

Controlling telescopes, antennas and airborne radars: BARC's five-decade-long journey from Ooty to Hanle

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This article provides a case study of antenna control servo system development in the Department of Atomic Energy over the last five decades, starting with the pioneering efforts for Ooty Radio Telescope (1970) and Arvi Earth Station (1971). While tracing the evolution of technology, the challenges and motivations, we evaluate these efforts against the basic tenets espoused by Homi Bhabha and Vikram Sarabhai for the growth of science and technology in India, viz. self-reliance with commercial viability.

Keywords: Airborne stabilization, antenna control, radar seekers, radio telescope, servo systems.

Introduction

TWO events in the 1960s nucleated the development of telescopes and antenna systems in India – Homi Bhabha's invitation to Govind Swarup to return to India leading to the Ooty Radio Telescope (ORT) and Vikram Sarabhai's decision to entrust Indian engineers with building the 97 ft antenna for Overseas Communication Services at Arvi, Pune.

ORT and Arvi laid the foundations of enduring indigenous capability in the development and manufacturing of antennas and telescopes in India. This capability stood the nation in good stead by supporting programmes in space, astronomy, communication and defence sectors. The Servo Group of the Bhabha Atomic Research Centre (BARC), Mumbai, which inherited this legacy went on to develop servo systems for Satellite Launch Vehicle (SLV) trackers in the 1970s, Earth station antennas for the Master Control Facility (MCF) of INSAT in the 1980s, Unmanned Aerial Vehicle (UAV) trackers and Giant Metre Wave Radio Telescope (GMRT) in the 1990s, radars, seekers and 32 m deep space network antenna for supporting the moon mission in the 2000s and Multiple Atmospheric Cerenkov Experiment (MACE) telescope in the 2010s. These projects helped nurture expertise over three generations in BARC, maintaining the cutting-edge, while expanding the product portfolio of a profit-making strategic business unit in the

Electronics Corporation of India Ltd (ECIL). The servo domain also defined the career aspirations of hundreds of professionals in BARC, Indian Space Research Organization (ISRO) and ECIL. The umbilical memory had held on; ISRO, BARC and ECIL continue to team up, bringing together their complementary competencies to set new benchmarks in antenna development.

Ooty Radio Telescope

ORT remains an engineering marvel even today – a 500 m long, 10 m wide cylindrical parabola weighing about 500 tonnes, erected on the slopes on the verdant hills of Ooty¹ (Figure 1). Its cylindrical axis lies parallel to the earth's north-south spin axis and is driven at constant speed by geared synchronous motors powered by stable inverters. The drive system was developed by the Electronic Prototype Engineering Laboratory (EPEL) at Trombay, the forerunner of the Reactor Control Division (RCnD) of BARC, led by S. N. Seshadri, considered to be the father of servo systems in India. Seshadri would go on to build a robust servo team in BARC.

ARVI: ASCON project

To provide overseas communication services via INTELSAT, a 97 ft antenna was proposed to be built at Arvi in the late



Figure 1. The Ooty Radio Telescope.

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1960s. At the early planning stage, when the question of assigning the entire project as a turn-key job to a foreign firm was being contemplated, Sarabhai insisted that the entire work should be engineered by an Indian team². Arvi would be the very first antenna of that size built in India through indigenous efforts showcasing the country's technical, engineering and project management capabilities (Figure 2).

The Arvi project marked the beginning of antenna control servo systems in India. The 97 ft diameter antenna with Cassegrain geometry, weighing around 300 tonnes was steered in azimuth (AZ) and elevation (EL) axes to track geosynchronous satellites within 0.03° . The servo system supported automatic tracking, manual positioning and slew modes of operation.

Unlike ORT, Arvi required variable speed drives with full torque delivery capability at all speeds. Only armature voltage-controlled DC servo motors fitted the bill. This required armature DC voltage to be variable. Thyristor-controlled rectifiers of the required rating were still a few years away. Hence the project chose Ward–Leonard drives with a generator of 18 kW, powering a low-inertia 20 HP DC servo motor. The field of the WL generator was controlled by a reversible thyristor amplifier. Each antenna axis deployed two such drives in torque-sharing mode with a 2.3 kW counter-torque generator to eliminate the effect of gear backlash.

For the first time in the country, 20 HP servo motors were designed and built by BARC. For the first time too, cascade control strategy was being put in practice in India for tracking control of antenna. For each axis, two inner current loops were enclosed by a common speed loop which in turn was enclosed by the position/track loop. Operational amplifiers (OPAMPs) – still a novelty – were deployed in numbers to realize these controllers. In AUTO track mode, the position loop was closed through monopulse tracking receiver and in MANUAL positioning mode through synchros. Antenna angles were measured by a set of course/fine synchros, and then digitized and displayed on a NIXIE display (LED seven segments were still years away). That was the only ‘digital’ subsystem in the entire servo chain.



Figure 2. The ARVI achievement commemorated by a postal stamp.

The Arvi Earth Station was commissioned in February 1971. Along with its sibling at Dehradun, these served as international communication gateways for decades, carrying majority of the traffic. The speed with which the Arvi Station was erected was remarkable. Within three years of the project launch, the Arvi Station was up and running. The project had put together a team of young engineers – microwave, mechanical, control, civil, electrical – who went on to lead new groups in ISRO, ECIL, SAMEER and BARC.

The underlying technologies were changing at a scorching pace. By the time a similar earth station was erected at Dehradun two years later by ECIL, BARC could come up with a thyristor-controlled drive system doing away with the Ward–Leonard drive.

Within a decade, microelectronics, microprocessors and software would enter the scene. In 1981, the Arvi and Dehradun stations – now named Vikram and Ahmed respectively – were fitted with an 8080-based step-track control system, replacing the monopulse tracking system. This would be one of the earliest applications of microprocessors in real-time control in India.

SLV trackers

With the newly formed ISRO launching ambitious space programmes, BARC went on to develop and deploy tracking radars for satellite launch vehicles at SHAR and Tracking Telemetry and Command (TTC) terminals at Port Blair, Car Nicobar, etc. By 1973, BARC had designed and commissioned the angle tracking servo system for the tracking radar at SHAR (Figure 3). The servo system had a total average power of 2 HP and tracked rockets up to 1 radian/sec angular velocity. Analog computer was used for simulation studies. This was a significant step in mastering the technology of tracking servo.



Figure 3. Servo system for SLV Radar under test at BARC, Mumbai.

Meanwhile, ISRO was building its servo team and technology was transferred by BARC to the former.

MCF Hassan

ISRO deployed the first of its geosynchronous INSAT series of satellites in 1982 – it would open up the era of satellite broadcasting in India. To manage INSAT satellites, ISRO proposed to build a Master Control Facility (MCF) at Hassan. ECIL was awarded the contract to build two 14 m fully steerable antennas (Figure 4). BARC was entrusted with the development of the servo system.

Thyristor-based motor drive was the contemporary technology then and RCnD was a leader in thyristor drives. Three-element cascade control strategy was also well-established for antenna servos. A host of OPAMP circuits implemented monopulse track loop, speed loop, current loop, torque bias and protection functions such as over-current and over-speed. Antenna position was measured by axis-mounted two-speed synchros digitized by synchro digital converters to 16-bit resolution. The synchros were coupled to the axis through spring-loaded data gears.

The servo system supported auto track, programme track, manual positioning and slew modes. In the Programme track, the satellite angle predicts were supplied by an external computer. This required the servo system to compute position errors digitally in real time as the difference between predicted and measured angles.

Even though BARC was developing a microprocessor-based step-track system around that time, questions were raised on the prudence of relying on an ‘unknown’ techno-

logy for such a mission-critical application. Hence the entire ‘digital logic’ was built around 54 series TTL hardware.

These antennas continued to serve successive INSAT missions.

MCF Hassan turned out to be a green pasture for ECIL, which went on to build dozens of antennas of various sizes over the subsequent decades as the Indian space turned denser with ISRO satellites.

In the ‘make-in-India’ spirit that inspired that generation, most of the subsystems that went into the servo system were developed in-house at BARC. The servo motors, thyristor-based drive cabinets, control console (Figure 5), angle sensor assembly including data-gears, card guides and card cages were all designed and manufactured in-house. The import dependence was limited to semiconductors and synchros.

Giant Meter wave Radio Telescopes (GMRT)

As one drives from Pune towards Narayangaon on the way to Nasik, the horizon comes alive with a large number of white, strange structures in some kind of a celestial dance. These are the telescopes of GMRT, an international radio astronomy facility located at Khodad, one of the world’s largest facilities for frontline research in radio astronomy (Figure 6). Set up by NCRA/TIFR in the 1990s, under the inspiring leadership of Govind Swarup, GMRT consists of 30 45-m diameter, parabolic, wire-mesh dishes arranged along the arms of a Y extending over 25 km. The radio signals received by the array from distant celestial sources are electronically correlated to provide a high-resolution radio image of the sources.



Figure 4. The 14m antenna erected at MCF Hassan in 1982.



Figure 5. Antenna control console for MCF Hassan.

BARC had developed the servo systems for these elevation (EL) over Azimuth (AZ) telescopes (Figure 7). Almost a decade had passed since the MCF project and servo technology had evolved meanwhile. Permanent magnet brush DC servo motors driven by thyristor amplifiers still ruled the roost. Synchros had ceded space to absolute optical encoders for position measurement and the project chose 17-bit encoders with 20 arcsec accuracy.

By the end of the 80s decade, computers already controlled nuclear reactors in India. Hence there was no reservation on software-based control for GMRT. The Station Servo Computer (SSC), was the end-point of a long chain of computers that connected it to the Central Control Room from where astronomers would initiate experiments, feeding position demands to each of the 30 telescopes for tracking the celestial targets in synchrony.

In addition to remote communication, data acquisition, interlocks and operator interface functions, 8086-based SSC

hosted the real-time task of closed-loop position control. The inner current and speed loops continued to remain analog. All the operational and safety interlocks were duplicated by hardwired relay logic.

BARC had developed a library of bus-structured boards by that time for other projects and these were reused. A couple of 8051-based IO boards were developed working in a tightly coupled multi-computer architecture.

Tuning the servo at the site had its moments of anxiety since an oscillating dish made mechanical engineers jittery. This was a trial-and-error affair, informed by the knowledge of the locked rotor frequency alone since we did not have the simulation tools then. Unlike in the MCF days when re-tuning often involved desoldering capacitors and resistors, a digital servo facilitated the change of gains and time constants from the keyboard.

GMRT was to be the first major servo control project deploying a computer-controlled servo system in an Indian telescope. It marked an important step in the evolution of servo technology in India. Implementing the position loop compensators in software was a novel challenge. There would be multiple concurrent processes running – in addition to the main control process scheduled every 100 msec, there were event-driven tasks linked to host communication, user interface, etc. A homegrown real-time executive was deployed for managing these multiple tasks. The software development was carried out on a Microprocessor Development System (MDS) using PASCAL cross-compiler and emulator support for 8086. That meant one could not modify the code at the site. Even though PCs had begun to penetrate offices, they were yet to mature as a cross-development platform. A PC in the control room was years away.

However, all those would change within a few years. PCs invaded the development and deployment platform space. MDS became obsolete soon, replaced by desktop PCs hosting sub US\$ 100 cross compilers.

GMRT stands as a shining example of ‘make-in-India’, built with a shoe-string budget. However, even by the late 1980s, India was losing the battle for technology independence in electronics. Servo motors, angle sensors and almost all semiconductor components had to be imported even as system design, circuit design and software remained our core strength.

Antenna control units for UAV programme

BARC’s foray into military servos began with the development of a tracking system for UAV being built by DRDO. The truck-mounted, 6 ft antenna was required to be continuously steerable in azimuth, and support scan and track modes. Tracking would use the monopulse technique. All the equipment was required to qualify to ground-mobile military standards.

Except for the military qualification issues, the rest of the design followed a well-trodden path. By this time, BARC had a library of field-proven hardware.

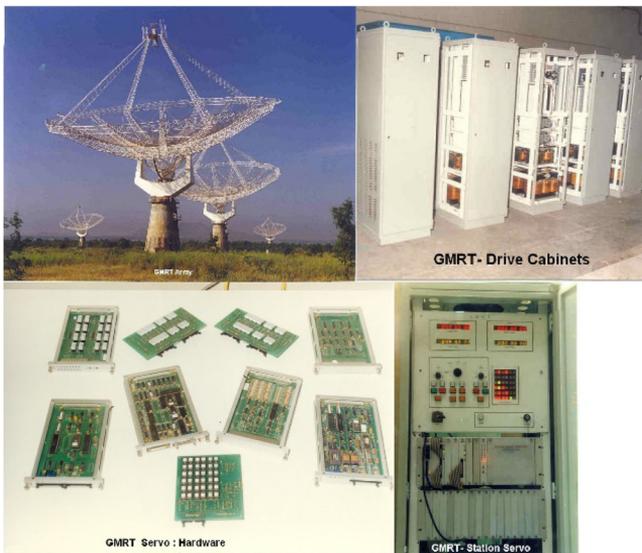


Figure 6. GMRT array and servo system.

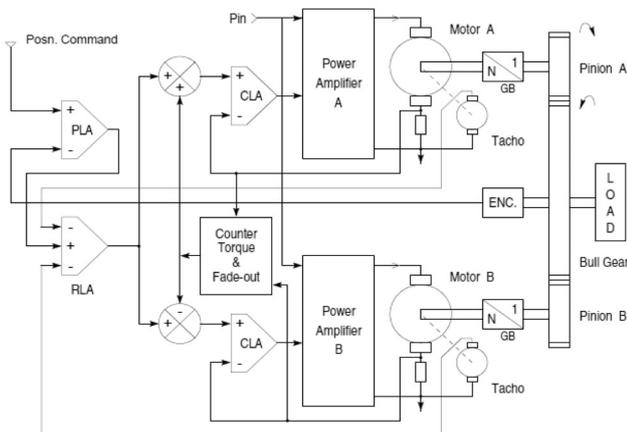


Figure 7. Block diagram of GMRT servo system.

Within a couple of years, the UAV tracker was successfully developed and deployed; ECIL eventually received limited series production (LSP) orders too. This was followed by a couple of variants including dual-axis pedestals and trackers for pilotless target aircraft (Figure 8). However, the programme never delivered the promise of series production so essential for sustaining a production line.

These projects launched an enduring collaboration between ECIL and BARC for the joint development of antenna systems for DRDO. What began as a small UAV tracker project in the 1990s, led to the development of missile seekers, airborne SATCOM terminals and a successful antenna platform for the multi-mode radar for light combat aircraft (LCA).

Stabilization and tracking system for Active Radar Seeker for missiles

Around 1997, DRDO and SAMEER approached BARC to partner with them to build a state-of-the-art Active Radar Seeker. Seekers are missile-borne radars that help guide the missile towards a target in the terminal guidance phase. A radio frequency (RF) seeker consists of an antenna, RF transmitter/receiver electronics and radar signal processor – the latter computes the target's range, speed and direction using pulse Doppler radar techniques. The RF beam needs to be steerable to point towards the target at all times – for this purpose antenna is mechanically steered by mounting it on a two-axis gimbal mechanism. Hence, a servo mechanism is needed to position and stabilize the antenna against the missile's body disturbances. All these are housed in a compact, rugged conduction-cooled housing inside the missile nose-cone enclosed by the radome.

The seeker interfaces with the missile's inertial measurement unit and guidance computer. It is initially provided with the target's estimated position. Once detected, the seeker locks onto the target and tracks it till interception.



Figure 8. UAV tracking systems.

As the missile moves towards the target, the seeker measures the angles and angular rates of the line of sight vector (LOS) and feeds them to the guidance computer (GC). The GC uses this LOS information to guide itself towards the target.

While antenna boresight should be always aligned with the LOS, missile body disturbances couple to the gimbals and make the antenna move away from the boresight. The performance of the stabilization system is measured by its ability to hold the antenna steady by isolating it from these disturbances. The probability of interception depends on the accuracy of LOS angles and rates computed by the seeker. However, achievable isolation is limited by servo bandwidth, which in turn is limited by structural resonances. Hence, it is necessary to have a mechanical arrangement that offers low inertia and high stiffness.

Till then, the BARC servo team was not aware of seekers outside the spiritual world. In course of time, one learnt about missiles, stabilization, inertial systems, frame transformations, guidance and control, MIL 1553B and airworthiness. This was a steep learning curve to climb. Since the technology was of restricted nature, there was not much available in the open literature. Simulators were used extensively for modelling the dynamics, performance analysis and controller synthesis.

It took many iterations to arrive at a functioning gimbal configuration. There were conflicting demands on size, weight, power, stiffness, inertia and steering envelope. The specifications of the antenna and RF transmitter which formed the 'payload' for the stabilization system kept changing, forcing frequent design changes.

The electronics for the stabilization system was to be developed bespoke. SHARC Digital Signal Processor (DSP) was selected for executing control software. Miniature motors, gyros, resolvers, 1553 components, etc. were identified after some search. The electronic circuit boards and software were ready in a couple of years, setting the stage for integrated testing.

Yet, the road from a laboratory prototype to a qualified, air-worthy seeker proved to be full of hurdles. Primarily, dependence on imports for some of the critical subsystems such as RF transmitters led to numerous iterations and jeopardized the project.

While the design iterations continued well into the 2010s, ECIL won a development contract around 2012 for another class of RF seekers. It was to be one more DRDO–ECIL–BARC collaboration. All the previous learnings were brought to bear on the new development. Slowly but steadily, the new seeker took shape, passed various tests and was made ready for flight trials (Figure 9).

Finally in April 2018, news broke out that an indigenous seeker was tested successfully on-board a missile flight. The seeker had locked onto the assigned stationary ground target from the designated range and hit the bull's eye. This event marked the addition of a vital indigenous capability.

Antenna platform unit for air-borne radar

The Antenna Platform Unit (APU) for airborne multi-mode radar was one of the most successful R&D projects executed by the BARC Servo Group – both in terms of technical complexity and commercial value. The project was taken up by ECIL and BARC in 1999 under a contract by Aeronautical Development Agency (ADA), Bengaluru.

The APU was required to support scan modes of the multi-mode radar (MMR) of LCA by precisely positioning the two-axis, gimbal-mounted flat plate antenna, as commanded by the on-board radar processor (RP). Since the radar would be tracking multiple targets simultaneously, the accuracy of detection and tracking depended on precise knowledge of the antenna's position at any instant of time. For this, the servo system had to stabilize the antenna against the aircraft's pitch, roll and yaw motions. This was achieved by transforming the NED (north, east, down) frame demand angles to scanner frame at a high rate, resolving them to AZ/EL angles of the gimbal and then carrying out closed-loop position control.

All these required a high-bandwidth tracking servo capable of fast accelerations and decelerations, and quick turn-

around during the scan. Transport lags and computation delays had to be controlled precisely within a few microseconds.

Each axis was driven by a pair of geared permanent magnet synchronous motors (PMSM). This required ab-initio development of a 300 W vector-controlled drive using ADMC401 motor control digital signal processors (DSPs). Following the expertise gained in the seeker project, SHARC DSP was adopted as the control engine.

Extensive modelling and simulation study was carried out during analysis and design. The software was designed with built-in support for testing, tuning and troubleshooting the system. Every parameter was logged in real time for offline viewing and analysis. These would become standard features in later systems.

The control electronics were air-cooled and housed in rugged cassettes that took care of thermal, EMC and air-worthiness issues. Being an avionics unit in a manned aircraft, APU had to be flight-worthy and certified by SEMILAC. The control software had to conform to ADA's verification and validation standards. Much of it was uncharted territory for the development team.

By 2006, APU had cleared safety-of-flight tests setting the stage for on-board trials, as well as initial operational clearance and final operational clearances³. ECIL went on to qualify and supply scores of APUs, each costing more than Rs 2 crores (Figure 10).

Many factors led to the success of this project, viz. enlightened project management, unstinted backing to indigenous efforts even as setbacks threatened to derail the efforts, excellent team effort, clear, frozen and unambiguous specifications and a clear road-map for series production.



Figure 9. Indigenous RF Seeker.



Figure 10. Antenna Platform Unit.

Indian Deep-Space Network: IDSN32 antenna

In 2004, when ISRO set about planning a 32 m antenna for the upcoming Chandrayaan-I mission, there were helpful suggestions to follow the import route. However, ISRO's faith in indigenous capability reinforced by the ECIL–BARC team's proven track record prevailed and the contract was awarded to ECIL.

IDSN32 supports tracking, telemetry, command (TTC) and science data reception functions in *S*- and *X*-bands. The 32 m diameter parabolic reflector with f/D of 0.35 is made using Al panels ground to 300 μ m surface accuracy. The antenna has Cassegrain geometry with a 3.2 m hyperboloid sub-reflector fixed on quadripods. It features beam-guide optics directing the RF energy via a series of dichroic mirrors to the instrument room below the antenna.

The entire 300-tonne behemoth is steerable in elevation and azimuth to point anywhere at the sky. The pointing/tracking accuracies are of the order of a few millidegrees in the *X*-band. The servo system supports a host of tracking modes, remote/network modes of operation and scheduled tracking.

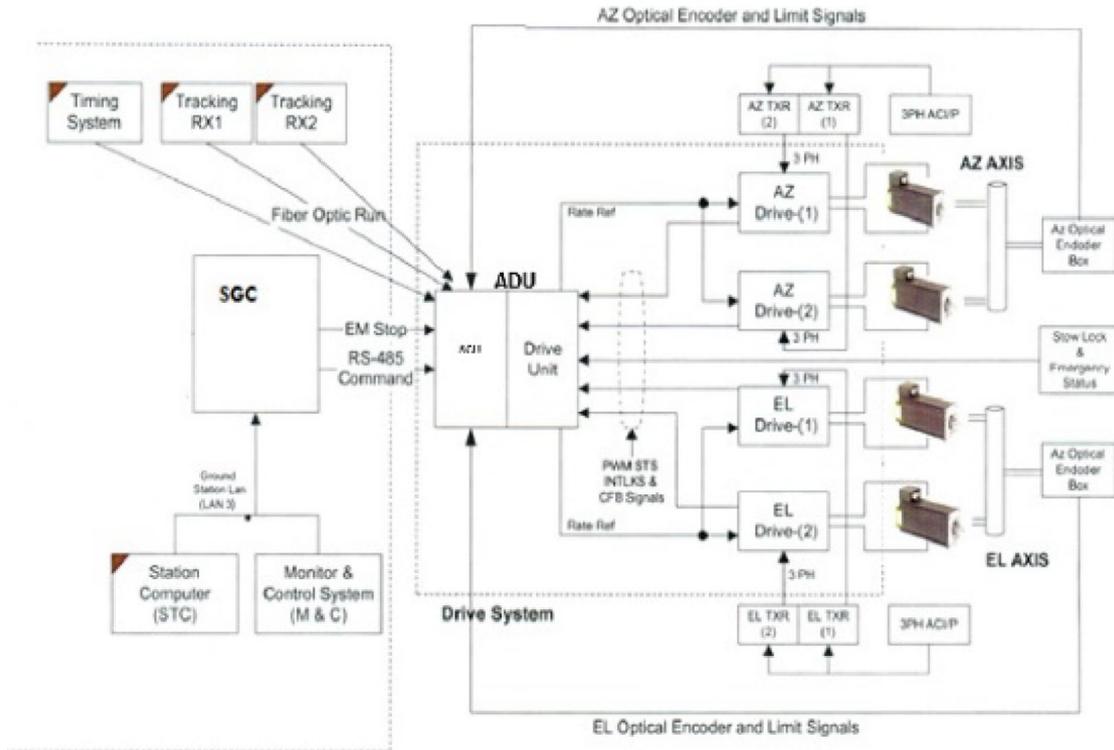


Figure 11. Block diagram of ACSS.

GMRT was already more than a decade old and in the interim, servo technology for large antennas had progressed substantially. Brush DC motors had finally ceded space to robust PMSMs powered by DSP controlled pulse width modulated (PWM) vector control drives switching insulated gate bipolar transistor (IGBT) devices. ‘Digital’ and ‘software’ had conquered the hard-real-time domain of power electronics and motor drives. However, PMSMs and drive amplifiers were not made in India, and had to be imported.

Designing an accurate AZ encoder assembly posed severe challenges. Beam-wave guide optics of IDSN32 precluded an on-axis encoder in AZ, while the off-axis arrangement was error-prone. This had to be measured and compensated for. The unevenness of the AZ track would cause pointing errors of a few arcsecs – it was to be measured and compensated using tilt sensors. The RF axis would deviate from the mechanical axis due to gravity droop – a five-axis sub-reflector positioner was developed to compensate for this. Provision was also made in the software to compensate for other systematic pointing errors.

The Antenna Control Servo System (ACSS) was developed around a generic motion control engine that was built as a cPCI/RT-LINUX/Pentium platform, maximizing the use of commercial off-the-shelf (COTS) hardware and software (Figure 11). Few interfaces such as discrete input/output, EnDAT and CAN were specifically developed. The objective was to develop a platform that could be re-used during the next decade.

A similar long-term goal drove the development of modular software architecture. Drawing on the experience from past projects, built-in test equipment (BITE) capability was incorporated to facilitate servo testing, tuning and re-configuration.

Except for basic maintenance-mode operations, hard panels were replaced by soft human machine interface (HMI), hosted on a separate LINUX workstation which also functioned as a gateway for remote terminals.

IDSN32 was up and running by the end of 2007, ready to welcome Chandrayaan-I (Figure 12).

Seven hours after the epochal launch of Chandrayaan-I from Sriharikota on the morning of 22 October 2008, IDSN32 picked up the signals from the spacecraft as it first appeared on the horizon as predicted. As it continued to track the satellite through its maiden orbit around the earth with clockwork precision, the assembled gathering of engineers from ISRO, BARC and ECIL broke into applause. While ushering India into the elite club of space-faring nations, that rainy day in Bengaluru also marked a milestone in the journey of servo systems in India⁴.

BARC continued to support improvements in IDSN32 with smooth, low-speed tracking and advanced control algorithms. A linear-quadratic-Gaussian (LQG) controller was integrated in January 2020 with much increased bandwidth promising better wind disturbance rejection and tracking accuracy for future Ka-band upgrades⁵.

The IDSN32 project helped renew BARC’s collaborations with ISRO. It enabled the BARC servo team to upgrade



Figure 12. IDSN32 antenna with servo cabinets.

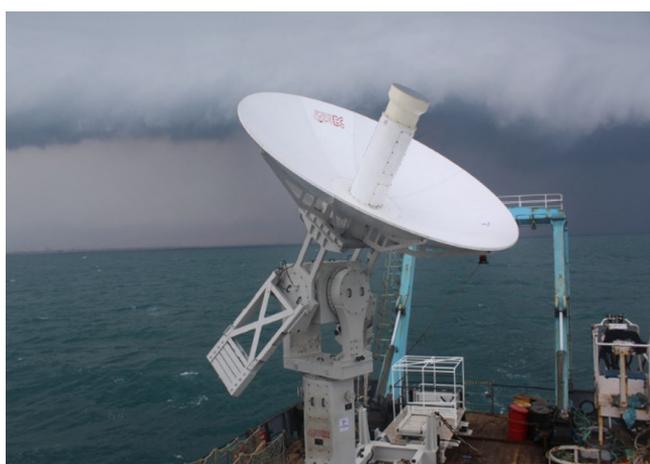


Figure 13. SBT deployed on-board a ship.

knowhow and master new technologies. This led to other projects with ISRO–BARC–ECIL combination, viz. shipborne terminal for tracking reentry vehicles and ISDN18, an 18 m sibling to the 32 m big brother.

Shipborne terminals for ISRO

ISRO's Telemetry Tracking and Command Network provides TTC (telemetry, tracking and control) support for launch vehicles and spacecraft for all its missions. BARC, ECIL and ISTARC teamed up again after the IDSN32 project, to develop a shipborne antenna terminal (SBT) to support ISRO's upcoming re-entry and manned missions to space.

SBT is a multirole, three-axis TTC terminal that is ship-worthy and can be deployed on a ship deck where the ship can be positioned in the high seas, thus extending TTC support capability even in remote areas. This 4.6 m shipborne terminal can track the target in programme or monopulse tracking mode even in the presence of the ship's rocking movements. The antenna is actively stabilized against ship movements by the use of an Inertial Measurement Unit (IMU).

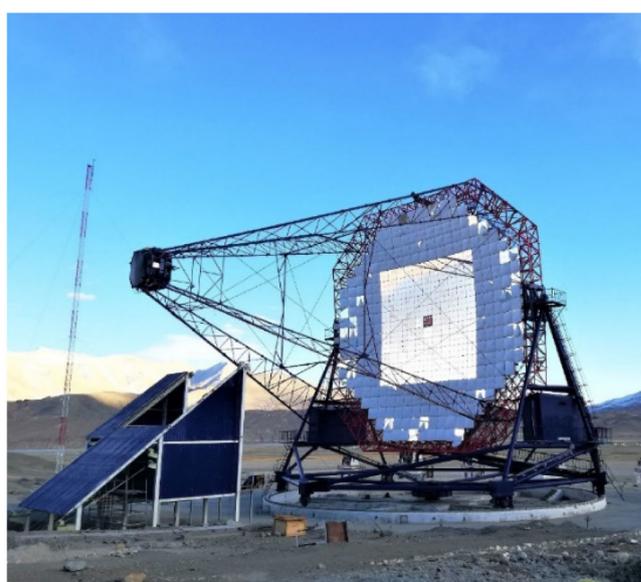


Figure 14. MACE telescope at Hanle.

SBT was validated by tracking a PSLV from mid-sea in 2017 (Figure 13).

MACE telescope

The Astrophysical Sciences Division of BARC proposed to build a 21 m Cerenkov telescope for Gamma-ray astronomy. Named Major Atmospheric Cerenkov Experiment (MACE), this telescope is intended to supplement the worldwide efforts to open up the hitherto unexplored energy range of the 20 to 200 GeV window to the observable universe.

Hanle in Ladakh at 4000 m amsl was selected as the most suitable site and ECIL was given the contract in 2008 to build the telescope with design inputs from BARC.

The MACE telescope consists of a large area tessellated light collector made up of 356 numbers of 1 m × 1 m size pre-aligned spherical mirror panels (Figure 14). The individual mirror panels are fixed on a rigid mirror basket

made up of a tubular space structure. A 1400-pixel camera made up of photo multiplier tubes (PMTs) forms the focal plane instrumentation of the telescope. The camera and mirror assembly can be pointed in any direction in the sky by steering the mirror basket.

The mirror basket is mounted on an elevation over the AZ mount. The AZ track of the telescope is about 27 m in diameter and overall height of the telescope is about 43 m. The main servo system is required to steer the telescope in azimuth ($\pm 270^\circ$) and elevation (-26° to 100°), and support the positioning of the telescope and tracking of celestial sources to 1 arcmin accuracy at up to 30 kmph wind speeds.

The servo system of MACE reuses proven hardware/software components developed for IDSN32. It supports the programme to track, manual positioning and slew modes. One of the essential features of MACE is a fast-slewing mode ($180^\circ/\text{min}$ in AZ) required to capture gamma-ray bursts on receiving alerts. Another novelty is the active mirror alignment system which corrects for the defocusing effect of gravity deformation of the mirror basket by tilting each mirror panel slightly using a two-axis tilt mechanism. Some 700 actuators work in tandem to keep the telescope in focus at all EL angles⁶.

The construction of MACE threw umpteen surprises, technical and logistical. The remoteness and inaccessibility of the site added to the delay. Even though the servo system was integrated successfully during the proof-assembly trials at ECIL in 2014, a series of setbacks in the telescope structure had delayed site installation and commissioning till 2020.

IDSN18M

By 2008, ISRO had established two TTC ground stations at Byalalu near Bengaluru for deep space network requirements – the indigenously built 32 m antenna and an imported 18m antenna. These have provided TTC support for Chandrayaan and Mars orbiter missions. The performance of the antenna systems has met the design goals and has been validated by NASA during the Mars orbiter mission.

To support the upcoming Aditya and Mars Orbiter2 missions, ISRO awarded a contract to ECIL in 2018 to build an additional 18 m antenna system operating in the S and X-bands. The decision was to build it indigenously. ISRO, ECIL and BARC teamed up once again on the lines of the IDSN32 project.

The ACSS has all the salient features of a modern digital control system available in any of the latest ground stations, using state-of-the-art technology. The major performance challenges in servos of this class are achieving low pointing/tracking errors (a few milli degrees) and low smooth tracking speeds (0.1 milli degrees/sec).

Most of the hardware and software could be reused from the IDSN32 and MACE libraries. Cabling issues precluded the use of on-axis encoders in AZ; an off-axis

scheme with attendant gearing-induced errors was not a viable option. Learning from previous experience, an untried option was taken to go for large-diameter hollow-shaft encoders with multiple read-out heads. This decision eventually turned out to be the right one.

Despite the challenges posed by the pandemic, the teams succeeded in commissioning the system by September 2021 (Figure 15). IDSN18 joined the growing family of antennas at the Byalalu site. The timely completion of the IDSN18 project is testimony to the expertise gained by the collaboration in building large antennas.

Evolution of technology

Figure 16 sketches the five decade-long journey by BARC evolving the technology of ACSS in India.

Table 1 lists two extremities of performance specifications encountered during this journey. At one end are large telescopes and antennae such as Arvi, GMRT, IDSN32 and MACE, demanding arc-second tracking accuracies and a large range of speeds (1 : 4000). On the other extreme are fast, high-bandwidth, airborne radars requiring high speed and acceleration. Operating environments range from airconditioned control rooms to the nose cone of a combat aircraft. The mission times vary from 24×7 operations to those lasting for a few minutes.

However, whether the antenna to be controlled is for a small airborne radar or large terrestrial telescope, the performance is often limited by the structure. Servo designer requires high loop gain to attenuate random external disturbances such as wind and body rates – achievable gain is limited by the structure's natural frequency. Other factors such as friction and measurement noise also degrade the performance.

Yet, advancement in technology has made it possible to obtain improved performance over the years. Table 2 captures the evolution of key technologies in the journey from Arvi to Hanle.



Figure 15. Indigenous 18 m Deep Space Network System installed at Byalalu.

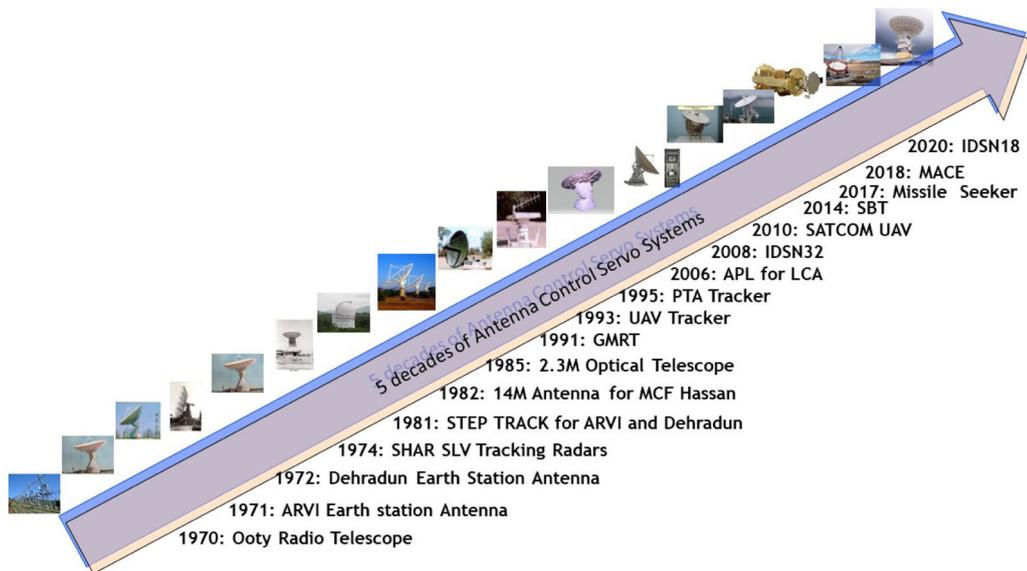


Figure 16. Journey of servo systems over five decades.

Table 1. Servo system performance range

Parameter	32 m Antenna	Airborne radar
Size (diameter)	32 m	600 mm
Steerable mass	230 T	5 kg
Steerability (deg)	± 270 , 0–90	± 70 , ± 60
Locked rotor frequency (Hz)	> 2	> 40
Speed range ($^{\circ}/\text{sec}$)	0.0001–0.4	0.1–300
Pointing accuracy ($^{\circ}$)	0.010 (X-band)	0.1
Servo bandwidth (Hz)	> 0.5	10
Motor power	15 kW	300 W

The advent of DSP-hosted, vector-controlled drives for permanent magnet synchronous motors along with power switching devices such as IGBT has made it possible to have drive systems with zero cogging, large speed range and high torque even at crawling speeds. This coupled with advancements in gear technology and bearings have resulted in low friction, wobble-free, low-backlash drive systems. Advancement in angle sensor technology has made arcsecond accuracies affordable. Problems of drift, offset and noise inherent to the analog world have disappeared – high-speed DSPs, field programmable gate arrays, microprocessors and data converters have facilitated fully digital/software implementation of complex control algorithms.

While the time-honoured proportional integral controllers have served the servo well, arcsecond pointing error budgets demanded by Ka-band operations have led to the introduction of advanced control algorithms such as linear quadratic Gaussian and H_{∞} , enabled by the availability of high-speed processors. With this, the constraint imposed by the system's natural frequency on servo bandwidth is relaxed substantially, affording an order of magnitude improvement in wind rejection in large antennas.

The easy availability of powerful simulation tools for analysis and design has helped in the development of detailed models, control strategies and improvement of servo performance.

On the downside, dependence on imported components, equipment, subsystems and software tools has grown over the years. Critical items such as precision bearings, angle sensors, rotary joints, motors, drives, resolvers and micro-electronics that form part of any servo system are not made in India.

BARC–ECIL collaborations

ECIL was formed in 1967 to commercialize electronics components and instruments developed by the TIFR and the Atomic Energy Establishment at Trombay. The founders of ECIL's Antenna Product and Servo System Divisions had earned their spurs, building the Arvi telescope. The MASEG Group got merged with ECIL in 1972, and Antenna Products Division was formed in ECIL to take up commercial production of microwave and earth station antennas.

Under the enlightened leadership of A. S. Rao, ECIL could quickly build up a profitable business on antenna products and servo components, delivering turn-key solutions to ISRO, Doordarshan, All India Radio and defence customers, catapulted by India's television and space revolutions in the 1960s through 1980s. The company played a pioneering role in supporting the ambitious programmes of INSAT and remote sensing satellites.

The BARC–ECIL collaboration would thrive over the next decades, jointly executing many projects. This has helped ECIL consolidate its position in the space sector and gain new business in the defence sector.

Table 2. Evolution of servo technology

Feature	32 m Arvi (1970)	14 m MCF (1982)	GMRT (1992)	IDSN32 (2008)	IDSN18 (2020)
Motor	DC brush	DC brush	DC brush	PMSM	PMSM
Drive amplifier	Von Leonard	Thyristor	Thyristor	IGBT, vector control	IGBT, vector control
Angle sensor	Synchro	Synchro + SDC (16 bit)	Encoder (17 bit)	Encoder (25 bit)	Encoder (25 bit)
Controller	Analog	Hybrid (analog + digital)	Hybrid (analog + software)	Software	Software
Control topology	Three-loop cascade	Three-loop cascade	Three-loop cascade	Three-loop cascade	Three-loop cascade
Control law	PI	PI	PI	PI+	PI+
HMI	Hard	Hard	Hard	Soft	Soft
Remote operation?	No	No	Yes	Yes	Yes
BITE, diagnostics	–	–	–	Yes	Yes
Communication	None	Parallel	Serial RS485	TCP/IP	TCP/IP

Conclusion

This case study of the evolution of antenna control servo control systems in BARC demonstrates the lasting legacy of Bhabha and Sarabhai. Indigenous technology has endured and advanced while being commercially viable against global competition. It measures well against the tenets espoused by Bhabha for growing science and technology in India: (a) We did not run after foreign technologies at any stage. (b) Successive BARC management encouraged and supported these developments, taking a broader view of the Department's 'mandates'. (c) R&D effort was always delivery-focused, time-bound and commercially viable.

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