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Competence building in complex systems in the developing countries: the case of satellite building in India

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Abstract

Since 1975, India has built 25 satellites under the satellite programme. By judicially combining the foreign technological imports and local knowledge, India appears to have acquired a high level of capability to build very complex and world-class satellites for remote sensing and communications. This paper analyses the process of technological learning in satellite building in India. Particularly, it illustrates the role of foreign imports and the local efforts at different phases during this process. This paper demonstrates that achieving the goal of technological self-reliance in a developing country like India, particularly in a complex area like satellite systems, is unlikely to be possible without significant foreign imports in the formative period. It also demonstrates that without strong indigenous effort India would not have reached threshold capability in the accumulative phase. Foreign imports and local knowledge appears to have played a complementary role in competence building in satellite technology in India. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Technological learning; Technological accumulation; Competence building; Indian space programme; Indian satellites; Satellite building; Complex systems; Technological imports; Indigenous R&D

1. Introduction

Since the early 1980s, there has been a growing interest in the study of the process of acquiring technological capabilities in the developing countries, particularly after the successful emergence of newly industrialised countries (NICs) in South East Asia (e.g. Kim 1980, 1993; Kim and Lee, 1987; Westphal et al., 1985; Bell and Scott-Kemmis, 1985; Lall 1987, 1990; Katz, 1987; Enos and Park, 1988; Enos, 1991; Bell and Pavitt, 1993; Hobday, 1995). The focus was mainly on the process of capability building in relatively less complex industrial technologies. The experience of developing countries showed the important role of imported inputs in the process of technology accumulation. However, as some developing countries such as Korea are trying to enter rapidly changing science-based sectors, with increasing technological complexity, the process of technological accumulation has become more difficult and demanding. While competence building in complex technologies requires significant foreign inputs, international technology transfers in these areas are becoming difficult, as developed countries appear to be reluctant and concerned of loosing their competitive advantage. However, India's experience in competence building in satellite technology suggests that developing countries need significant foreign inputs to build threshold capabilities in complex systems. It appears that without significant foreign inputs at the formative phase and some form of imported inputs at later phases, developing countries are unlikely to succeed in building capabilities in complex systems.

Satellite technology is very complex and most satellites are expected to survive between six to seven years in the hostile environment of space. They involve components and systems with very high reliability. Even many developed countries do not have the capabilities to manufacture such components and systems; let alone a developing country like India. Very few countries are self-sufficient in satellite technology. However, India appears to have successfully accumulated a high level of capabilities in satellite technology, by judicially com-

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bining both the foreign imports and the local knowledge. This paper analyses how the technological learning in the area of satellite building in India occurred between the early 1970s and the late 1990s. It particularly illustrates the role of foreign and local technological input in the competence building process.

First, the paper gives a brief account of the history of satellite building in India. Then, it discusses in detail the process of competence building during the formative and accumulative phases. Finally, it analyses the importance and impact of foreign imports and local knowledge in these phases.

2. Competence building in the formative phase

The satellite programme is part of the space programme, which started in 1962. The Indian Space Research Organisation (ISRO) is responsible for the programme. Vikram Sarabhai, founder of the space programme, defined the final goal as the acquisition of capabilities to build and launch geostationary communication satellites, weather and remote sensing satellites. Between 1975 and 1999, India has built 25 satellites of different kinds (see Table 1). The satellite building activities in India can be divided into two phases, that is, the *formative phase* (1971–1985) and the *accumulative phase* (since 1986). Fig. 1 illustrates the activities under these phases.

India appears to have followed a step-by-step approach towards technology accumulation. A spacecraft consists of the following major sub-systems: (i) structure, (ii) thermal control system, (iii) spacecraft mechanisms, (iv) power system (v) attitude control system, (vi) attitude sensors, (vii) propulsion system (viii) telemetry, tracking and command system, and (ix) payloads. Initially, India started importing whole sub-systems. Then, it started assembling the sub-systems by importing most of the components and developing some locally. Eventually, it started to make most of the sub-systems using mostly local inputs and reducing imports to very high precision items, micro-electronic components and advanced materials.

India's quest to master satellite technology began with the setting up of an Experimental Satellite Communication Earth Station (ESCES) at Ahmedabad in 1967. When the application of satellites for communication was not widespread, even in the US, Indian space scientists believed that they had potential applications for India and tried to demonstrate this scientifically. They conducted various experiments on the ground under the Applications Technology Satellites Test Plan of National Aeronautics and Space Administration (NASA), the US. They had undertaken a pilot satellite–TV project called

Table 1
Satellites built by ISRO since the 1970s

Satellite	Weight (kg)[a]	Date of launch	Launched by[b]
Aryabhata	360	April 1975	Intercosmos (USSR)–
Bhaskara I	444	June 1979	Intercosmos (USSR)–
Rohini	35	August 1979	SLV–3 (India)*
Rohini–I	35	July 1980	SLV–3
Rohini–D1	32	May 1981	SLV–3
APPLE	650	June 1981	Ariane Test Launch (ESA)–
Bhaskara II	436	November 1981	Intercosmos (USSR)–
Rohini–D2	41.5	April 1983	SLV–3 (India)
SROSS–1	150	March 1987	ASLV–D (India)*
IRS–1A	975	March 1988	Vostok (USSR)
SROSS–2	150	July 1988	ASLV–D2 (India)*
IRS–1B	975	August 1991	Vostok (USSR)
SROSS–C1	106	May 1992	ASLV–D3 (India)
INSAT–2A	1906	July 1992	Ariane (ESA)
INSAT–2B	1906	July 1993	Ariane (ESA)
IRS–1E	846	September 1993	PSLV–D1 (India)*
SROSS–C2	113	May 1994	ASLV–D4 (India)
IRS–P2	804	October 1994	PSLV–D2 (India)
IRS–1C	1250+	December 1995	Molniya (Russia)
INSAT–2C	2050+	December 1995	Ariane (ESA)
IRS–P3	922	March 1996	PSLV–D3 (India)
INSAT–2D	2500	June 1997	Ariane (ESA)*
IRS–1D	1200	September 1997	PSLV–C1 (India)
IRS–P4	1050	May 1999	PSLV–C2 (India)
INSAT–3B	2070	March 2000	Ariane–5 (ESA)

[a] +Weighed at lift-off.
[b] *Launch failed; –Cost free launch.

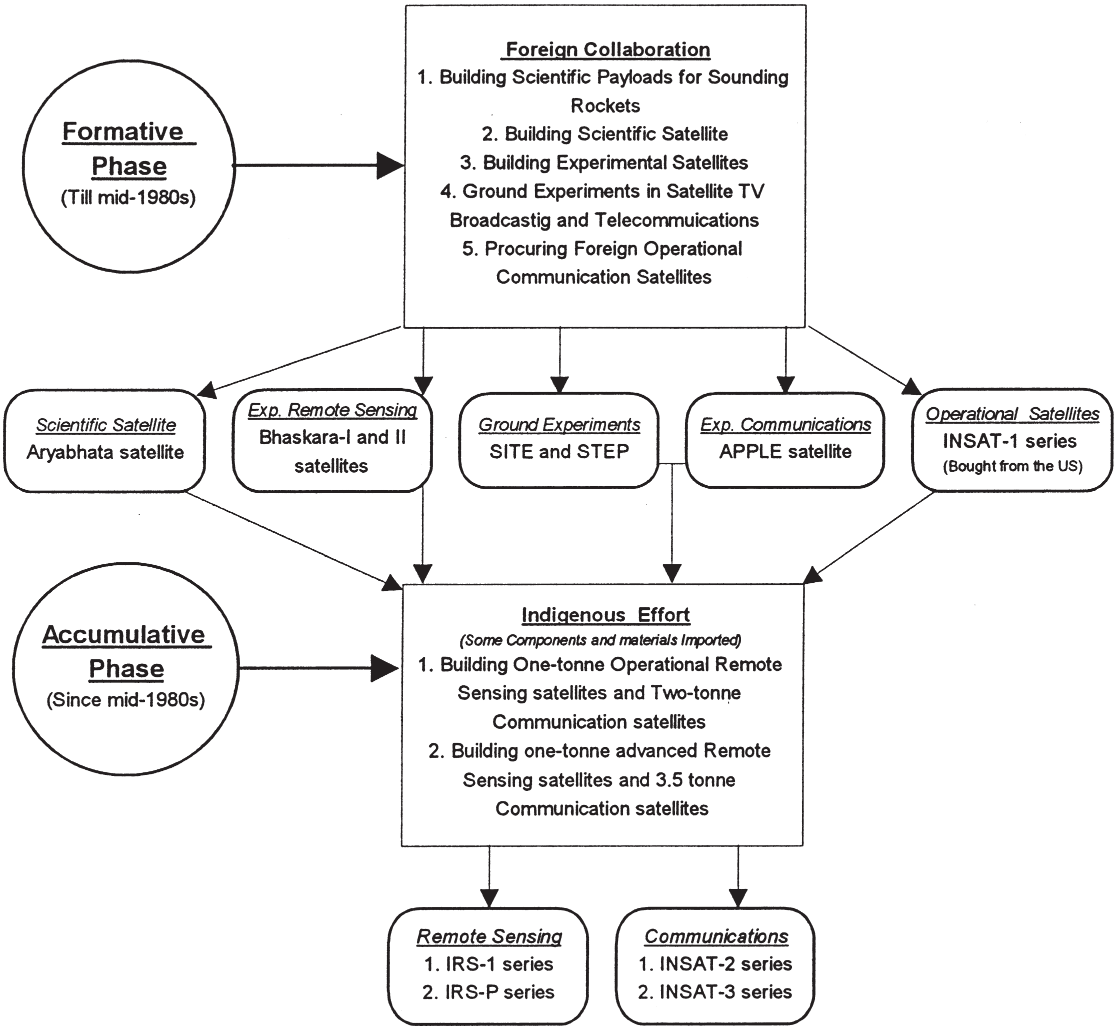

Fig. 1. Formative and accumulative phases of competence building in satellite technology in India.

Krishi Darshan in January 1967 covering 80 villages around Delhi (DAE, 1967–68, p. 66; 1969–70, p. 70). At the same time, India was conducting joint studies with NASA to determine the right system for telecommunications and television coverage. It also sent a team of eight engineers to the US in 1969 to conduct joint studies with General Electric and Hughes Aircraft and to gather technical data from US and Canadian sources (DAE, 1969–70, p. 70). In the late 1970s, India carried out a joint study known as the ISRO–MIT study with the Massachusetts Institute of Technology (MIT) in the US, which focused on the optimal systems design and cost estimates of an Indian National Satellite (INSAT).[1] In the following year, ISRO initiated detailed planning for the telecommunication satellite programme and sent its engineers to NASA for training (DAE, 1970–71, p. 154).

Meanwhile, ISRO was also learning to build different kinds of payloads for sounding rocket experiments. Payloads constitute the application packages in satellites. ISRO tested the first “completely India built payload” during 1969–70 (DAE, 1969–70, p. 71). Subsequently, it built different kinds of payloads for different missions at Thumba Equatorial Rocket Launching Station (TERLS), and Physical Research Laboratory (PRL) at Ahmedabad. This included meteorological payloads based on British Meteorological Office (BMO) payloads (DAE, 1970–71, pp. 34–35). In the early 1970s, Indian engineers, with training in France, started developing sensors for airborne remote-sensing surveys and processing of imageries provided by NASA. ISRO also started receiving real time data from American and Canadian scientific satellites such as Solrad–9 and 10, S–66, Alouette–11 and ISIS–I and II, that were orbiting over India (DAE, 1971–72, p. 159). This enhanced the knowl-

[1] The influence of this study on the actual definition of INSAT–1 and 2 series operational satellites in the 1980s and 1990s is quite evident.

edge of Indian scientists. While doing the studies on defining INSAT, ISRO started working on the design and fabrication of a small satellite weighing 40 kg and a bigger scientific satellite weighing 350 kg. Thus, the era of satellite building began in India.

2.1. Indian scientific satellite — "Aryabhata"

In 1972, the Academy of Sciences, USSR, agreed to launch a satellite built in India, cost free. When the project to build the satellite called as Aryabhata started, there was almost no existing infrastructure. The Satellite Systems Division, consisting of around 200 scientists took up the project in the early 1973. Building Aryabhata proved to be formidable. In the words of Prof. U.R. Rao, project director: "starting from scratch, working day and night inside the asbestos roofed sheds with practically no infrastructure" ISRO "had to conceive, design, fabricate and test a satellite, in an incredibly short time of just over two and half years" (ISRO, October 1991–March 1992, p. 17).

The project employed both foreign imports and local knowledge. The satellite structure was fabricated at Hindustan Aeronautics Limited (HAL), Bangalore. Various tests were carried out at the Controllerate of Inspection Electronics (CIL), and the National Aeronautical Laboratory (NAL), Bangalore. All together, eight major public enterprises, one large private firm and a number of small private firms had worked in the project (Times of India, 12 April, 1975). Most of the equipment needed for fabricating and testing the satellite had to be imported (Tribune, 28 May, 1975). Space qualified components that "were specifically selected from the preferred parts list of NASA" were imported from various countries (DOSa, 1972–73, pp. 26–27; Rao, 1978, p. 122). "Practically all the components like transistors and chips, used in the satellite, were obtained from abroad" (Hindustan Times, 25 May, 1975). "The high quality tape recorders, the spin up system, the solar cells, were supplied by the Soviet Union. Instruments needed to conduct the experiments onboard were purchased from the US and elsewhere" (Tribune, 28 May, 1975). Soviet Union provided a number of subsystems and considerable technical help such as assistance for conducting tests on various models of the spacecraft, and operating the ground station (Rao, 1978: p. 129; Times of India, 21 April, 1975). Finally, India built two flight models of Aryabhata. One was launched on 19 April 1975. Although it faced problems in orbit, it performed better than expected and was in operation until 11 April 1981 (Times of India, 12 April, 1981).

From Aryabhata, ISRO learned the techniques involved in the design and fabrication of a satellite, testing, and quality control. It gained valuable experience in thermal and power control systems, stabilisation and attitude sensor systems, orbital predictions, telemetry, tracking and telecommand through in-orbit operations and experiments (Rao, 1978, p. 128). Aryabhata also helped ISRO to build a "core team of scientific and technical personnel" (ISRO, October 1991–March 1992, p. 17).

2.2. Satellites for earth observation — "Bhaskara I and II"

After Aryabhata, in 1978, the Soviet Union agreed to launch another Indian satellite, again cost free. The satellite called Bhaskara–I, for earth observation was to be built modifying the unused second flight model of Aryabhata. Thus, ISRO could cut the cost and time. The objectives behind Bhaskara–I were more ambitious. With Aryabhata, the aim was to establish the capability to design and fabricate the satellite main bus. The applications of its payload were not considered seriously. In the case of Bhaskara–I, the immediate goal was to "obtain scientific information about meteorology, hydrology, and oceanography, using satellite based sensors" (Times of India, 19 April, 1976). The long-term objective was to evolve an operational remote-sensing satellite system for India.

In the early 1970s, ISRO started developing methods of remote sensing data analysis using the ERTS–1 satellite pictures, provided by NASA. It also started developing sensors for airborne remote sensing. In 1971–72, Indian engineers had fabricated an infrared scanner in collaboration with Laboratories de Meteorology Dynamique in France. By using this experience, they constructed an identical scanner "with the minimum of imported components" (DOSa, 1971–72, p. 184). ISRO also bought a few Hasselblad 70-mm cameras and multiband cameras from the US (DOSa, 1972–73, p. 42). Subsequently, ISRO was conducting aerial remote sensing surveys in different parts of the country and it set up facilities to analyse the data collected from these surveys. The next step in the learning curve was to build a remote sensing satellite. Bhaskara–I provided this opportunity.

"In an ideal case, an earth observation satellite needs to be three-axis stabilised so that the sensors can point towards the earth continuously" (Joseph, 1992, p. 25). However, ISRO decided to utilise the standby model of Aryabhata that was only a spinning satellite. The Bhaskara–I project work started in 1975. It was the first major inter-centre effort of ISRO. What is known today as ISRO Satellite Centre (ISAC), in Bangalore, was given responsibility for the overall project. The design and development of payloads and the responsibility to generate data products were given to Space Applications Centre (SAC) at Ahmedabad. The responsibility for ground management and operations was assigned to Sriharikota (ISTRAC) Centre. Altogether, 14 Indian and 20 Soviet agencies were involved in implementing the project. Around 400 Indian scientists were involved in the project and it took nearly four years to complete (Times of India, 8 June, 1979; Hindustan Times, 13 June, 1978). A number of facilities for the generation of data products, processing of imageries, analysing satellite health, receiving data from satellite and testing components and subsystems were established.

The major indigenous effort was the development of the payload that comprised two TV cameras and three satellite microwave radiometers (SAMIR). Overall, about 25 per cent of the components were imported (Times of India, 9 June, 1979). This included solar cells, Nickel–Cadmium batteries, space worthy tape recorders, and TV camera systems. SAC, Ahmedabad designed the cameras, and assembled them using imported components from France and the US (Patriot, 24 May, 1978). The television tubes were specially made and supplied by Thompson–CSF of France (Patriot, 13 July, 1979). As the company made the tubes for the first time, it was very keen to see the system successfully employed in space. Bhaskara–I was launched on 7 June 1979. It was expected to last only for one year but was operational for more than two years. After some initial problems, its TV cameras started sending pictures, which were comparable to those taken by other meteorological satellites such as Nimbus.[2] The TV camera system transmitted nearly 800 images (DOSb, 1981–82, p. 50).

As with Aryabhata, Soviet assistance for Bhaskara–I was considerable, especially in carrying out the final tests. A team of 25 Soviet engineers worked with Indian scientists in Bangalore from 24 March to 22 April 1978 (Patriot, 24 May, 1978). After Bhaskara–I, the Soviet Union agreed to launch another satellite for earth observation, Bhaskara–II. It also supplied tape recorders, solar panels, and batteries, besides providing cost free launch. To reduce cost and time, ISRO refurbished the Bhaskara–I proto-type for Bhaskara–II, following the same method used with the proto-type of Aryabhata. Bhaskara–II incorporated major improvements in the design and fabrication of payloads and testing and evaluation methodologies. Bhaskara–II was launched on 20 November 1981. Although its Camera–1 failed, the Camera–2 functioned well and provided more than 2000 pictures (DOSa, 1982–83, p. 11).

The experience gained from Aryabhata had helped Indian scientists to execute the Bhaskara–I, to a large extent without the assistance of Soviet experts. For example, the Indian and Soviet scientists had held just four joint meetings for Bhaskara–I compared to thirteen such meetings during the Aryabhata project (Patriot, 24 May, 1978).[3] Bhaskara–I and II enabled ISRO to gain experience in building and operating remote sensing satellites. ISRO also learned the methodologies for data utilisation, real time data processing and orbit and attitude determination. For the first time, it learned about co-ordination and management of a satellite project involving many space centres, firms and other organisations.

2.3. Experimental communication satellite — (APPLE)

To define an appropriate operational communication satellite system for India, ISRO had undertaken extensive ground experiments using foreign satellites. During 1975–76, the Satellite Instructional Television Experiment (SITE) was conducted extensively, using an American satellite ATS–6. Then the Satellite Telecommunications Experimental Project (STEP) was carried out between 1977 and 1979 by using the Franco–German satellite, Symphonie. These activities culminated in design and fabrication of an experimental geo-stationary communication satellite called the Ariane Passenger Payload Experiment (APPLE). Through this project ISRO took “really a quantum jump” in many aspects of satellite building.[4] It was not part of ISRO’s original space plan. It was the result of an unexpected offer from European Space Agency (ESA) to launch an Indian geo-stationary communication satellite by using one of its Ariane test launchers, cost free. ESA made this offer because of ISRO’s collaboration in the development of the Viking liquid engine for Ariane.

The objectives of APPLE were to gain experience in designing, fabricating and testing a 3-axis stabilised communication satellite. A communication satellite is one of the most complex and difficult to fabricate. It carries its own propulsion system and it has to go through a series of development manoeuvres in orbit. At the time, only few countries such as the US, the USSR, the UK and France–Germany (combined) were capable of building communication satellites. Therefore, it was a formidable task for a country like India that built its first satellite only in 1975.[5] ISRO had to set up various fabrication and test facilities in different space centres, as APPLE was a different class of satellite from Aryab-

[2] Interview with Prof. Satish Dhawan, former Chairman of ISRO, Bangalore.

[3] From Interview with Prof. N. Noviko, vice-president of Intercosmos, USSR Academy of Sciences.

[4] Interview with Kiran Karnik, Former ISRO scientist, Space Applications Centre (SAC), Ahmedabad.

[5] Prof. Roy Gibson, Director General of ESA, visited ISRO when APPLE was being constructed at the Peenya Industrial Estate in Bangalore. Seeing the asbestos sheds and witnessing how the work was being done, he was not at all impressed and expressed his doubts about ISRO’s ability to meet the launch schedule. Satish Dhawan, then chairman of ISRO, assured him that it would be ready for the launch. To allay further doubts, ISRO gave a dummy block of APPLE to ESA so that Ariane could be launched if APPLE were not ready. Ironically, APPLE was completed seven months before the actual launch, and the launch was delayed by ESA’s satellite, a co-passenger to APPLE (Interview with Dhawan and U.R. Rao).

hata or Bhaskara. These facilities were set up using both indigenous and foreign equipment and components (DOSb, 1978–79, pp. 53–54).

An important development under this project was the involvement of the industry. Because of the tight time schedule, ISRO was forced to subcontract fabrication work to industry and other R&D institutions, wherever possible. The fabrication of APPLE's structure was carried out by HAL. The fabrication of PCBs was done by Bharat Electronics Limited (BEL), and Hegde and Golay, Bangalore. Electronics Corporation of India Limited (ECIL) and CIL provided the component screening services. Many other firms and institutes such as Indian Institute of Technology (IITs), Indian Institute of Science (IISc), Babha Atomic Research Centre (BARC) and Solid State Physical Laboratory (SSPL) and NAL also were involved (DOSb, 1980–81, p. 61).

Various models were developed and tested both in India and abroad. The thermal model was tested at SOPMER's facility in Toulouse, France. The engineering model was tested by ESA at Les Meureause, France. The critical design review and the analysis of the major results of engineering, thermal and structural model tests were jointly undertaken by ISRO and ESA (DOSb, 1979–80, pp. 74–75). The short launch schedule forced ISRO to import most of the items required, as indigenous development would take longer than the launch schedule. ISRO imported most of the critical components and sub systems such as momentum wheel, solar array drive, reaction control system, batteries, sensors, and transponder elements, ground check out equipment, travelling wave tube and titanium gas bottles (DOSa, 1978–79, p. 9; Patriot, 23 July, 1981; Financial Express, 29 July, 1981).[6] ISRO also indigenously developed certain items like momentum wheel assembly, solar array drive, deployment mechanisms, C–band antenna and C–band communication payload (DOSb, 1979–80, p. 75). Further, it started indigenous development of many of the items imported for APPLE project to meet the needs of future satellite projects.

From APPLE, ISRO learned to design, fabricate, test and evaluate various sub-systems involved in a communication satellite. It learned new techniques like 3-axis body stabilisation, Apogee booster motor (ABM) firing, thruster firing, solar panel and antennae deployment. It gained new expertise by using C–band transponders for different kinds of experiments. It was able to test indigenously developed technologies such as the momentum wheel, Sun and Earth sensors, graphite antenna, and solid propulsion ABM. ISRO engineers gained experience in manoeuvring a satellite from a geo-stationary transit orbit to the geo-stationary orbit.[7]

2.4. Procurement of INSAT–1 satellites from the US

With the launching of Bhaskara–II and APPLE, the experimental phase ended. In the next phase, the objective was to build two satellite systems — the Indian Remote Sensing Satellite system (IRS) and the Indian National Satellite system (INSAT), for commercial operations. The question confronting ISRO was whether it could build them indigenously and provide them to user agencies on a continuous basis. Any discontinuity would seriously affect services like telecommunication and TV broadcasting in the country. ISRO realised that though it was confident about building operational commercial systems indigenously, it might take more time than stipulated to develop them. However, it viewed remote sensing and communications separately. After a realistic appraisal of its capabilities, It decided to build the IRS–1 series indigenously and buy the INSAT–1 series from abroad. It decided to build the INSAT–2 series indigenously. There were reasons behind these decisions. As INSATs were communications satellites, they were more complex and ISRO needed longer development time. Further, as it was a high priority area, ISRO was not willing to take any risks. In contrast, the risks involved in building IRS–1s locally were considered to be low. Because, India was already receiving data directly from foreign satellites, such as LANDSAT (NASA) and SPOT (France), which could be provided to users in case of problems with IRS–1s.[8]

In 1977, ISRO finally defined INSAT as a multipurpose system consisting of telecommunication, meteorological and TV broadcasting elements. It was the world's first geo-stationary satellite system to combine these three elements, and it remains unique even today. During 1978–79, the Department of Space (DOS) entered into a contract with Ford Space and Commerce Corporation (FSCC) of USA for the supply of two INSAT–1 spacecraft, and the equipment for the Satellite Control Centre (SCC) at the Master Control Facility (MCF) in India. The satellites were to be designed by Ford to ISRO's specifications. ISRO also concluded an agreement with NASA to launch the satellites on a commercial basis.

Indian engineers worked with their counterparts at Ford Aerospace for five years. They monitored the implementation of the contracts. Barring one or two, most of the team stayed in batches.[9] They acquired

[6] The solar panels were bought from Spectrolab, USA, Ni–Cd batteries from Saft of France, sensors form Lockheed, control systems from Hamilton Standard, microwave components from Hughes International, solar array drive from British Aerospace, and one momentum wheel assembly from Teldix of West Germany.

[7] This is an extremely difficult manoeuvre. Before India, only the US, the Soviet Union, France, and Canada had demonstrated this capability.

[8] Interview with D.V. Raju, Former Deputy Director, National Remote Sensing Agency, Hyderabad.

[9] Interview with D.V. Raju.

experience in two aspects: project management, and testing and integration procedures. The project management was related to the process of building a complex spacecraft like INSAT–1. In Ford's case, it was about managing sub-contractors. In ISRO's case, it was about managing various space centres, other R&D organisations and firms in India. Therefore, the learning was in terms of managerial techniques, systems control and systems engineering and documentation. Regarding testing, the learning concerned the kinds of tests, how they were carried out, and how problems were analysed. Further, ISRO engineers also brought back to India a wealth of technical data.[10] From INSAT–1s, ISRO also gained considerable experience in failure analysis and in-orbit manoeuvres, as three of the four satellites faced post-launch problems. This subsequently helped ISRO in building the INSAT–2 satellites.

3. Competence building in the accumulative phase

The period beginning in the mid-1980s could be considered as the accumulative phase. By the mid-1980s, ISRO has attained threshold capability to build locally both remote sensing and communications satellites (IRS–1s and INSAT–2s), within a comparable time scale, for commercial operations. However, it was still dependent on foreign countries for some critical components and materials. These satellites were more sophisticated and complex than the older generation and they required very advanced microelectronics components and materials. For this, India was largely dependent on the Western countries. At the same time, it was becoming increasingly difficult to import many of them because of the restrictions imposed by export controls. This appears to have forced ISRO to strategically manage the indigenous R&D to avoid dependence on foreign countries for critical items.[11]

3.1. Indian remote sensing satellites (IRS)

The IRS–1A project was begun in June 1982 and it took much longer to develop IRS–1A than had been expected. ISRO had to set up certain facilities like a 3-metre thermo-vacuum chamber, scene simulators, charge coupled devices (CCD) calibration set up, satellite interface simulator, and data acquisition and analysis set-up (DOSa, 1985–86, p. 19). By early 1984, several major subsystems such as the reaction control system, reaction wheels, vertical sensors, horizon sensors, communication systems and vital components of the camera were developed indigenously by various ISRO centres (DOSa, 1982–83, p. 12). Subsequently, the solar array drive mechanism, altitude reference system, and slip ring unit for the solar array drive assembly also were indigenously developed (DOSa, 1983–84, p. 22). These activities clearly indicate ISRO's thrust towards achieving total indigenisation in the area of spacecraft control systems. This is a critical area of satellite technology and some of the components discussed above face export controls. Therefore, it is likely that India decided to develop them indigenously to avoid export control problems.

IRS–1's cameras involved an entirely new technology in remote sensing sensors. When ISRO started planning IRS–1A's main features, the remote sensing satellites used only opto-mechanical scanners like the Landsat–MSS and TM for multispectral imaging. In June 1983, Linear Imaging Self-scanning Sensor (LISS) using CCD in the push broom mode was flight tested on board the shuttle flight STS–7 in a German Experimental Earth Observation programme, MOMS. At the time, France was also planning to use such a camera for SPOT. In India, a single-band CCD camera for an aircraft platform was designed and flight-tested in 1980. Another sensor using a linear photo diode array was flown on its ROHINI–D1 satellite in June 1981. Using these experiments, ISRO was able to do a comparative study of the opto-mechanical scanner and the LISS and decided to use solid state CCD cameras in IRS–IA. The experience gained from using the LANDSAT data (NASA) helped ISRO in deciding to employ the LISS payloads with two different spatial resolutions (DOSa, 1983–84, pp. 30–32).

IRS–1A was launched on 17 March 1988 by a Soviet launcher. The satellite was designed to operate for three years only, but it continued to operate long after its expected life. The performances of its cameras were "very good, producing very high quality imaging" and there was "no deterioration of performance even after the design life of three years" (Joseph, 1992, p. 35). A number of new technologies incorporated in the satellite such as a large area solar panel, reaction wheels and gyroscopes, hydrazine-based reaction control system, S–band and X–band communication systems, a variety of solar, earth and stars sensors, "have performed to specification much beyond the expected life of the satellite" (DOSb, 1993–94, p. 18). The quality of imagery received from IRS–1A was comparable to LANDSAT–D (Patriot, 16 March, 1988).[12] Unlike the cases of Aryabhata, Bhaskara–I and II, the Soviet technical assistance for IRS–1A was "equal to zero," except for the launch services on a commercial basis (Patriot, 16 March, 1988). Most of the technology involved was indigenous and some critical components and subsystems, such as

[10] Interview with a former ISRO engineer.

[11] Interview with Kiran Karnik.

[12] By December 1992, IRS–1A provided 450,000 images, which had been disseminated, to over 700 users. ISRO has been paying US$600,000 every year simply to get access to Landsat data plus a separate fee for every picture actually used.

CCD and the imaging lenses, were imported (DOSb, 1984–85, p. 22).

Following IRS–1A, IRS–1B and IRS–1C were built and launched in 1991 and 1995 respectively. IRS–1B was identical to IRS–1A with some improvements. IRS–1C is considered as “one of the best remote sensing satellite systems available compared to any other civilian operational remote sensing satellite system” (Joseph, 1992, pp. 36–37). Its “data is marketed world wide through a tie-up between ANTRIX, and the EOSAT Corporation of the US” (ISRO, 1996, p. 1). IRS–1D was identical to IRS–1C. It was launched by the indigenously built Polar Satellite Launch Vehicle (PSLV)–C1 on 29 September 1997. Between 1994 and 1999, India has built IRS–P2, IRS–P3, and IRS–P4 remote sensing satellites and launched successfully by PSLVs. This enabled India to operate “the world’s largest constellation” of civilian remote sensing satellites (DOSa, 1997–98, p. 7). Data from IRS satellites have been acquired under commercial agreements by a number of countries including North American and European countries, Japan, Korea, Thailand and Dubai (DOSa, 1998–99, p. 5).

3.2. INSAT–2 satellites

The experience gained from APPLE and INSAT–1s, particularly the post-launch difficulties with INSAT–1s, had helped ISRO in developing the INSAT–2s. These satellites were nearly twice as big and more advanced than INSAT–1s. The INSAT–2 project was started in 1985. ISRO had to build various facilities including the Large Space Simulation Chamber (LSSC) to test satellites of 4-m width and 5m height and an 1100 m^3 acoustic chamber. LSSC can simulate $-173°C$ and provide hard vacuum (hundred thousandth of a millibar) and solar radiation conditions. Only about half a dozen such facilities exist around the world (The Hindu, 1 July, 1992). ISRO developed indigenously a number of critical subsystems, components and materials such as communication and VHRR payloads, liquid ABM, a unified propulsion system, reaction control thrusters, solar array, nearly all sensors for attitude and orbit controls, carbon–fibre antenna, titanium pressurant tanks, Nickel–Cadmium cells, inertial systems such as a reaction wheel, momentum wheel, solar array drive, and miniature inertial reference unit, composite elements, various alloys and alloy forging (DOSb, 1997–98, p. 46–54). However, ISRO was also dependent on imports for a number of items. They included radiation hardened integrated circuits (ICs), solar cells for solar arrays, sensors, infra-red and visible channel detectors and highly polished beryllium mirrors for VHRR, cells for nickel–cadmium batteries, thermal blankets to maintain the satellite temperature regime, light-weight, high precision and high reliability parts, such as propellant tanks for ABM and mirco-thrusters, micro-processor for attitude and orbit control system, and microwave transistors (The Hindu, 1 July, 1992; India Today, 30 September 1992, p. 145; DOSa, 1986–87, p. 15).[13]

India built four INSAT–2 satellites and except INSAT2–D, others were successful after launch. INSAT–2C was qualitatively different from 2A or 2B, especially regarding the payload. The successful launch of INSAT–2A, 2B, and 2C clearly demonstrated India’s capability to build complex and sophisticated communication satellites. Some capacity of the next satellite in the series, INSAT–2E, already has been leased to INTELSAT (DOSa, 1996–97, p. 19). Since the late-1990s, ISRO has started building the next generation communication satellites, the 3.5 tonne class INSAT–3 satellites. Already it has built the INSAT–3B. It clearly shows that India acquired a high level of capabilities that are comparable to other nations that are more advanced in this field.

3.3. Exports

Since the mid-1990s, India has been selling remote sensing data to a number of countries through Space Imaging–EOSAT, an American company. India also started exporting to the US and European companies a small number of sub-systems and components like shaft assemblies, pressure transducers, fill and drain valves, solar wing actuators and hinge assemblies, C–band receive and transmit filter assemblies, magnetic torquer rods, reaction wheel assemblies with drive control electronics, solar array drive assembly with electronics and software packages. India has established a Telemetry Control and Ranging (TCR) station for World Space Inc., the US, to provide in-orbit support for its satellite systems. It also provided technical and consultancy services to Korea for its spacecraft mission control system, and telemetry, tracking and command services to PanAmsat and Systems Loral, the US (DOSa, 1997–98, p. 81; 1998–99, pp. 84–85; DOSb, 1997–98, p. 48).

4. Role of foreign imports and indigenous efforts in technology accumulation

The main objective of India’s satellite programme was to achieve capability to build commercial scale satellites for remote sensing and communications. For this, it was required to accumulate skills in the areas of design, various analysis, fabrication, testing, integration and spacecraft control. It also had to establish various ground facilities. Despite following “self-reliance” policy, from

[13] The momentum wheel and propellant tanks were from Teldix and MBB of Germany respectively. The microprocessor was bought from Harris of the US; the ICs from SGS–Thompson, France; and microwave transistors were from NEC and Fujitsu, Japan.

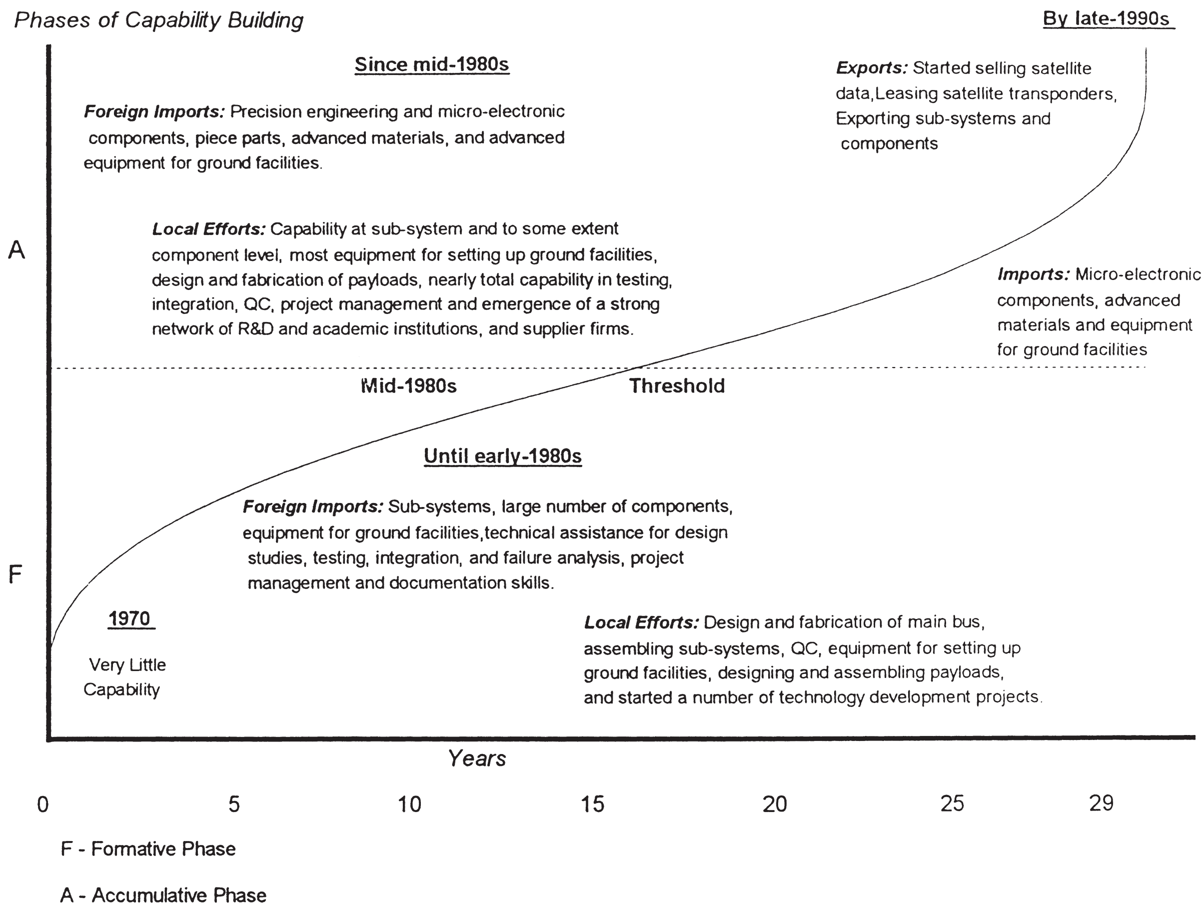

Fig. 2. Process of satellite technology accumulation in India.

the beginning, India considered foreign collaboration was necessary to learn these skills from advanced countries. Dhawan, former chairman of ISRO argued: "simply saying nationalistically that we will do it ourselves, we will land in all kinds of problems…industrially we are a small country. We cannot afford…" to do every thing indigenously.[14] At the same time Indian scientists were fully aware that they had to make strong and sustained efforts to develop locally whatever technologies they could by employing available resources. In the early 1970s, India's capability in all aspects of satellite technology was nearly zero. By the late 1990s, it has acquired capabilities to build 3-tonne class satellites and started exporting satellite data products, spacecraft subsystems and components in a small scale. India reached this position by judiciously combining local effort with foreign collaboration. This is illustrated by the Fig. 2.

This paper clearly showed that foreign collaboration appears to have played a very significant role during the formative phase of competence building, that is, until the mid-1980s (see Table 2). In the area of remote sensing satellites the Soviet Union was the foreign actor while, in the case of communications satellite, it was the US and the European countries, particularly France. Under the Aryabhata, Bhaskara–I and Bhaskara–II projects, India learned how to design, fabricate and test a spinning low-earth orbit satellite. Under the APPLE and the INSAT–1 projects, India learned a number of techniques involved in building and operating geo-stationary, 3-axis stabilised communication satellites. During this period, it appears that India was able to import almost anything needed for its programme without hindrance. At the same time, it was clearly evident that India was making strong efforts indigenously to develop all the components it could by using existing knowledge and capabilities.

This paper also demonstrated the predominant role of local efforts during the accumulative phase, that is, since the mid-1980s. It is clear that India's dependence on foreign imports has significantly declined during the IRS–1 and INSAT–2 projects (see Table 3). The developments under these projects suggest that due to export controls India started planning and managing its indigenous efforts in a manner so as to reduce dependence on foreign countries for most critical items. During this per-

[14] Interview with Dhawan.

Table 2
Balance between imported and local technological inputs in the formative phase

Period and projects	Foreign imports	Local inputs
Late 1960s and early 1970s — before Aryabhata	Joint experiments and training with NASA.	Ground experiments such as pilot satellite–TV project.
	Joint studies with NASA, General Electric and Hughes Aircraft, and MIT to design INSAT.	Designing and building different kinds of small payloads for sounding rocket experiments.
	Assistance from French space agency–CNES, to develop infrared scanner and supply of components.	Designing small satellites.
	Direct data reception from the US and Canadian satellites.	Setting up small ground facilities
	Imported remote sensing cameras from the US.	
1973–1975: Aryabhata	Imported most of fabrication and testing equipment; almost all subsystems, components and instruments used for experiments in the satellite.	Major part of satellite design.
	Significant technical assistance from the Soviet Union for design studies and testing various models of the spacecraft and spacecraft control. Cost free launch by the Soviet Union.	Fabrication of the satellite main bus. Assembling the system and sub-systems. Quality control at component level.
		Setting up basic infrastructure, including training the core team of scientists. Developing local firms as sub-contractors and suppliers.
1975–1981: (a) SITE and STEP; (b) Bhaskara I and Bhaskara II; (c) APPLE	The US, France and Germany provided satellites for experiments. NASA and British Aircraft Corporation provided design, training and testing assistance.	Supplied most ground equipment.
	Imported about 25 per cent components for Bhaskara I and II.	Design and development of payload for Bhaskara I and II.
	Soviet assistance in final tests and free launch. ESA assistance for design, testing, and free launching of APPLE.	Design and fabrication of main bus and sub-systems using imported components.
	Imported most of critical components and sub-systems.	Development of technological partnership involving firms and various institutions.
		Development of non-critical sub-systems for APPLE. Initiated local development of most of imported critical items.
1979–1990: INSAT–1s	Ford Space and Commerce Corporation designed, built, and supplied INSAT–1s and equipment for satellite control centre. It imparted project management, testing, integration and documentation skills.	Design specifications for INSAT–1 and project co-ordination with Ford.
	Failure analysis by NASA.	Failure analysis and spacecraft control

iod, India appears to have accumulated a high level of capabilities in the areas of design, fabrication, testing, integration and spacecraft control. It has also established world class facilities for spacecraft simulation, testing, and various analyses. Overall, India appears to have achieved threshold capabilities in satellite building by the mid-1980s. Therefore, it is likely that the role of foreign technological inputs in competence building in future may decline further.

The major factor, which helped India to gradually reduce foreign technical assistance and import appears to be the emergence of a technological partnership among ISRO, other R&D institutions, universities, and industry (see Fig. 3). Leading scientists such as Sarabhai and

Table 3
Balance between imported and local technological inputs in the accumulative phase

Period and projects	Foreign imports	Local inputs
I. Mid 1980s to Mid 1990s: IRS–1A to IRS–1D	Import of limited equipment and components for setting up ground facilities.	Setting up facilities such as simulators, environmental chambers, calibration facilities with mostly local supplies.
	Some critical components and sub-systems such as Charge coupled devices (CCD) and imaging lenses were imported.	Major indigenisation effort was taken. Most of the sub-systems and some critical components such as reaction control system, reaction wheels, attitude reference system, solar array drive mechanism, and various sensors were developed locally.
	Imported solar panels and cells for nickel–cadmium (Ni–Cd) batteries.	Indigenously made solar cells, Ni–Cd batteries.
	Unlike the Aryabhata, Bhaskara I and II, nearly total absence of Soviet assistance.	Indigenous propulsion system — a hydrazine based Reaction control system (RCS).
II. Mid 1980s–Mid 1990s: INSAT–2A to INSAT–2D	Imported a number of critical items below sub-system level such as solar cells, highly polished beryllium mirrors, cells for nickel–cadmium batteries and thermal blankets.	World class facilities such as Large Space Simulation and Acoustic chambers were built by using largely local knowledge and resources.
	Imported microelectronic components and advanced material and high precision parts such as radian hardened integrated circuits (ICs), micro-processor for attitude and orbit control system, microwave transistors and titanium propellant tanks for Apogee booster motor (ABM) and microthrusters.	Number of critical sub-systems such as communication and VHRR payloads, liquid ABM, reaction control thrusters, solar array and carbon-fibre antenna.
		Nearly all sensors for attitude and orbit control, inertial systems and Ni–Cd cells.
III. Since late 1990s: (a) Next generation IRSs and INSATs; (b) Exports	Importing certain microelectronic and high precision components and advanced materials.	Indigenous capability in most areas at sub-systems level and to some extent at component level.
	Small number of imported equipment for ground facilities	Nearly total indigenous capability in ground facilities. Selling satellite data, providing satellite transponders on lease, exporting components and sub-systems for spacecraft systems.

Dhawan actively fostered local firms in both public and private sectors and forged linkages with other R&D and academic institutions such as Council of Scientific and Industrial Research (CSIR) laboratories, IISc, IITs and universities. With a steady increase in the number of new projects since the mid-1970s, the demand for supplies also has increased. ISRO was not in a position to meet all of them by in-house effort. Therefore, ISRO started developing local firms to meet as many demands as possible.

ISRO has fostered a network of supplier firms through applied R&D, proto-type development, technology transfer, training, sharing of information and facilities, and quality management systems. ISRO and in some cases other R&D organisations provided the "know-how" to firms, which either was developed locally or absorbed from a foreign source. The firms were involved in development and engineering (D&E), R&D related to production problems, and final production. The "know-why" and the basic research remained under the domain of ISRO, other R&D organisations and academic institutions. By the late 1990s, ISRO has transferred 231 technologies to the firms and over 500 small, medium, and large firms, from both public and private sectors, were involved in the space programme (DOSa, 1998–99, p. 82). Some of the large firms have established separate space divisions to meet ISRO's demands. Simultaneously, ISRO also developed links with universities through a programme known as Sponsored Research (RESPOND) and brought in other public R&D institutions. Gradually, it has helped to forge links among firms and between various institutions.

The wider technology diffusion through creation of strong links between ISRO, other R&D performing organisations, academic institutions and firms appears to have helped India to accumulate a high level of capabilities in space technology. The trend of its exports suggests that India would have to depend on foreign collaborations to enter the international market in this area. It is very unlikely that India would become a competitor to other developed countries in this area. On the other hand, it is likely to complement their capabilities by col-

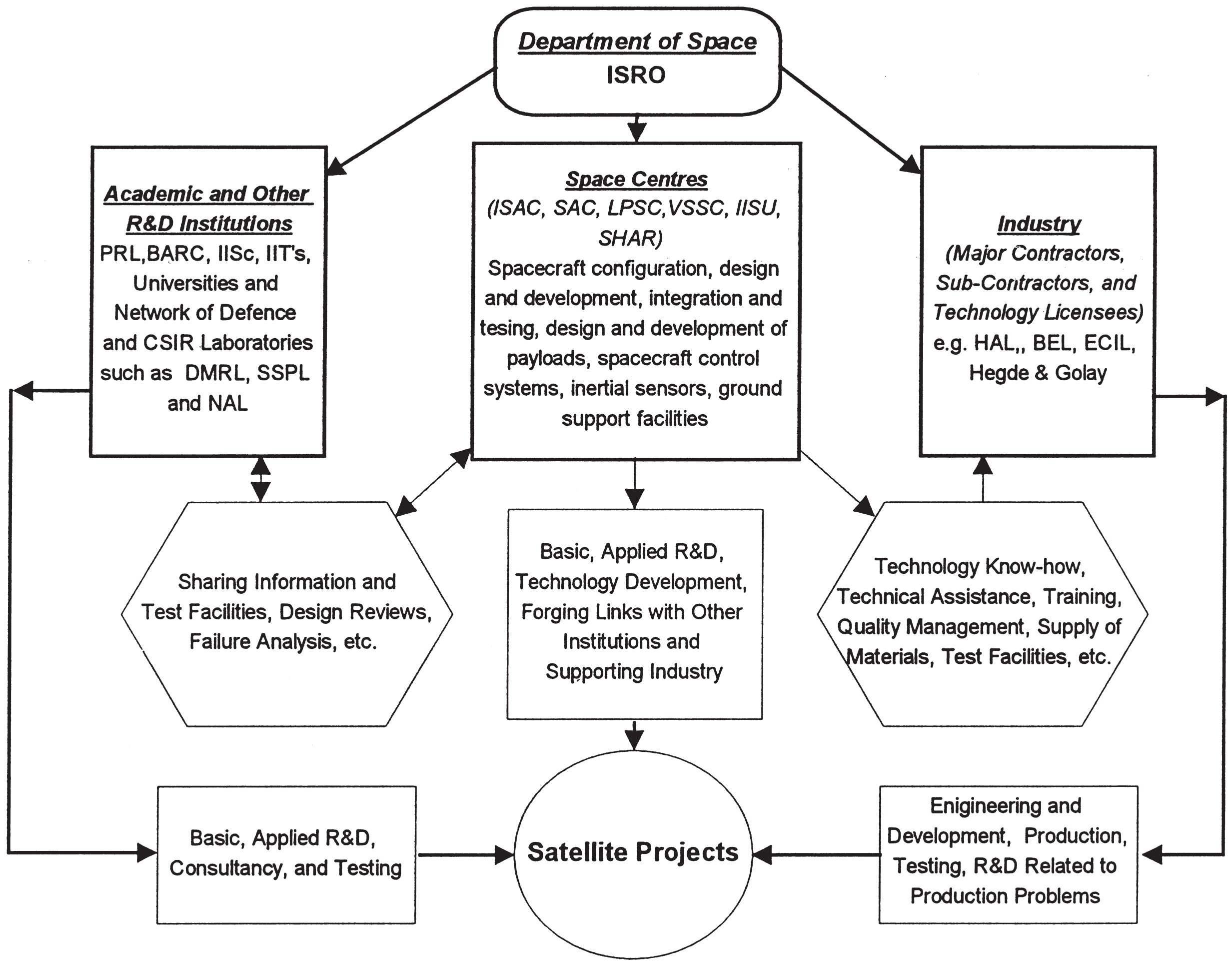

Fig. 3. Technological partners in India's satellite programme.

laborating with them at sub-contacting level (DOSa, 1997–98, p. 81; 1998–99, pp. 84–85).[15] Further, it is also likely that with increasing complexity of its next generation satellite projects, India will continue to depend on foreign imports for high precision and micro-electronic components, materials and advanced equipment for ground facilities. This suggests that competence building in complex systems in a developing country would continue to depend on considerable foreign technological inputs, even after it reached threshold level. Also, India's experience suggests that for entering international market in the area of complex systems, which is very competitive, a developing country may have to forge foreign collaborations.

[15] This trend is clearly discernible as space organisations and companies in the US, France, the UK, Germany, Japan and Korea are showing interest in India's capabilities in spacecraft and launch vehicle systems.

5. Conclusions

This paper has shown that since 1975, India has accumulated a high level of capabilities to build world class remote sensing and communications satellites. India's experience in satellite technology has shown that the importance of foreign technological imports varies at different periods during the process of building capabilities. This paper clearly demonstrated that foreign technological inputs played a major role during the formative phase (from the early-1960s to mid-1980s) and it considerably diminished during the accumulative phase (from the mid-1980s). However, the evidence demonstrated the importance of foreign technological imports for competence building in a developing country during all phases. Although they are less important in the accumulative phase than in the formative phase, their role is still considerable during the accumulative phase. This shows that foreign technological inputs in some form are indispensable to a developing country for building capabilities in complex systems such as space technology. It appears from this case study that technological self-sufficiency cannot be achieved without foreign inputs in some form. Even after reaching threshold level, competence building in complex systems in a developing country is likely to depend on considerable foreign inputs on a continuous basis.

This paper has also shown that without strong indigenous effort India's capability in satellite technology would not have grown to the present level. It is possible that the Indian satellite programme might have failed even if foreign technological imports had been "freely" available, because it is unlikely to have met with success without the necessary local effort and knowledge. The evidence in this paper has shown that both internal and external knowledge played important roles in competence building. The rate of technological accumulation achieved at a given time seems to have been decided by the combination of these factors.

The general observation from this paper is that both external and internal knowledge appear to play an important role in competence building. However, the importance of foreign inputs and the indigenous efforts varies at different phases during this process. The foreign inputs may play a major role during the initial phase while indigenous R&D may play an important role during the later phase. Both appear to be very effective in influencing the pace of capability building when they are combined, particularly in the case of complex technologies. Therefore, internal and external knowledge appear to play a complementary role in building technological capabilities. In other words, both foreign imports and local effort are necessary for building capabilities in complex systems in a developing country.

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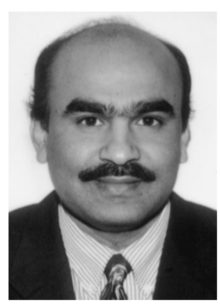

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