outlines technological trends for the evolution of communication space platforms, as well as scientific and remote sensing satellite systems. Tracing the developmental efforts since Aryabhatta, the first Indian satellite, through the experimental phase of application-oriented remote sensing and communication satellites namely Bhaskara-I, Bhaskara-II and Apple, the state-of-art operational INSAT and IRS series of satellites are presented. The communication satellite platforms namely I-1K, I-2K, I-3K and I-4K with lift off masses in the range of one to four tonnes, power generation capabilities of 1 kW to 10 kW and more, meeting multifarious requirements of telecommunication, telecasting, DTH (Direct to Home TV) multimedia applications and meteorological services have been developed. The improvements derived from the usage of multijunction solar cells, lithium-ion batteries and other mass optimization techniques are passed on for larger payload compliment and longer life. Technological trends in the design of communication payloads and the advancements in key elements such as antennas, microwave power amplifiers and receive systems as well as spacecraft mainframe are discussed. Commercialization of developmental efforts in the form of design, building and commissioning of communication satellites for the international service providers are highlighted in brief.

Keywords: Astrosat-I, Chandrayaan-I, bent-pipe, multispectral, panchromatic, spacecraft technology, transponder

THE launch of the first man-made satellite Sputnik by the then Soviet Union, five decades ago, heralded a new era of space exploration. Spectacular advances have been made since then, leading to utilization of outer space for enhancing the quality of life on earth, in addition to scientific investigation and planetary exploration. Space-based services such as telecommunication, television broadcasting, weather forecasting, navigational assistance, management of natural resources and natural disaster situations have now become essential elements in our life. Personalized multimedia services are also in the offing. Central to these developments and also to the exploration of outer space is the development of spacecraft, which can withstand the rigors of space environment and provide cost effective, flawless services for years. The spacecrafts have to be essentially optimized for minimizing mass, volume and power, but with high performance, reliability and longevity. Considerable progress is achieved over the last few decades in the design of space platforms through the use of new lightweight composite materials and alloys, miniaturized electronics and computer-aided design and analysis techniques and also, better understanding of outer space environment. This coupled with cost effective and increased space transportation capability has brought benefits of space to the common man.

Spacecraft development efforts in ISRO were initiated as early as four decades ago. Initial learning efforts culminated in the successful realization of Aryabhata[1], a scientific satellite carrying celestial X-ray, solar neutron, gamma and ionosphere experiments, with a modest power generation capability of 40 W and weighing about 360 kg. The Aryabhata Project was a crucial learning tool that provided lessons on the design of light weight platform structure and its flight qualification, passive thermal control, spin stabilization with cold gas control, solar power generation, storage and conditioning, attitude control, telemetry, telecommand, payload data handling/storage and RF links as well as ground reception and data dissemination. It also provided opportunity to develop expertise in the field of project management, system engineering, system integration and space system quality and reliability assurance, in addition to development of expertise in subsystem designs. With this backdrop, ISRO entered into what is now recognized as an experimental phase of application-oriented spacecraft development in the early eighties of the 20th century, with remote sensing and communication as thrust areas in view. Bhaskara-I, the very first experimental remote sensing satellite as well as its follow on satellite Bhaskara-II[2], carried slow scan video cameras with 1 km resolution and a passive microwave radiometer in K-band. A payload opportunity available on experimental Ariane launch vehicle flight of European Space Agency (ESA) was utilized to build India's first communication satellite, Ariane Passenger Payload Experiment (APPLE)[3]. APPLE provided opportunity to introduce state-of-the-art technologies of the day, such as momentum biased three-axis stabilization techniques, motor driven deployed solar array, earth sensing for altitude control, C-band transponder design, inclusive of composite reflector, orbit raising, station acquisition, station-keeping and a host of mission management and flight dynamic techniques.

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The multipurpose Indian National Satellite INSAT-1 procured as per ISRO design and indigenous Indian Remote Sensing Satellite IRS-1A, ushered in the operational era. INSAT-1 with 12 transponders in C-band for Fixed Satellite Services (FSS) and 2S-band transponders for TV broadcasting and a Very High Resolution Radiometer (VHRR) providing visible and infra red imageries for meteorological applications, established operational capabilities for communication and broadcasting, weather data collection and dissemination and satellite control. IRS-1A[4] on the other hand, established a whole gamut of natural resources management system through optical remote sensing that required image data collection, processing, categorization, product generation, dissemination, user-oriented application development and user agency co-ordination. The second generations Indian National Satellites (INSATS) were totally developed indigenously, retaining the multipurpose capabilities of INSAT-1, but enhancing the overall throughput and capacity in terms of number of transponders and spectrum and also the resolution of visible and infra red imageries of VHRR. It also introduced a new upper extended C band for Very Small Aperture Terminal (VSAT) applications.

Over the last two decades ISRO has been providing through second and third generation of INSAT and follow on IRS satellites, operational services meeting communication, broadcasting, meteorological, natural resource management, agricultural produce estimation, forest mapping, arid area delineations, flood mapping and disaster management requirements.

The scientific satellite development since Aryabhata has grown both in terms of sophistication, complexity and capability through the intermediate phase of Rohini and Stretched Rohini programs and has now embarked on a mission to moon and exclusive state-of-the-art satellite for astronomical observations. ISRO aided development of small satellites at the Universities (e.g. Anusat at Anna University) is also on the anvil. A number of international agencies such as NASA, ESA, have shown active interest through utilizing the opportunities available in Chandrayaan-1 (Moon mission) and Astrosat for their scientific payloads.

ISRO's communication satellite buses namely I-2K and I-3K have attracted a number of satellite manufacturers and operators all over the world, resulting in fruitful commercial ventures, also.

The space environment

The spacecraft configured and designed for any specific purpose at Low Earth Orbits (LEO) or at Geostationary Equatorial Orbits (GEO) has to operate in an environment characterized by[5]

- Absence of atmosphere
- Weaker gravitational and magnetic fields.
- Hostile charge particle/radiation effect.

Further, the satellites operating at GEO have to weather the geomagnetic storms, caused by intense solar activity, solar flares and also micrometeorites. During geomagnetic storms, the increased electron flux impinging on the satellite can cause electrostatic charging of exposed surfaces to as high a level as 20 to 30 kV, leading to surface degradation, charge blow off, scintillations resulting in severe degradation and malfunctioning of the onboard equipments. Similarly, the LEO polar satellites, while passing over the auroral region may encounter deleterious effects of particle and electromagnetic radiations.

The satellites have to work in vacuum. This means the advantages of thermal convection are not available. Moreover, the surfaces exposed directly to the Sun get heated and those in the shadow or not facing the Sun, see the space temperature and become very cold.

During the launch the spacecrafts have to endure

- Depressurization
- Acceleration
- Vibration and acoustic loads.

The launch and space environment have considerable influence on configuration and design of satellites and their subsystems[6].

Communication space platforms

Communication and access to information play an important role in our everyday life. Traditionally, these requirements are met by the terrestrial radio, television and telephony services, which concentrate on providing these services to the metropolitan and urban parts of the country only. Communication requirements of India with its vast land mass and diverse cultural traditions cannot be met with terrestrial networks alone. Indian space programme realized this way back in 1970s and initiated the development of space-based communication system, which meets the national requirements. This called for development of communication space platforms and adequate infrastructure on ground to control and utilize the capabilities of these platforms. Communication applications have been discussed in detail in Bhaskaranarayan *et al*. (this issue).

Space-based communication system

Figure 1 shows a typical space-based communication system. The overall satellite network architecture consists of space and ground segments, in which space segment is one or more satellites, while the ground segment consists of User Terminals (VSAT or USAT), Gateway Terminals or Hub, Network Operations Center (NOC) and Satellite Management Center (SMC). Three key elements that define network architecture are the network topology, data rates supplied and multi-user access scheme. Over the years, various network topologies and architectures for satellite-based communication system have been developed. Some of the most commonly used architectures in vogue are wide area bent pipe, spot beam bent pipe and onboard processing architectures[7].

Wide area bent pipe architecture: This is the most traditionally used system in C and Ku band networks and uses fixed assigned star topology. In the star topology, all user terminal communications go through a hub and user-to-user transmission involves two satellite hops. This architecture is shown in Figure 2. Bent pipe payload simply receives and transmits signals from the same beam's coverage area. Because of wide area coverage user terminals, hub and operation centre can communicate with each other via satellite.

Spot beam bent pipe architecture: This takes advantage of possible frequency reuse and employs pre-assigned star topology. Ground elements within the same beam can communicate to each other via satellite. However, ground elements, which do not reside in the same beam, cannot communicate with each other via satellite and significant ground infrastructure is required to interconnect them. Gateway or hub is required in each spot beam to provide user access. For inter-beam user services, all the hubs are interconnected via terrestrial network.

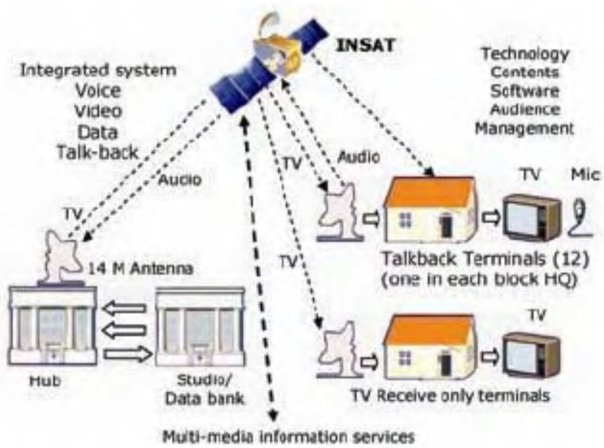

Figure 1. Space-based communication.

Onboard processing architecture: Onboard processing provides onboard inter-beam connectivity allowing hubless user-to-user communication via satellite and is advantageous for demand assigned mesh topology networks. The capacity of resulting network is larger than the bent pipe as a result of the frequency reuse without a terrestrial infrastructure. Onboard processing eliminates the inherent disadvantages of bent pipe transponders. Overall C/N0 is independent of uplink C/N0 in regenerative transponder. This reduces the uplink Effective Isotropic Radiated Power (EIRP) requirement by 5–6 dB resulting in reduction in size and cost of ground terminal compared to bent pipe transponder. Onboard processing can efficiently utilize resources by assigning fractions of transponder bandwidths to different coverage areas and has more operational flexibility.

Processed and demodulated uplink signals are routed to the destination beam in a preset and reconfigurable fashion by circuit switching if traffic is fairly stable and concentrated. When traffic is bursty and unpredictable, switching of the packets of fixed or variable sizes based on asynchronous transfer mode (ATM) or statistical multiplexing uses system resources effectively. Circuit switching and packet switching architectures are pictorially shown in Figure 3 and Figure 4 respectively.

Space segment development

Communication spacecraft architecture consists of spacecraft bus and payload system. Payload segment provides the required service, whereas the spacecraft bus provides necessary support for the payload to be operational in orbit. Presently, communication satellites are employed to provide TV broadcasting, radio networking, trunk telephony and

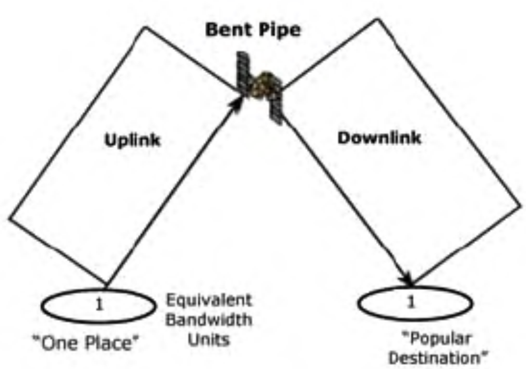

Figure 2. Wide area bent pipe architecture.

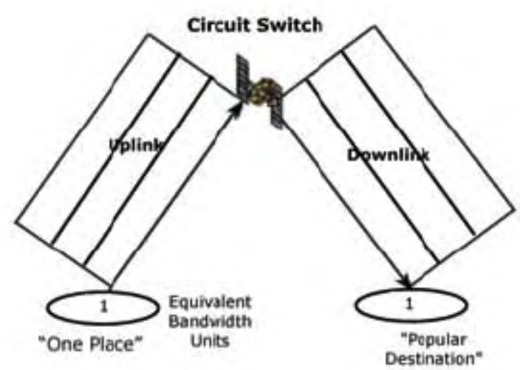

Figure 3. Onboard processing architecture (circuit switching).

networking of VSAT systems. The most preferred spectrum resources are C and Ku-bands. There is shift in global telecommunications from voice-driven to video-driven and data-driven services and from analogue to digital broadcast services. Figure 5 shows the global growth of satellite usage in the next few years and significant increase in the transponders usage for the Internet[8].

ISRO space segment development: Over a period of time, satellite communication development in India went through experimental to developmental to operational phases and has presently reached the commercial phase.

Indian communication space segment development started with the initiation of experimental APPLE spacecraft (Figure 6), which was launched in 1981. The payload consisted of two C-band transponders with TWTAs in the high power stage for providing 31.5 dBW effective isotropic radiated power (EIRP) over India. The realization of APPLE satellite gave first hand experience in the development of geo-synchronous satellite technology. The satellite weighed 670 kg, with a power generation capability of 210 W and provided service for a period of two years.

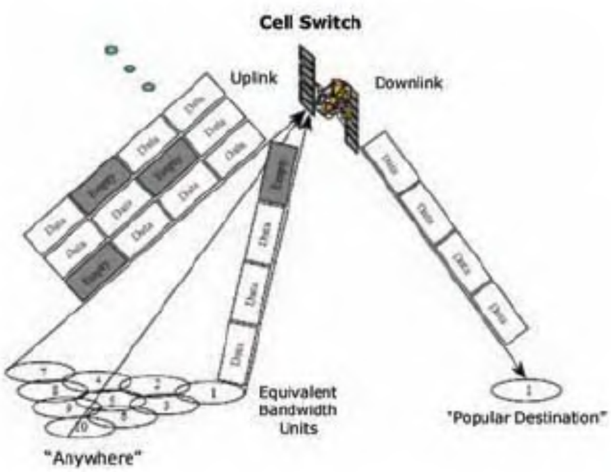

Figure 4. Onboard processing architecture (packet switching).

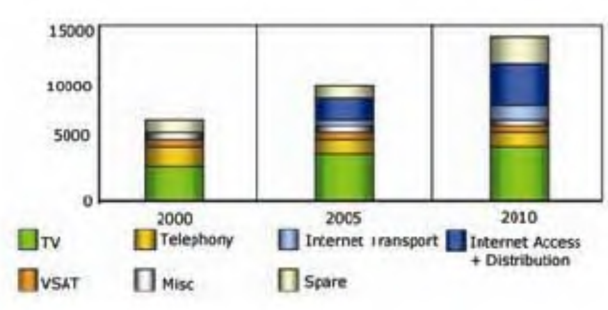

Figure 5. Utility of equivalent 36 MHz transponders.

The Indian National Satellite System (INSAT), one of the largest domestic/national satellite systems in the world[9], was conceived in 1970s. Ford Aerospace Communication Corporation (FACC) built the INSAT-1 series satellites. INSAT-1B, which became operational in mid-1983, was the first operational satellite in this series and it provided telecommunication, TV broadcasting, radio networking, weather observation and forecasting services.

The second and subsequent generation satellites were designed and built indigenously. The INSAT-2 series[10] was conceived with five spacecraft INSAT 2A to 2E, with the first two, INSAT 2A and 2B planned to be realized as multipurpose satellites on the lines of the INSAT-1 system. To meet the user community demands, the next two satellites[11], INSAT 2C and 2D were reconfigured as exclusive communication satellites. Figure 7 and Figure 8 depict INSAT-2A/2B and INSAT-2C/2D satellite configurations respectively. INSAT 2E satellite, the last of the second generation INSAT 2 series was evolved as the forerunner for the future INSAT-3 bus. INSAT-2E offered 17 communication transponders with near hemispherical and zonal coverage in addition to 3-channel VHRR and CCD camera payload providing improved resolution in both visible and infrared bands. Figure 9 gives footprint of INSAT-2E dual gridded wide beam antenna coverage.

INSAT-3 series comprising five satellites, INSAT-3A to 3E and was configured with a mix of multipurpose as well as dedicated communication and advanced meteorological satellites employing C, EXT-C and KU band transponders. INSAT-3D carrying state-of-the-art advanced 6-channel imaging and 19-channel sounding system is scheduled for launch in 2008. Figure 10 depicts INSAT-3A satellite.

Figure 6. APPLE spacecraft configuration.

INSAT-4A/INSAT-4B are identical satellites configured with high power Ku-band payload for DTH services and C-band payload for conventional applications.

Over the last two decades the capabilities of ISRO satellites have grown considerably in terms of power generation, service variety, service content and outreach, as well as service quality through INSAT-1 to INSAT-4 satellite series. Spacecraft power has grown from 1 kW to 6 kW (6 times), number of 36 MHz transponders has increased from 12 to 36 (three times) per satellite and satellite design life has increased to 15 years from 7 years (two times). The evolution of spacecraft power and mass trends over the years for ISRO satellite is depicted in Figures 11 and 12.

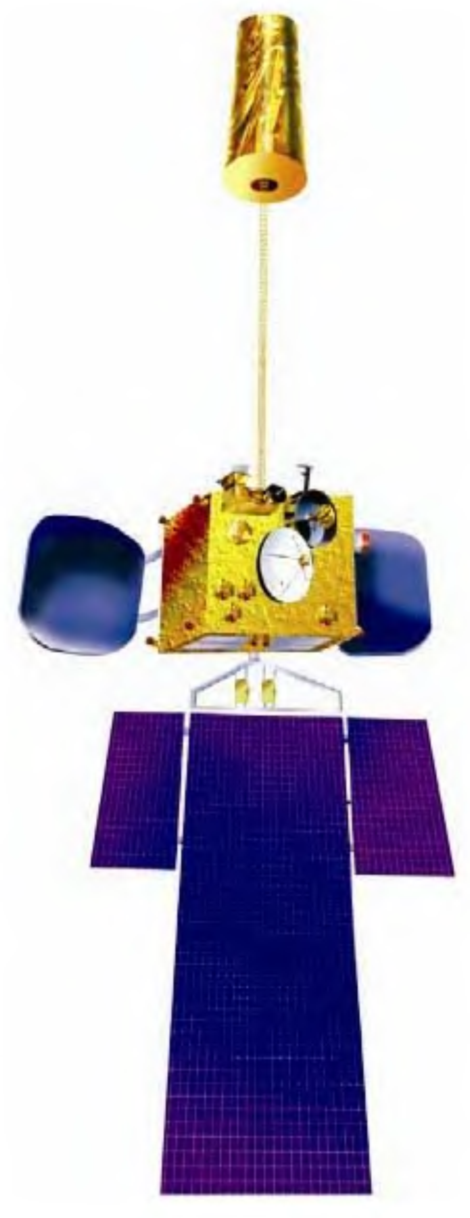

Figure 7. INSAT-2A/2B spacecraft.

Payload technology development: (i) Communication payloads[13] – A typical payload system[12] consists of antenna and repeaters. The antenna system is responsible for providing adequate coverage over the service area and meeting RF power requirement at the ground-receiving terminal. The repeater ensures reception, frequency translation, channelization and amplification of all the signals. The payload operating frequency band is finalized based on orbital slot after co-ordinating with other users as per international norms. Typical frequency plan and corresponding block schematics for INSAT-4C communication payload with twelve channel Ku-band transponders are furnished in Figures 13 and 14 respectively.

Table 1 gives evolution of ISRO payloads over the years. The improvement seen in major payload performance parameters is depicted below:

Figure 8. INSAT-2C/2D spacecraft.

Figure 9. INSAT-2E C-band wide beam coverage.

Figure 10. INSAT-3A satellite.

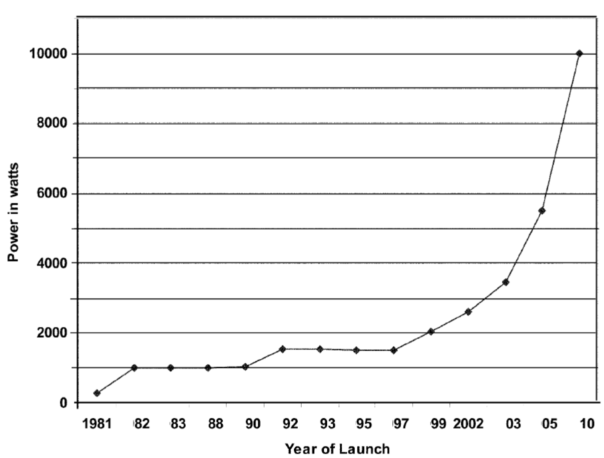

Figure 11. Satellite EOL power trend.

- EIRP has grown in C-band from 32 dBW over India coverage to 37 dBW over expanded coverage and in Ku-band from 42 dBW to 52 dBW over India coverage and 55–57 dBW over regional spot beam coverage.
- The figure of merit (G/T) has improved from –5 dB/degK to +1 dB/degK in C-band and from –2 dB/degK to +7 dB/degK in Ku-band.

(ii) Antenna technology – Evolution of antenna technologies at ISRO has started with the development of 0.9 M body mounted parabolic dish employing Carbon Fibre Reinforced Plastic (CFRP) technologies for APPLE. Subsequently, deployable CFRP reflectors operating over S, C and Ext-C band frequencies have been developed for second generation INSAT series satellites. Shaped reflectors targeting desired land mass coverage, avoiding energy spill over to the adjacent regions or sea are developed for third generation INSAT systems. For EDUSAT type applications and to meet higher EIRP requirements of DTH and broadband services, coverage area is split into a number of smaller zones, served by spot beams. The system capacity is increased by reusing the available spectrum, through optimum allocation of frequencies and polarization

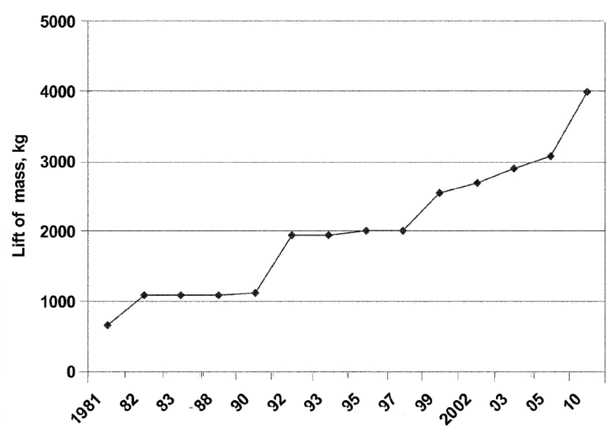

Figure 12. Spacecraft mass trend.

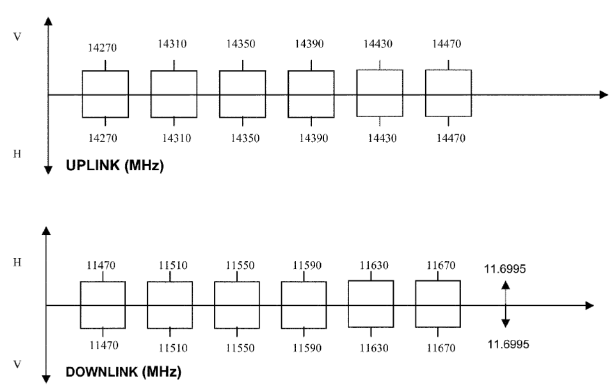

Figure 13. INSAT-4C frequency channelization plan schematic.

Table 1. GEOSAT payload evolution

Satellite	Payload band	Coverage	EIRP
INSAT-2A/2B	12 NOR-C	India	32 dBW
	6 EXT-C	India	32 dBW
	2 S-BSS	India	
INSAT-2C/2D	12 NOR-C	10 India	7CH 36 dBW, 3CH 32 dBW 36 dBW
	6 EXT-C	2 Expanded	2ICC 35 dBW, 4ICC 32 dBW
	3 KU	India	41 dBW
	S-BSS	Metro	42 dBW
	S-MSS	India	F-35 dBW R-30 dBW
INSAT-2E	12 NOR-C	Wide and Zonal	36 dBW
	5 EXT-C		36 dBW
INSAT-3A	12 NOR-C	Expanded and India	9 ECC 38 dBW, 3ICC 36 dBW
	6 EXT-C	India	36 dBW
	6 KU	India	46 dBW
INSAT-3B	12 EXT-C (Dual Pol)	India	37 dBW
	3 KU	India	45 dBW
	S-MSS	India	F-35 dBW R-30 dBW
INSAT-3C	24 NOR-C (Dual Pol)	India	36 dBW
	6 EXT-C	India	36 dBW
	S-BSS	India	42 dBW
	S-MSS	India	F-37 dBW R-35 dBW
INSAT-3E	24 NOR-C (Dual Pol)	India	36 dBW
	12 EXT-C (Dual Pol)	India	36 dBW
GSAT-2	4 NOR-C		36 dBW
	2 KU		42 dBW
	S-MSS		F-37 dBW R-35 dBW
GSAT-3	6 EXT-C	India	37 dBW
	6 KU	Spot and National	5 Spot 55 dBW 1 National 50 dBW
INSAT-4A/4B	12 NOR-C	Expanded	39 dBW
	12 KU (Dual Pol)	India	53 dBW
INSAT-4CR	12 KU (Dual Pol)	India	53 dBW

for the spot beams. Figure 15 depicts GSAT-3 (EDUSAT) Ku-band multi-beam antenna coverage. GSAT-4 Ka-band India coverage using eight conjugate spot beams with frequency reuse is being realized through a novel design of 2.2 m × 1.6 m shaped segmented multi-beam trans-receive reflector.

Planar Array Antenna (PAA) gives higher gain with lower mass and overall lower volume. A 550 × 550 mm PAA with 16 × 16 radiating elements was flown in Kalpana-1, a dedicated meteorological satellite.

(iii) Transmit receive technology – As depicted in Figure 14, transmit-receive chain consists of input filters, receivers, low noise amplifiers, demultiplexers, switches, driver amplifiers, power amplifiers, multiplexers and output filters.

(iv) High power amplifiers – APPLE and INSAT-1 series satellites employed 4W C-band Travelling Wave Tube Amplifiers (TWTAs), whereas the second generation satellites, INSAT-2 series of satellites used 4 W to 10 W C-band Solid State Power Amplifier (SSPA) for similar applications. To provide improved Effective Isotropic Radiated Power (EIRP) for the extended coverage as required in INSAT-2E and INSAT-3 series satellites, higher power SSPAs (15 W to 19 W) and TWTAs (32W/63 W) were used in C-band. To meet DTH service requirements 140 W Ku-band TWTAs are used in high power stage in INSAT-4 series. TWTA amplifiers can provide high power levels at higher frequencies with much better efficiency and reliability. Indigenous developmental efforts in this vital area initiated at Centre for Electronics and Engineering Research Institute (CEERI), Pilani and Bharat Electronics Ltd (BEL), Bangalore have culminated in successful realization of 60 W C-band and 140 W Ku-band TWT. They will be flown in the forthcoming satellites. Indigenously developed 140 W Ku-band TWT by ISRO, CEERI and BEL is shown in Figure 16.

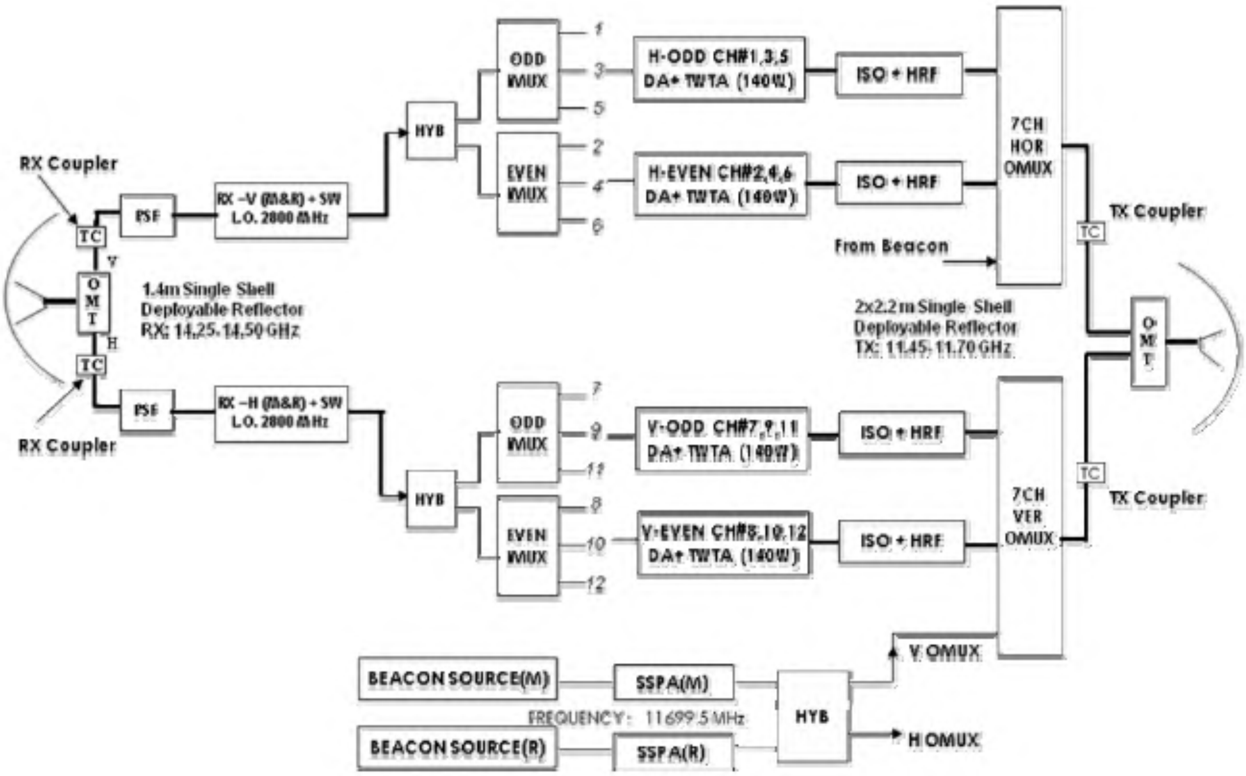

Figure 14. INSAT-4C communication payload block diagram.

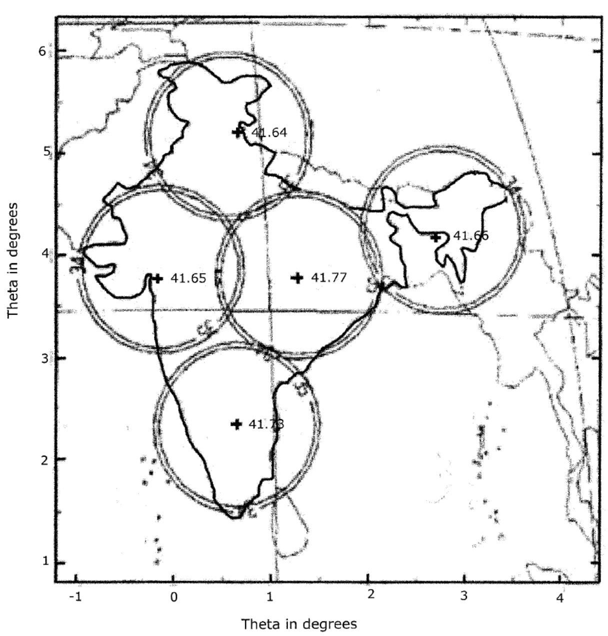

Figure 15. GSAT-3 Ku-band multibeam coverage.

(v) Receivers, filters and switches – Indigenously developed contiguous input and output cavity filters in the demultiplex (DEMUX) and multiplex (MUX) designs have been extensively used in all INSAT/GSAT series of satellites for channelization. Keeping pace with the state-of-the-art development in this crucial area, dielectric loaded resonating filters for DEMUX have been successfully flown in the GSAT3 and INSAT 4 series. Monolithic Microwave Integrated Circuit (MMIC) technology is being introduced in a phased manner in the forthcoming GSATs for realization of miniaturized receivers and channel amplifiers.

(vi) Meteorological payloads – Use of 3-axis stabilized platform from GEO enabled realization of compact VHRR capable of providing images in visible and Thermal Infra Red (TIR) regions of electromagnetic spectrum. The VHRR payload development involved realization of a whisk broom imager using eight inch reflective optical telescope, a passive cooler to cool down the mercury cadmium telluride detector to 105 K and a scan mechanism to provide bi-directional scanning. The INSAT-1 series imagers provided 2.75 km visible and 11 km TIR images. The second generation imagers were realized indigenously with improved spatial resolution of 2 km for visible and 8 km for TIR. This capability was further enhanced in INSAT-2E, Kalpana and INSAT-3A to imaging in three channels, viz. visible, TIR and water vapour channels.

Figure 16. Ku-band 140W TWT developed by CEERI and BEL.

Platform system technologies: Platform systems support the payload operation, protect and insulate payloads from launch environment, guarantee long mission life (>15 years) and are optimized to provide maximum possible resources for payload configuration. Payload demands significantly better performance from the spacecraft bus, in terms of requirement of higher DC power, higher heat rejection capacity, larger payload mounting area, increased antenna accommodation, stringent platform stability and larger life. The bus system also ensures that the pointing requirements of the payload are met.

(i) ISRO bus architecture – By keeping in view various national communications requirements, ISRO developed an array of communication spacecraft bus configurations, which cater to both in-house and commercial needs of ISRO. The standard bus configuration, presently operational or under development are I-1K, I-2K, I-3K and I-4K buses.

(a) I-1K Bus – I-1K bus is developed mainly to carry out geostationary imaging or communication missions with lift off mass of around 1100 kg and are compatible with the Indian PSLV launch vehicle. This provides a very cost effective way of launching a reasonably useful 100 kg payload to GEO orbit. KALPANA-1 spacecraft carrying VHRR payload is an example for this operational bus. Indian Regional Navigational Satellite System (IRNSS) series of satellites and Chandrayaan-1 mission are configured employing I-1K bus.

(b) I-2K Bus – I-2K bus is the workhorse for 2 t class INSAT/GSAT series of satellites and is primarily configured taking into account indigenous Geosynchronous Satellite Launch Vehicle (GSLV) capabilities and also compatible with most other commercial launch vehicles. With the spacecraft lift-off mass ranging between 2 and 2.3 tonnes and maximum payload mass of 300 kg, I-2K bus can support 12 years of mission life. I-2K bus is ideally suited for configuring satellites with payload power up to 2.5 kW and antenna size of 2.2 m in diameter. GSAT-2 and GSAT-3 (EDUSAT) satellites employing this bus are already providing operational services. INSAT-4CR, GSAT-4, 5, 6, 7, 9 and INSAT-3D are under realization with I-2K bus configuration.

(c) I-3K Bus – I-3K bus is the operational workhorse for realization communication satellites. With lift off mass in the range of 2.5–3.5 tonnes and payload mass in the range of 300–400 kg and maximum payload power of 4.8 kW, I-3K bus provides 15 years of mission life. Satellite operators have showed considerable commercial interest worldwide in this bus, for inducting satellites based on I-3K bus in their fleet. Six spacecrafts in this category namely INSAT-2E, 3A, 3C, 3E, 4A and 4B are operational. INSAT-4B was launched in March 2007.

(d) I-4K Bus – I-4K bus is presently under development and it is compatible with GSLV Mk-III launch vehicle, which is also under development by ISRO. With lift-off mass in the range of 4–4.5 tonnes and payload mass in the range of 450–550 kg and maximum payload power of 7 kW, I-4K bus will provide 15 years of mission life. The bus is being evolved incorporating the advanced technologies such as deployable thermal radiator panels, complex deployment mechanisms, electric propulsion and use of advanced materials.

A comparison of ISRO buses capabilities is given in Table 2 and a disassembled view of the spacecraft subsystems is given Figure 17.

(ii) Bus subsystem technologies[14]

(a) Structure – The primary functions of spacecraft structure are to provide mechanical support within the framework of spacecraft configuration, to satisfy subsystem requirements such as alignment of sensors, actuators, antenna, etc. to meet system requirements for launch vehicle interfaces, integration and tests and to survive all direct and cumulative static and dynamic load combinations occurring during fabrication, testing, ground handling, transportation, launch and orbit manoeuvres without permanent deformations.

Lightweight composite, high modulus fibre structures fabricated using purest form of carbon, achieves low mass to strength ratio. Carbon fibre reinforced plastic (CFRP) structures have already been flown in METSAT, GSAT-3 satellites and are planned for all the future INSAT/GSAT missions. Use of advanced materials to fabricate structures with better thermal and electrical conductivity properties, apart from the superior strength, stiffness and better hygroscopic properties are planned in the future. The spacecraft bus configuration is evolving to modular bus concept, where equipment panels which houses the payload, housekeeping and propulsion elements are modular in design and can be tested independently and integrated at a later stage. It is implemented for the first

Table 2. ISRO communication payload bus capabilities

Parameters	I-1K	I-2K	I-3K	I-4K
Mission	MET	COM/MET	COM/MET	COM
Lift off mass (kg)	1100	2300	3100	4500
Max. propellant loading (kg)	850	1400	1700	2400
S/C dry mass (kg)	500	900	1400	2100
Payload mass (kg)	100	250	300–400	450–550
Max solar power gen. (W)	1000	2800	6000	10000
Solar cell technology	Si/GaAs	Si/GaAs/MJ	Si/GaAs/MJ	Si/GaAs/MJ
Battery options	24 AH NiCd	70 NiH_2	100 AH Li–Ion (3)	160 AH Li–Ion(3)
Capacity/technology		40 AH Li–Ion	70 AH NiH_2 (3)	
		160 AH Li–Ion(2)		
Payload power (W)	550	2400	4800	7000
Date of 1st launch	12/9/2002	8/5/2003	3/4/1999	
No. of S/C in orbit	One	Two	Six	

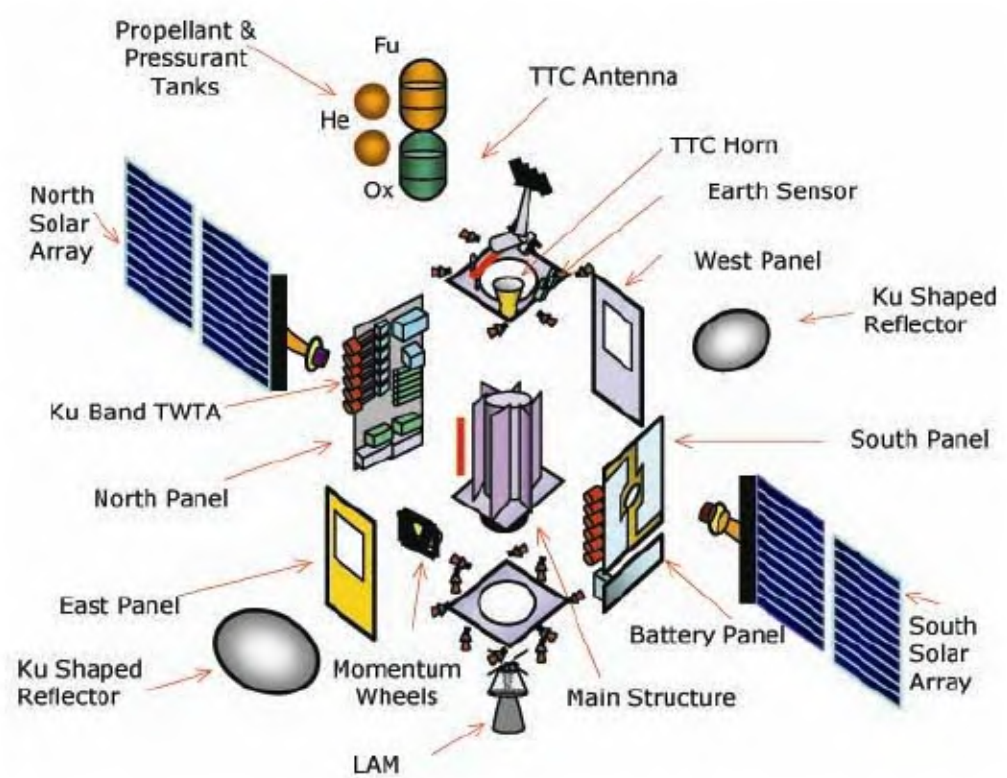

Figure 17. Disassembled view of spacecraft sub-systems.

time in INSAT-4B and will be followed from GSAT-5 onwards.

(b) Mechanism – Due to constraints of launch vehicle dynamic envelope, satellite appendages, such as antenna reflectors and solar array have to be in stowed condition during launch and need to be deployed, once the satellite is injected into the orbit as per the sequence of initial phase mission operations. Deployment mechanisms facilitate stowing of these appendages during launch through appropriate hold down and deployment in orbit through ground command.

Simple deployment mechanism concepts for solar array, with one panel on each wing in APPLE has been considerably innovated and matured to deploy lightweight, rigid solar arrays with three to four panels in each wing in what is now popularly known as accordion deployment scheme. The scheme has been successfully used for all the INSAT/GSAT series of satellites. Multipurpose satellites like, INSAT-2A/2B/2E and 3A use a remarkable, in-

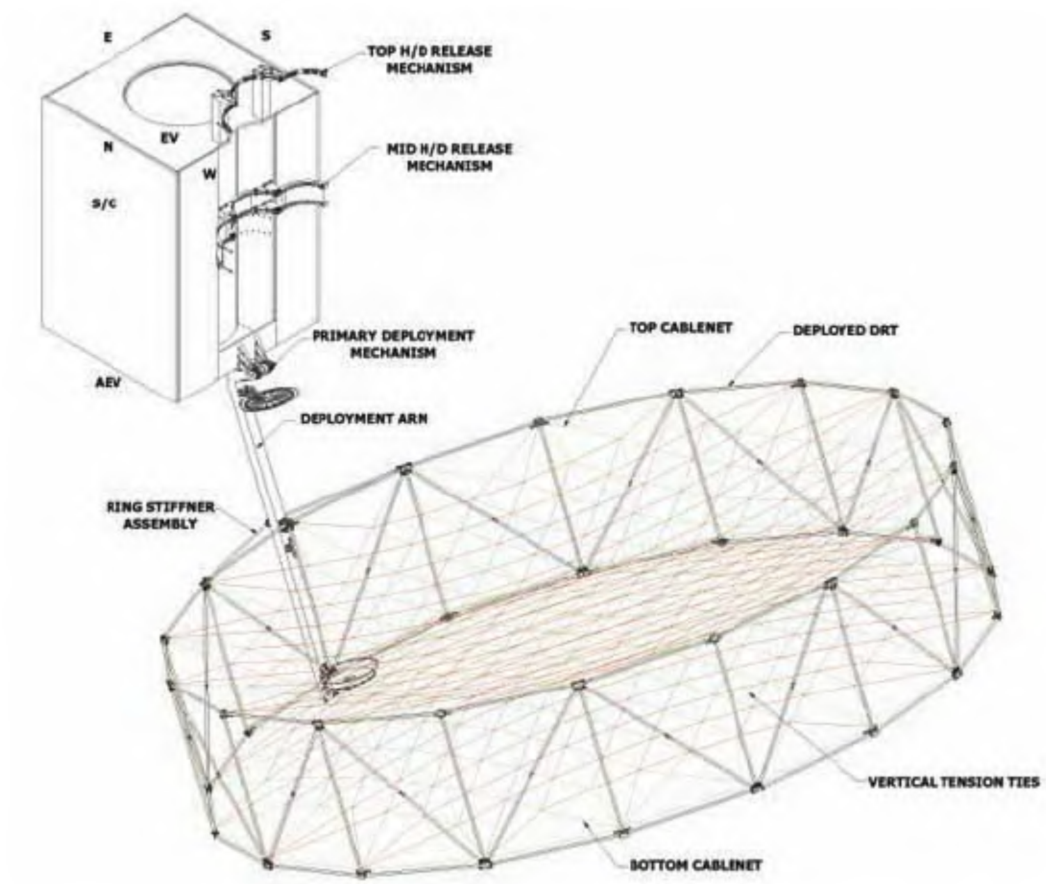

Figure 18. Unfurlable antenna for geo-mobile communication.

digenous development of solar sail and boom to compensate for the radiation pressure of south wing solar panels, without causing thermal heat input into the VHRR payload passive cooler. Deployment schemes of reflectors inclusive of shaped and dual gridded configurations are used in INSAT-2/3/4 series of satellites, handling increased reflector mass, complexity and finer pointing/coverage requirements. To meet the geo mobile communication requirements, large antenna of the size of 12 m or bigger is required to reduce the size of the ground terminals to a hand-held system. Such a large antenna has to be essentially an unfurlable one, with complicated deployment mechanisms. A 5.5 m unfurlable antenna with complex multi-stage deployment mechanism (Figure 18) is already under development and will be used in GSAT-6 spacecraft to provide S-band mobile multimedia services.

(c) Thermal control system – The primary functions of spacecraft thermal control system is to maintain temperature of bus electronics packages, batteries, propulsion components, IR detectors and payload elements, within the stipulated limits under varying diurnal and seasonal conditions of sun satellite geometry and heat dissipation within. Passive thermal control system for INSAT/GSAT series has been evolved using optical surface reflectors, multilayer insulating blankets and thermal heaters. Heat conduction to the radiator was done using a number of techniques, such as, heat sinks; conductive modular blocks were used in low power second-generation satellites.

Use of heat pipe network has paved the way for efficient conduction of heat to radiators in INSAT-3/4 series, high power satellites. Qualification of indigenous heat pipe development has enabled accommodation of higher payload power dissipation in I-2K series of satellites. Use of large unified dual core criss-cross heat pipe embedded panels to handle higher thermal radiation was done first in INSAT-4A. Use of high power radiatively cooled TWTAs employing fin or cone-type collectors is done in GSAT-3, INSAT-4A Ku-band transponders and in future spacecrafts. Heat radiation by use of Deployable Thermal Radiator (DTR) panels to increase heat rejection area and use of Reservoir Embedded Loop Heat Pipe (RELHP) system consisting of multiple evaporators within the payload panel; a condenser within the deployable radiator panel and vapour and liquid tubes connecting these elements capable of high heat transport capacity and dissi-

Table 3. Electric propulsion system applications

Orbit	Delta (v m/s)	Satellite mass (kg)	Thrust (mN)	Time	Power (kW)
GEO station keeping	50/year	2000–4000	20–200	2–6 h/day	1.2–2.5
HEO orbit control	100/year	2000–3000	10–250	3–6 h/day	2–2.5
GTO	5 k–15 k	5000–8000	100–2000	3–12 months	3–5
LEO-LEO orbit raising	20	300–1500	10–100	Weeks	0.5–1

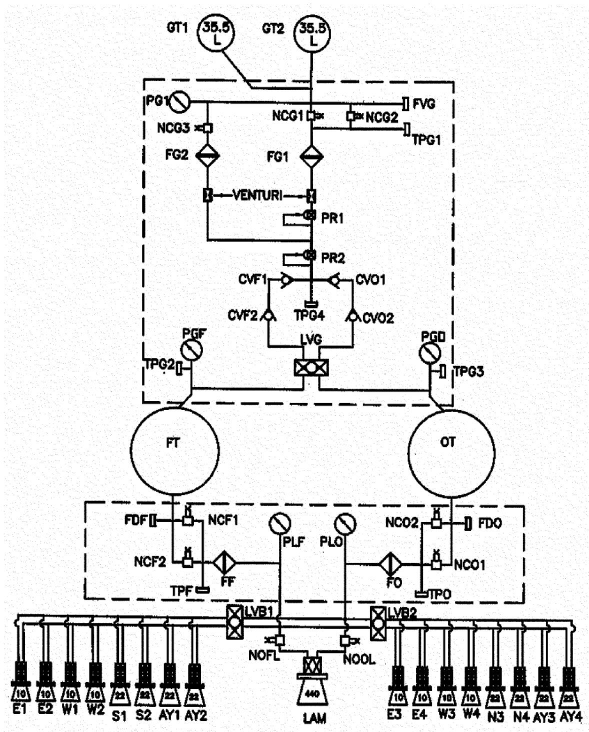

Figure 19. Bipropellant system block schematic.

Figure 20. GSAT-4 Hall effect thruster configuration.

pating few kilowatts of heat will be done in future broadband payload satellites.

(d) Propulsion system – Orbit raising, orbit maintenance and attitude control require specifically designed propulsion system that functions as per the control regime defined by onboard attitude and orbit control system. Experimental communication satellite APPLE employed solid booster for orbit raising from GTO to GSO and monopropellant hydrazine-based attitude control thrusters. INSAT-2 series onwards, indigenous unified bipropellant system has been used with liquid apogee motor (440N) and 22N/10N bipropellant thrusters for attitude control and station keeping purposes. R&D efforts for the realization of unified bipropellant system involved development of bipropellant LAM, 22N/10N thrusters, propellant tanks, pressurant tanks to hold helium at 250 bar pressure and host of latch valves, regulators, filters and transducers. Specific impulse (Isp) above 315 s for LAM and above 290 s for thruster has been achieved. Typical bipropellant system scheme is depicted in Figure 19.

Electric propulsion offers a cost effective and sound engineering solution for space applications. Use of high performance electric propulsion system (EPS) will result into reduced chemical propellant and tankage requirements, in exchange for significant usage of power. Electric propulsion thrusters are classified according to the mechanism of transfer of electric energy to kinetic energy into three broad categories of electrostatic, electromagnetic and electrothermal propulsion. Table 3 explains the applications of various EPS systems[15].

EPS is generally used for north–south station keeping operation. Since less than 5 m/s per year delta velocity needs to be imparted for east–west station keeping (EWSK), EPS system usage is not advantageous for EWSK, as overheads will negate the benefits. Similarly, use of EPS systems for orbit raising involves months of continuous operation and a very long wait to reach GSO, nullifying the advantage. However, this could be a backup option for conventional chemical propulsion. Two indigenously developed and two imported SPT will be flown on board GSAT-4 to cater for north and south station keeping operations. Figure 20 depicts GSAT-4 ion thruster configuration.

(e) Electrical power system[15] – Electrical power system provides regulated power to housekeeping subsystems and payload elements. It involves power generation, conditioning and management and storage for eclipse support.

Normally, power generation is achieved through solar power conversion into electrical power, using photovoltaic cell technology. As the spacecraft power requirement increases, higher power generation is desirable, without increasing the solar array size. Traditional single bandgap Si solar arrays are very inefficient in converting solar radiation into electrical power. Development of dual junction cells, with technique to dope layers of GaAs epitaxially on germanium substrate increases solar cell efficiency to 25%. Extensions of this process lead to design and fabrication of multi junction or cascaded cells. Arrays that stack three to four types using III–V compound materials, such as GaAs, GaInP, GaInAsP and GaSb have shown efficiencies of the order of 28–35%. Multi-junction/cascaded cells, with higher efficiency of the order of 27% are already in use in I-2K and I-3K buses of ISRO.

For total eclipse support, presently, NiH_2 batteries are used in the high power satellites. Li-Ion battery is a fastest growing technology and is being pursued to meet the larger eclipse power demand. It is mass and volume efficient and has wider temperature range of operation. Energy density of Li–Ion technology is 130 Wh/kg compared to 30–40 Wh/kg and 50–60 Wh/kg for NiCd and NiH_2 technologies, respectively. INSAT-4B uses 100 AH Li–Ion battery and GSAT-4 is designed with 36 AH Li–Ion battery for eclipse support.

In power electronics area, use of modular and scalable power generation architecture to suit power demands from 3 to 30 kW is being planned. Use of planar magnetic components and state-of-the-art radiation hardened MOSFETs achieves 96% efficiency for direct energy transfer. Higher bus voltage (70 V or 100 V as against 42 V) will result in reduction in bus current and power harness mass. All the INSAT/GSAT series of satellites use 42 V regulated bus. GSAT-4 will use for the first time 70 V bus for Ka-band payload.

(f) Attitude and orbit control system – Attitude and orbit control system (AOCS) consists of attitude sensors (sun, earth and/or star, inertial reference unit or gyros), control electronics and actuators (momentum and reaction wheels, magnetic torquer, bi-propellant thrusters, liquid apogee motor and solar flaps). AOCS design is based on body stabilized momentum bias system, employing momentum wheels in V configuration and reaction wheels in L configuration, as a backup. The overall platform stability is of the order of ±0.2 degrees in Pitch and Roll axis and ±0.4 degrees in yaw axis. Additional features like antenna beam pointing from inclined orbit operation up to 2.7 degrees to enhance spacecraft life by three years, as well as satellite manoeuvrability for payload in-orbit tests are also included in AOCS.

Use of miniaturized gyros, hemispherical resonating gyros (HRG), micro electromechanical sensors and multi-functional sensors is planned in the near future. Fast response sensors and actuators will be used to provide stable platform. Micro-machined optics for sensors to improve system performance multifold and control of satellite bus for improved jitter performance will be order of the day. Future system will use intelligent design with capability of on-orbit reconfiguration and modification to the soft-core architecture to support dynamic mission requirements.

(g) Telemetry tracking and command system – Telemetry, Tracking and Command (TT&C) system is configured to serve the requirements of spacecraft health monitoring through telemetry, commanding for control, tracking and ranging for orbit determination, during all the phases of the mission. Satellite parameters are monitored at 1 kb data rate in normal and/or dwell format. The dwell format facilitates super commutated sampling of specific parameters as required by the ground operations. Normal and dwell format are transmitted using 32 kHz and 128 kHz sub-carriers, respectively. The modulation scheme employed for telemetry transmission is PCM/PSK/PM. The telecommand system provides the link between the ground control and different subsystems on-board the spacecraft for decoding the command information and data for their operation. Telecommand system employs shortened BCH code for error-free command message reception. The command message consists of four command frames with 10 bit gap between the frames and 5-bit satellite address. The command bit rate is 100 bit/s. The modulation scheme employed for commanding is PCM/FSK/FM. ASIC based TT&C base band system is modular in design and the same basic system by enhancing or pruning can be used to meet requirements of I-1K to I-4K buses.

The TT&C RF system consists of telecommand receiver and telemetry transmitter operating in C-band. TT&C transponder is also used for tone ranging. The system is designed with omni directional coverage for telecommand and omni/global coverage for telemetry. TT&C system omni coverage is used during the initial phase mission operations in transfer orbit and under the loss of lock conditions in on orbit.

(h) Bus electronics technologies[13,15] – The AOCS, power and TT&C systems are designed with the extensive use of microprocessors, Applications Specific Integrated Circuits (ASICs), Field Programmable Arrays (FPGAs), Hybrid Micro Circuits (HMCs) and Micro Integrated Circuits (MICs). The basic designs undergo morphological changes periodically with availability of space qualified cutting edge device technologies. The technologies likely to be considered in the near future are:

- Low power CMOS devices
- Deep sub-micron ASICs
- High performance complex radiation hardened FPGAs
- Multi Chip Modules (MCMs)
- System On Chip (SOC)
- Micro Electromechanical Systems (MEMS)

Use of advanced technologies facilitates design of versatile, miniaturized bus management unit (BMU), employing 1553 bus for data transfer that combines functions of TT&C base band, AOCE and sensor electronics. Such a BMU is currently planned in GSAT-4 and INSAT-3D.

Remote sensing spacecraft

ISRO has established an operational Remote Sensing (RS) satellite system by launching its first satellite, IRS-1A (ref. 4) in March 1988, followed by a series of IRS spacecraft. The IRS-1C/1D satellites with their unique combination of payloads have taken a lead position in the global remote sensing scenario. Realizing the growing user demands for the 'multi' level approach in terms of spatial, spectral, temporal and radiometric resolutions, ISRO launched the Resourcesat-1 satellite in 2003 as a continuity mission with enhanced capability. These series of spacecrafts provided valuable data for various applications covering the land features. The Oceansat-1 mission launched in 1999 with an ocean colour monitor and a microwave radiometer catered to ocean and meteorology-related applications. The technology experiment satellite with the novel concept of step and stare imaging and Cartosat-1 with 2.5 m resolution stereo imaging capability, enhanced the cartographic and strategic application potential. Cartosat-2 launched on 10 January 2007 is a highly agile satellite with a PAN camera providing images with less than 1 m resolution. This mission will provide spot imaging using 'paint-brush' coverage for any given area of interest.

Figure 21 shows the evolution of ground resolution since 1988. A dedicated satellite for climate/atmosphere research and applications called MEGHA-TROPIQUES (scheduled for launch in 2009) will study the oceanic winds, humidity profile, liquid water, clouds, ice-clouds and radiation budget over the tropics. Commensurate with the ever increasing demands from the user community for higher spatial, radiometric, spectral and temporal resolutions, new technologies are being evolved for the remote sensing platforms – both in the areas of payload instruments and mainframe systems. Though the requirements of small satellite bus for specific scientific missions are growing all over the world, operational RS missions prefer medium/large spacecraft platforms to accommodate multiple payloads to meet their objectives. Hence, it is very essential to evolve technologies to minimize weight, volume and cost for the realization of such missions.

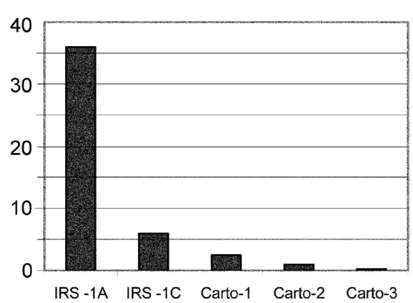

Figure 21. Ground resolution of IRS missions.

Payload instruments

As the science of remote sensing encompasses a wide range of the EM spectrum, from visible wavelength to millimeter waves, it calls for technology developments in diversified fields like optics, sensors/detector arrays, thermal control elements like coolers, antenna arrays, high power and low noise microwave devices, high speed analogue and digital electronics, etc. A brief review of these technologies is given in the following paragraphs:

Electro-optical payloads: The Earth Resources Technology satellite (later named as LANDSAT) launched in 1972 was the first RS satellite, which has set in motion the development of RS technology all over the world. It carried a multi-spectral scanner (MSS), providing a resolution of 83 m in 4 bands in VNIR. This was followed by a series of seven spacecrafts (till Landsat-7). From Landsat-5 the thematic mapper replaced the MSS with 7 spectral bands covering VNIR–SWIR–TIR channels. All these instruments adopted the electro-mechanical 'whiskbroom' scanning with a 410 mm aperture Ritchey-Chritien (RC) telescope and a scan mirror in conjunction with discrete detector elements (photo-diodes) in the split focal plane. In spite of the '*less*' reliable electro-mechanical components, Landsat series provided voluminous data of the entire globe, during the last three decades.

With the advent of the solid state Charge Coupled Device (CCD) imaging technology in late seventies for commercial business applications, the RS community quickly adopted these devices and evolved the 'push broom' scanning systems. This has resulted in a dramatic reduction of weight of the camera system by a factor of ~2–3, in addition to volume and power reduction. Most of the subsequent international RS missions, including Indian Remote Sensing (IRS) and French SPOT satellites used CCDs in their payloads. With the advances in photo lithographic techniques, the pixel dimensions could be reduced, thereby increasing the array length resulting in improved spatial resolution, still with wider swath. For example, CCDs with 13 microns pixel and 2K elements were used in the first IRS-1A/1B missions as against 7 microns pixel with 24 K elements that are available now. Presently, the CCDs are developed as linear and area array devices, including the Time Delay Integration (TDI) devices covering VNIR and SWIR range. Extending this technology to cover thermal IR channels with integrated focal plane cooler is under development. In the area of imaging optics, the basic trade-off between reflective and refractive (or a combination of both) optical systems is done, based on the parameters like orbit, ground resolution, type of detector, focal length, aperture, SNR, etc.

The optical systems realized for the IRS series of spacecrafts make use of refractive, reflective and a combination of both. The use of individual refractive optics for each multi-spectral band enabled optimization of payload radiometric and geometric performance as each band refractive optics could be designed without imposing on it the design requirements of other spectral bands. Individual refractive optics for a spectral band was used in all payloads like LISS1, LISS2, LISS3, WiFS, AWiFS and OCM. Use of refractive optics in OCM with tele-centric design enabled realization of a very large FOV (86 degrees) by using an aspheric first element. While refractive optics enabled realization of medium spatial resolution multispectral images, use of reflective optics was made for high resolution imaging systems. Realization of high resolution images requires long to very long focal lengths which along with the requirement of sufficient photon energy collection demands use of a large collecting apertures and larger spectral bandwidths. By its very nature refractive optics performance is sensitive to wavelength because refractive index of the material is a function of wavelength. This property is used in the optical design to compensate for chromatic aberrations. As refractive optical systems require light to travel through the bulk of the material, these factors impose a severe constraint on use of large aperture refractive optics as it becomes essential for the bulk transmission characteristics of the material to meet the stringent performance demands over a large aperture. Reflective optics overcomes the problems of wavelength-dependent performance as reflective optics does not make use of bulk transmission properties of base material. As the optical aperture grows beyond about 150 mm, one usually switches over to reflective systems. Reflective optics usually has limited FOVs restricting the realizable swath from a given satellite altitude. Design of compact telescope using unobscured three mirror aspheric optics to overcome this limitation was one of the major technological developments which enabled ISRO's remote sensing data from IRS-1C and cartosat 1 to make its mark as a source of international data. As the focal length increases further, the use refractive corrector elements to increase the field of view of telescopes requires refractive correctors and such systems have been developed for TES and carto-2 series.

Development of optics with excellent image quality over a wide field-of-view under severe space environment is a real challenge. Recent developments in the optical glass materials, precision mechanical fabrication equipments, space qualified adhesives and alloy metals with matching thermal co-efficient of expansion made it possible to realize precision imaging lenses. With the latest optical design optimization software, it is possible to miniaturize the refractive systems (a 12-band ocean colour monitor can be realized with a mass of <20 kg.). For large size reflective optics using Zerodur materials, light weighting up to 60% has been achieved by scooping the glass. Future systems will use silicon carbide and other such materials with high stiffness and lightweight properties. Cartosat-3, the next generation IRS satellite with 0.25 m resolution will use 1.2 m optics with 60% of weight removal. Use of adaptive optics, acousto-optical devices, in-orbit focusing using MEMs, large area-light weight mirrors is envisaged in future missions.

The availability of high-speed devices has significantly compacted the signal processing electronics so as to handle large CCD/TDI arrays data, efficiently. Using devices like FPGAs, ASICs and single chip analogue and digital signal processors, the camera electronics size and weight are shrunk and is a part of the electro-optics module. Further developments to integrate the processing electronics as a part of the Focal Plane Array (FPA) are under way. The design of payload camera structure is evolved with new materials and optimized weight/stiffness ratio. From aluminum-welded structures used in earlier IRS missions, the technology developments enabled to use light weight composite materials for Cartosat and future missions. Figure 22 shows the improved efficiency of the IRS payloads (ratio of mass per unit ground resolution) over the last two decades.

Microwave and millimeter wave payloads: Owing to their inherent advantages of all-weather operability and usefulness for study of global meteorological/atmospheric parameters, the demand for microwave RS instruments is steadily increasing. Though NASA has demonstrated the capabilities of microwave instruments for various applications through their SEASAT mission as early as in 1978, it took considerable time for other countries to embark upon this technology till ESA launched ERS-1 in 1991. Microwave Instruments are classified as active (synthetic aperture radar, altimeter, scatterometer, etc.) and passive (radiometers, sounders). ISRO has flown a 3-channel (19, 22 and 31 GHz) radiometer called 'SAMIR' on-board the Bhaskara-I and II satellites in 1979 and 1981 for the study of atmospheric water vapour/liquid water content over the oceans. This was followed by the Multi-frequency Scanning Microwave Radiometer (MSMR) flown on-board Oceansat-1 satellite in 1999. MSMR was a four-

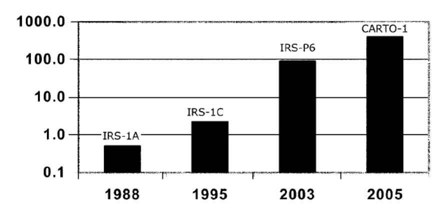

Figure 22. Improvements in payload efficiency (mass/resolution).

channel (6.6, 10.6, 18 and 21 GHz) dual polarization radiometer, useful for estimation of sea surface temperature, cloud water content and ocean surface wind magnitude. Presently, a Ku-band (13.515 GHz) pencil beam scatterometer is under development to be flown on-board the Oceansat-2 satellite. This will provide data on global scale wind vector fields over oceans.

Also, a C-band synthetic aperture radar with <3 m resolution is being developed and will be flown on the Radar Imaging Satellite. Development of advanced millimeter wave payloads, like synthetic aperture radiometer, atmospheric temperature and humidity sounders is being taken up. The major technology developments for these instruments include large area planar antenna arrays, high power pulsed transceivers, low noise amplifiers and receivers, down converters, corrugated horns, long life and stable electro-mechanical scanning motors, heat pipe embedded substrates, ground calibration systems and software tools for geo-physical model development, data validation, etc. Remote sensing applications have been discussed in detail in Navalgund *et al.* (this issue).

Remote sensing satellite bus elements

While the design of spacecraft for IRS series has many commonalities with the one for INSAT series there are many crucial differences. Both platforms are required to be 3-axis stabilized and earth-oriented with stringent attitude control to enable imaging from the optical sensors onboard the platform. Global remote sensing data collection demands polar orbit as against an equatorial orbit for INSAT. The geometrical relation, between observing instrument viewing axis on the satellite platform, the ground feature and sun, the source of illumination, plays a very major role in remote sensing observations. This requires using sun synchronous orbit with suitable choice of equator crossing time. The spacecraft subsystems have to be designed for an entirely different set of constraints encountered in equatorial geostationary orbit and polar sun synchronous low earth orbit. While the communication link for the geostationary satellite enables 24 × 7 access to spacecraft from ground station for the INSAT, the IRS series spacecraft subsystems have to cater to limited durations of communication between ground station and spacecraft. While the INSAT series of spacecraft AOCS has to grapple with the demands of moving the satellite from geostationary transfer orbit to the specified geostationary orbit and station keeping manoeuvres to keep the satellite from moving away from its designated longitudinal location and inclination, the LEO IRS AOCS has to meet the demands of frozen perigee and tight ground track control to enable repetivity demands of operational remote sensing.

Commensurate with the improvements in the payload instrument technology, the spacecraft mainframe systems also need to be evolved to support the payload function. The major thrust areas are light weight structures, high efficiency power systems, high speed data handling and storage systems, intelligent on-board processing architecture to achieve autonomy, highly stable and agile platforms, thermal control for high power dissipation elements, etc.

Structure: Continuing efforts of developing light weight composite structural materials for the satellite bus and the payload platforms resulted in significant weight reduction in realizing the 600 kg agile satellite – Cartosat-2 (Figure 23). The structural mass has reduced from 16% in IRS-1A/1B to about 10% in Cartosat-2.

(i) Electrical power system – Power generation on IRS satellites has seen migration from single junction solar cells to the multi junction and gallium arsenide cells with higher efficiencies thus improving the power/weight ratio of the solar panels. For example, in IRS-1A the power/eight ratio were 18.4 W/kg using Silicon cells compared to 41 W/kg in RISAT using triple-junction cells. Development of thin film solar cells/panels is in progress. In the area of power storage, nickel–cadmium batteries of a wide capacity range (18–40 AH) were used in IRS spacecraft. To meet the high power requirements, lithium–ion and nickel–hydrogen batteries are being planned to be used in the future missions like Chandrayaan-1, RISAT and Meghatropiques.

(ii) Thermal control system – Significant developments took place in the area of the thermal control system. Precise thermal control of large payloads within narrow limits calls for detailed analysis of a mathematical model with large number of nodes[16] (about 450 in IRS-1A as against ~2500 in Resourcesat). The use of thermo-electric cooler to cool the star sensor CCD detector and the short wave infra red detector of the imaging payload and the

Figure 23. Deployed view of Cartosat-2.

Table 4. Types of attitude sensors flown in IRS missions

Sensor type	Attitude measurement accuracy (degrees)	Sensors/ spacecraft	Heritage
4π sun sensor	1.0	4	All IRS S/C
Fine sun sensor	0.5	1	IRS-1A/1B
Precision yaw sensor	0.2	2	IRS-1A/1B
Digital sun sensor	0.125	2	IRS-1C/1D
Conical scanning earth sensor	0.1	2	All IRS S/C (except Carto-2)
Linear array CCD star sensor	0.8	2	IRS-1A/1B
Area array CCD star sensor	0.01	2	IRS-P5/P6/Carto-1/Carto-2

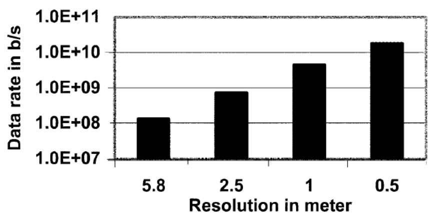

Figure 24. Data rate requirements.

development of ammonia filled heat pipe to take the heat away from the focal plane arrays are a few examples of this development. Development of a two-stage sterling cooler to achieve low temperatures for thermal IR detectors and photon detectors is under way.

(iii) Data handling and transmission – As the requirements of the spatial and radiometric resolution of the images are ever increasing, the data volume and hence, the data rate to be transmitted from satellite to ground stations also perpetually increases. Figure 24 shows the data rates for various spatial resolutions with a 70 km swath at an altitude of 817 km and with 10 bit quantization. The data transmission, which started with S-band RF system, has shifted to X-band to get more bandwidth and hence handling higher bit rate. Cartosat-1 has used QPSK dual channel X-band system to handle 210 M bits/s data rate. Microwave imaging satellite RISAT will transmit data at 640 Mbps using dual polarization technique. In order to meet the future demands, data compression, on-board data processing, high efficiency coding like Trellis, 8 PSK modulation, Ka-band transmission are planned. A significant development in RF data transmission area is the development of the Phased Array Antenna (PAA), which uses solid-state power amplifiers in place of more cumbersome Travelling Wave Tube Amplifiers (TWTA). Starting from Technology Experiment Satellite (TES), the PAA is successfully used in all IRS missions. Equally important development is the lightweight Dual Gimbal Antenna (DGA) used in Cartosat-2 satellite.

(iv) Onboard data storage – The on-board data storage systems have migrated from the electro-mechanical tape recorders flown in IRS-1C/1D to solid state recorders in the later missions. With increased memory capacity requirements, new packaging techniques like vertically integrated 3D modules are developed. A 64 Gb SSR was used in TES and Cartosat-2 and a 240 Gb SSR is being developed for RISAT.

(v) Attitude and orbit control system – In the area of platform pointing and stability, a linear array CCD-based star sensor was flown in IRS-1A/1B for measuring attitude of the satellite as a supplement to the earth sensor. Subsequently CCD-based star sensor was developed and flown in IRS-1C/1D as a full-fledged three-axis attitude sensor. Then onwards, star sensor is the main attitude sensor onboard all IRS satellites. The spacecraft pointing accuracy, which is measure of the geometrical accuracy of the imagery, has been improved from 0.4 deg in IRS-1A to 0.05 deg in Cartosat. These star sensors in conjunction with highly stable mechanical gyroscopes resulted in platform stability of about $5 \times 10e^{-5}$ deg/s. Table 4 provides the different types of attitude sensors and their evolution. Development of fibre optic gyro, which will give better performance in terms of drift stability, is under way. All IRS satellites are three-axis stabilized and they use reaction wheels as the main actuators. Earlier IRS satellites used three-wheel configuration with a skewed wheel for redundancy. The present generation IRS satellites use the tetrahedral configuration with four wheels. The demand on the higher torque capability and angular momentum for Cartosat-2 and RISAT satellites resulted in the development of 15 NMS and 50 NMS wheels respectively, with torque capability of 0.3 Nm.

(vi) Satellite positioning system – In order to improve the orbit determination and position accuracy, GPS-based satellite positioning systems (SPS) are developed and used on all present IRS platforms. The combination of star sensor attitude knowledge, SPS position knowledge and the improved control algorithms, which include the onboard IRU calibration, have resulted in ground image location accuracy of 50 m in Cartosat-1, which is a significant achievement in the satellite remote sensing.

(vi) Bus management unit – The concept of bus management unit is introduced in IRS satellites starting from

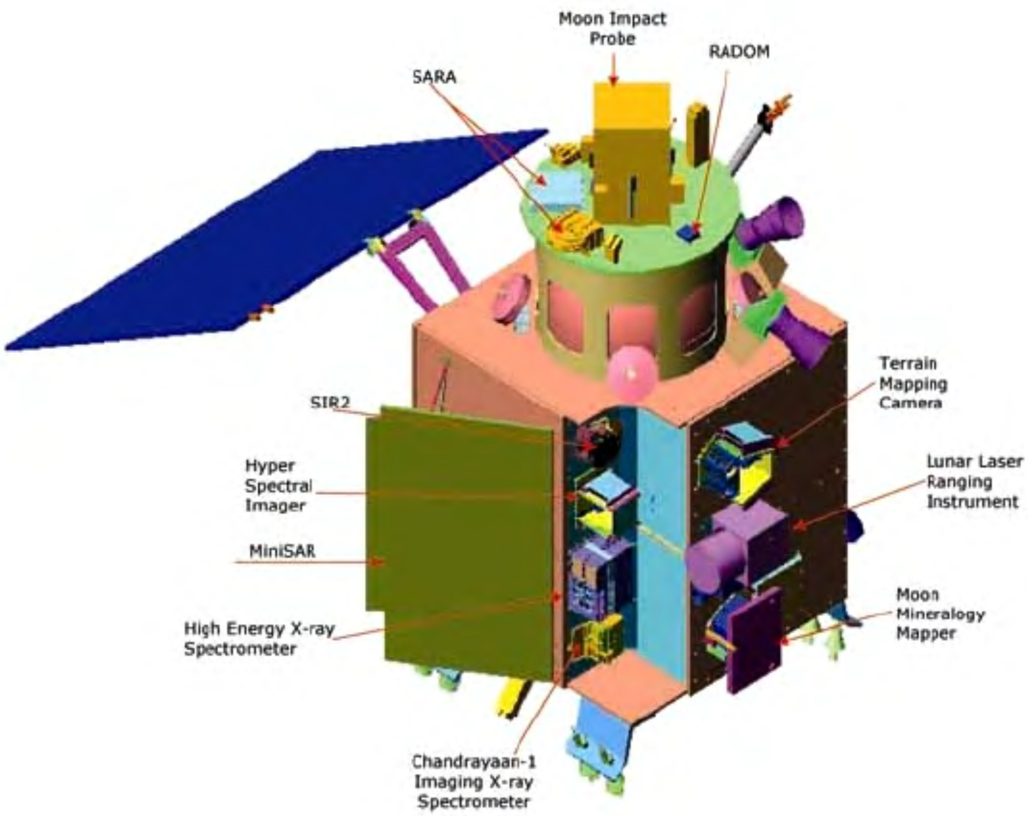

Figure 25. Chandrayaan-1.

Cartosat-2. Making use of high speed microprocessor, FPGAs, ASICs, HMCs and surface-mount-devices, this unit performs the functions of telemetry, telecommand, attitude and orbit control and thermal control. This along with the use of MIL-STD-1553B bus for electrical interface between subsystems, has significantly contributed in weight reduction, particularly in the weight of satellite level electrical interconnections. In conjunction with the hardware development, software algorithms, particularly in the area of control system and orbit determination have been developed. The step and star imaging in TES and paintbrush type of imaging in Cartosat-2 are the result of the complex algorithms realized by means of embedded software. The implementation of the Kalman filter resulted in low drift and jitter on IRS platforms.

Space science, planetary missions and small satellites

Even though the application of space technology for national development has been the main thrust for ISRO, space science has received special attention and has been yet another important element of the Indian space programme. The scientific instruments carried on-board spacecraft ARYABHATA, SROSS, IRS-P3, etc. have given impetus to space science research and have provided exciting and unique scientific results. The endeavour is to be continued through the development of a space science long-term plan. The plan includes pursuing planetary exploration and astronomy as one of the major directions of space activity in India. Presently ISRO has on hand three major scientific missions on planetary science, astronomy and environmental science.

Chandrayaan-I

As a first step towards planetary exploration, the Indian mission to Moon, called Chandrayaan-I, has been conceived (Figure 25). The main scientific objective of the mission is high resolution remote sensing of the Moon in visible, near infra red, low energy X-ray and high energy X-ray region with the purpose of preparing a 3-dimensional atlas (with a high spatial and altitude resolution of 5 m) of regions of scientific interest on the Moon and chemical mapping of the entire lunar surface for elements such as Mg, Al, Si, Ca, Fe and Ti with a spatial resolution of about 20 km. Simultaneous photo-geological, mineralogical and chemical mapping will enable us to identify different geological units, which will test the early evolutionary history of the Moon. The Chandrayaan-1 does include AO payloads from international space agencies that complement the scientific investigation as well as possible detection of water ice in poles.

The above scientific objective will be achieved with a Terrain Mapping Camera (TMC) in the panchromatic band, having a 5 m spatial resolution and 20 km swath; a hyper-spectral wedge filter camera operating in 400–900 nm band, with a spectral resolution of 15 nm and spatial resolution of 80 m with a swath of 20 km; a laser ranging instrument with height resolution of about 5 m; a collimated low energy (1–10 keV) X-ray spectrometer using silicon-based swept charge X-ray detector for measuring fluorescent X-rays emerging from the lunar surface and a high energy X-ray (10–200 keV) mapping, employing CZT solid-state detector to understand the transport of volatiles on the moon. The instruments and science expected from Chandrayaan-1 are discussed in detail in Agarwal *et al.* (this issue). The Chandrayaan-1 spacecraft will orbit Moon in a polar orbit at a distance of 100 km and for mission duration of two years. Since the launcher has to place the spacecraft at a distance of approximately 4 lakh km, the payload capability of the launcher will be limited. Hence, the spacecraft design for Moon and other planetary missions will be different from earth observation and communication missions, in the sense that emphasis should be placed on miniaturization. This means smaller weight, size and low power requirement. The optical imaging payload for this reason uses an Active Pixel Sensor (APS), wherein the conversion from the light energy to a voltage level takes place at the pixel level, thus minimizing the hardware and power requirements. The hyper-spectral imager for its spectral selection, in order to generate a large number of spectral bands, incorporates a new technology called wedge filter (an interference filter with varying coating thickness along one dimension, so that the spectral content transmitted through it varies in that direction). Besides, for weight reduction purpose, the telescope assembly uses CFRP structure. The laser ranging instrument uses a laser source as well as a receiver. The X-ray instrument uses SCD detector for low energy and CZT for high energy, with associated complexity in thermal management for optimal performance, with low background noise.

Eleven science payloads are being flown in Chandrayaan-1 mission to cover photo selenological features, mineralogical mapping, chemical mapping, magnetic field anomaly, as well as possible detection of water ice in the poles of the Moon. For this purpose, they require different orientation for observational purpose, like looking at Moon by optical instruments, sun by X-ray sky monitor, orientation of payload for the purpose of detection of water ice to look at poles, etc. This poses great challenge in accommodating different payloads in specific location/orientation in a small spacecraft. The data rates for different payloads are different, starting from a few kilobits to several megabits. These have to be properly formatted and stored for onward transmission to ground. Optical imaging payloads operate only during illumination portion of the orbital lifetime, whereas X-ray and other payloads operate throughout the mission life. This requires proper operational scenario of different payloads, storage of data and transmission to ground.

The development of spacecraft bus itself has thrown several technological challenges, due to less weight, volume and power availability. These include combining all the electronic functions of the satellite through a bus management unit, utilization of high efficiency solar cell for power generation, use of lithium-ion batteries for reduced weight and volume, special coding technique to have additional gain, since the data has to be received from a distance of 4 lakh km, low power data transmitters using MMICs, use of dual gimbal antenna for transmitting and the like. The spacecraft will have autonomous operations, when the spacecraft is placed in the moon orbit during non-visible period from ground. Another important technological challenge is the development of Deep Space Network (DSN) involving 32 m antenna for receiving data from Moon and beyond. This development is being realized within the country.

Very detailed and accurate mission planning is required to put Chandrayaan-1 in 100 km orbit around moon. The flight proven PSLV launcher will inject Chandrayaan-1 into elliptic transfer orbit (ETO). The spacecraft uses the 440 Newton liquid apogee motor for taking it to lunar transfer trajectory and from there to lunar orbit insertion (LOI). Lunar capture is planned at about 200 km × 1000 km altitude at polar orbit and the altitude is circularized through a series of in-plane manoeuvres to 200 km near circular orbit. The spacecraft will be finally moved to 100 km circular polar orbit around moon for photo selenological and chemical mapping of the moon. Thus in lunar orbit the configuration and operation of spacecraft will be similar to the earth imaging missions. However the following significant differences exist due to peculiar nature of lunar orbit. As the polar orbit around the moon is inertially fixed, and the earth/moon go around the sun, the orbit experiences 0 to 360 deg incidence of sun rays. Thus if the solar arrays are not canted, during noon/midnight orbit, 100% power would be generated, whereas during dawn/dusk orbit, no solar power generation is possible. Thus suitable canting of solar array is required to generate adequate power in noon/midnight as well as dawn/dusk orbits. This necessitates 180 deg yaw rotation of spacecraft once in six months. The mission planning of Chandrayaan-1 is discussed in more detail in V. Adimurthy *et al.* (this issue).

While Chandrayaan-1 development is progressing, efforts are under way to define Chandrayaan-2. Besides enhancing the scientific objectives of Chandrayaan-1, the Chandrayaan-2 mission is likely to include soft landing,

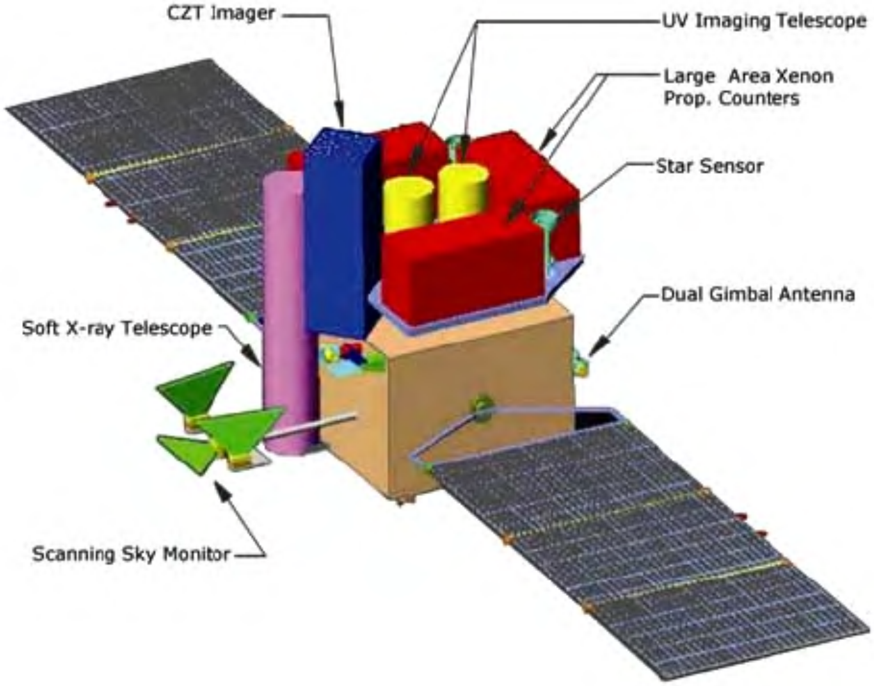

Figure 26. ASTROSAT.

rover, sample to return, etc. Hence the technologies related to these are to be realized. As a precursor to this, Chandrayaan-1 will carry a moon impactor probe as a technology demonstrator.

ASTROSAT

The astronomy mission ASTROSAT is meant for the multi-wavelength studies of different types of cosmic sources over a wide spectral band extending over ultra violet (130–300 nm), visible, low energy X-ray (0.3–8 keV) and high energy X-ray (2–100 keV) bands from simultaneous observations. These simultaneous observations are done with different instruments called Large Area Xenon Proportional Counter (LAXPC) consisting of three units with the combined geometric area of 6000 sq. cm, Soft X-ray Telescope (SXT) with 3 arcmin angular resolution, Cadmium Zinc Telluride Imager (CZT) with a two-dimensional four quadrant coded mask for hard X-ray imaging (10–100 keV), Scanning Sky Monitor (SSM) with continuous rotation for constantly scanning the sky, thus covering more than an hemisphere in one revolution, Charged Particle Monitor (CPM) and Ultra Violet Imaging Telescope (UVIT) incorporating two co-aligned 400 mm aperture telescopes, one for the far UV and the other for the near UV and visible (with a beam splitter) and with an exceptional angular resolution of less than 2 arcsec[17].

The simultaneous measurements from all these instruments will help in the broad band spectral and timing studies of X-ray binaries, pulsars, SNRs, AGNs and galaxy clusters; high resolution studies of galaxy morphology in UV; sky survey in hard X-ray and UV bands; detection of new X-ray transients and UV background studies. Astrosat (Figure 26) will be a National Space Observatory which will be available for astronomical observations to any researcher in India besides the payload scientists and their international collaborators.

Several new technologies were involved in the development of the payloads. ISRO had experience of developing high quality optics for the remote sensing payloads which operate in visible and near IR spectral bands. The UV telescopes need to operate in near UV and far UV spectral bands down to 120 nm. New technologies are developed in the area of coating and testing these mirrors. Another important development is the UV detector with a 25 micron resolution over a diameter of 45 mm. This is the first time in the world such a detector is flying on a UV telescope by means of which a resolution of 2 arcsec from the payload is made possible. The detector is fibre coupled to match the format of the APS detector which is used to readout the optical signal. The SXT payload uses a light weight Wolter-1 type grazing incidence optics[18] realized by concentric conical thin aluminum foils coated with gold. This foil technology was developed and qualified at TIFR, Mumbai. The detector used for this payload is a specially designed open well structure CCD responding to soft X-ray. The detector needs to be cooled to –80ºC in order to reduce the background thermal noise of the detec-

Table 5. Current and emerging technologies

Sub-systems	Current technology	Future
Structure/mechanisms	Graphite composite Bonded structures Explosive release devices	High modulus fibers Inflatable structural elements Payload isolations systems Shaped memory alloy actuated release devices
Thermal control	Panel embedded heat pipes Onboard processor controlled heaters	Thin, flexible heat pipes Deployable radiators
Attitude control	Star tracker Light weight reaction wheels GPS-based orbit determination	Multi-function sensors Micro-electro-mechanical devices
Electrical power	Thin multi-function cells on graphite face sheets Panel deployment Lithium ion battery Standardized harness	Thin film membrane solar array Lithium ion battery Sodium sulphide battery Harness imbedded in structure
Command and data handling	Centralized processing 31750 (1–20 MIPs) 1553 data bus Mother board back plane Solid state recorder	> 35 MIPs processors 1773 optical data bus MCM, 3D packaging High capacity solid state recorder
Communication	MIC Solid state power amplifier	MMIC High electron mobility transistor
Propulsion	Mono-propellant Blow down systems Titanium and welded lines	Gel propellants Elastomeric tanks Flexible lines Electric propulsion

tor. This cooling is achieved in two stages. A delta T of 40° is by means of a 3-stage thermo electric cooler and the remaining by means of a heat pipe and radiator. Large Area X-ray Proportional Counter (LAXPC) consists of three units each with an effective geometric area of 2000 sq. cm. These are very large proportional counters which are filled with xenon and methane gases at 2.5 atmospheric pressure to get an energy resolution of 10% at 22 keV. A gas purification system is developed for removing the impurities in the gas which can occur during the lifetime of five years of the payload. Two-dimensional coded mask design and analysis for the Cadium Zinc Telluride (CZT) payload and one-dimensional coded mask for SSM payload were also new developments carried at Raman Research Institute (RRI), Bangalore.

The spacecraft configuration with severe requirements of accommodating many large payloads co-aligned and meeting the optical field of view requirements within the envelope constraints of the PSLV launcher and the adaptor was a challenge which was squarely met. SXT and CZT detectors were required to be cooled to very low temperatures. These requirements were analysed and two large radiators with 6000 sq. cm and 2000 sq. cm area were designed. To mount these radiators to the structure and at the same time reduce the parasitic thermal loads, special flexures and brackets were designed. Astrosat being an inertial 3-axis stabilized satellite having any possible orientation at a given time with respect to the thermal loads from Sun and Earth albedo, thermal design and management is a real challenge. Added to this, the SXT and UVIT payloads need stringent thermal control within 2 degrees. New paraffin based actuators are used for the cover and shutter openings in UVIT and SXT payloads. 120 Gb solid state recorder with simultaneous recording and playback facility, in order to provide continuity of data recording of the science instruments even while playing the previously recorded data, is a new development. The data handling system unlike IRS system has to operate on a continuous basis. A flexi cable consisting of 100 wires is designed to carry the electrical signals from the rotating SSM payload to the fixed spacecraft. The SSM is free to rotate by ± 180 degrees. The instruments and science expected from Astrosat are discussed in Agrawal *et al*. (this issue).

In future Astrosat-2 will carry higher resolution imagers, spectroscopes and polarimeter to enhance multi-wavelength observations. Future planned missions also include Mars orbiter, Small Satellite for Earth's Near-space Environment (SENSE), Asteroid orbiter and Comet fly by; fly by to outer solar system and manned mission to the moon. ADITYA is a planned mission to study sun with an advance solar spectroscope. For the near future an X-ray polarimeter, an infrared spectroscope and a hard X-ray imaging system are planned on 100 kg class of small satellite with the payload weight being up to 40 kg.

Small satellite programme

Space exploration commenced with the launch of Sputnik, a small satellite. India's first satellite Aryabhata, to acquire know-how and technology in space systems, was in the small satellite class. In the early years, to support launch vehicle development, Rohini and SROSS series of satellites that were developed were in the small satellite class. Besides supporting launch vehicle development, these small satellites supported in technology demonstration as well as conducting small scientific experiments. From these modest missions, complex and operational communication and earth observation missions were evolved steadily over the years.

With rapid advances in light weight, miniaturized technologies especially exponential growth in electronic component performance, it is possible to build high performance satellite in small satellite class to achieve dedicated and stand alone missions. The key technologies towards small satellite development are autonomy, microelectronics, telecommunications, instrument technologies and architectures, Micro Electro-Mechanical Systems (MEMS) and modular multi-functional systems. In tune with the global trend, currently micro satellite in the 100 kg class and mini satellite in 400 kg class are being realized at ISRO. While the micro-satellite is being developed for technology demonstration besides conducting small scientific experiments, the mini satellite will be used to realize stand alone Earth observation missions as well as compact scientific missions. The key to realization of these missions is development of miniaturized systems like wheels, gyro and star sensors, adaptation of electronic miniaturization like systems in package (SIP), 3D modules, large scale use of MMIC, etc. Use of low voltage devices is the key to this development. Table 5 shows current and future technologies for representative spacecraft bus elements of earth observation, science missions and small satellite platforms[16].

Conclusion

The spacecraft technology has made tremendous progress over the last twenty five years and has reached almost state-of-art technology level. Today India has her own state-of-the-art constellation of satellites – INSAT and IRS, providing services not only to the user community in the country but also to many countries worldwide. With the experience gained from a number of general purpose satellites, ISRO has started developing and launching a series of unique thematic satellites such as METSAT, EDUSAT, Resourcesat, Cartosat and Oceansat in both communication and remote sensing satellite series, specifically addressing the core development issues facing the country. The Indian spacecraft technology has been well recognized in the world resulting into awarding of two communication satellites contracts to ISRO by European consortium ASTRIUM. With continuous improvements in the performance both at subsystem and system level, push towards higher reliability and longer lifetimes today satellites built in India are considered some of the best operational system in the context of application and scientific objectives. An additional feature of the evolution of satellite technology has been the introduction of several innovation in a number of areas including the optics design of remote sensing camera systems.

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