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3.6-m Devasthal Optical Telescope Project: Completion and first results

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Abstract: We present an update on the 3.6-m aperture optical telescope, which has been installed at Devasthal in the year 2016. In this paper, a brief overview of installation activities at site and first results are presented. The 3.6-m Devasthal Optical Telescope project was initiated in 2007 by the Aryabhatta Research Institute of Observational Sciences (ARIES; Nainital, India) in partnership with Belgium. The telescope has Ritchey-Chretien optics, an alt-azimuth mount, an active control of the primary and a corrected science field of view of $30'$ at the Cassegrain focus. The construction of the telescope enclosure building was completed in June 2014 and after successful installation of the telescope. The first engineering light was obtained on 22 March 2015. The on-sky performance of the telescope was carried out till February 2016.

1 Introduction

The Aryabhatta Research Institute of Observational Sciences (ARIES; Sagar 2006) - an autonomous research institute under the Department of Science and Technology, Government of India - has established a 3.6-m optical telescope at Devasthal in Nainital (India). Devasthal (meaning abode of God) is located in the Himalayan region. Fig. 1 shows the long distance view of the 3.6-m Devasthal Optical Telescope (DOT) on top of the hill. The DOT facility consists of a modern 3.6-meter optical new technology telescope, a suite of instruments, an Aluminum coating plant, a control room, and a data center. In the near future, the telescope will have a number of instruments providing high resolution spectral and imaging capabilities at visible and near-infrared bands. In addition to optical studies of a wide variety of astronomical objects, it will be used for follow-up studies of sources identified at the

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Figure 1: A panoramic view of the Devasthal Observatory operated by ARIES. The larger white dome houses 3.6-m DOT and the smaller enclosure houses a 1.3-m wide-field optical telescope.

radio wavelengths by the Giant Meterwave Radio Telescope (GMRT) and at UV/X-ray wavelengths by the Indian Space Observatory (AstroSat).

The characterisation of the Devasthal site was carried out on 80 nights during 1998-1999 with a differential image motion monitor using a 38-cm telescope with the mirror about 2 m above the ground. It yielded a median seeing estimate of about 1″.1 with the 10 percentile values between 0″.7 to 0″.8 (mean = 0″.75). For 35% of the time, the seeing was better than 1″ (Sagar et al. 2000). The microthermal measurements at Devasthal indicated that the seeing is in the range from 0″.2 to 0″.3 at 13 m to 18 m above the ground (Pant et al. 2001). The atmospheric extinction studies at Devasthal are described by Mohan et al. (2000). The key parameters of the Devasthal site are summarised in Table 1 which is based on Sagar et al. (2000), Mohan et al. (2000), and Sagar et al. (2011). The next section describes the telescope system and enclosure while the subsequent section gives an overview of the commissioning and initial performance of the telescope. The summary and the future events are described in last section.

2 The Telescope System

The science cases and circumstances which lead to locate a 4-m class optical telescope facility at Devasthal are described by Sagar (2006). The initial development of this project is summarised by Sagar (2007) and Flebus et al. (2008). The telescope is a two mirror Ritchey-Chretien system with an effective f-ratio of 9. The primary mirror (M1) is a thin meniscus of optical diameter of 3.6 m, f-ratio of 2, 165 mm thickness, and cast in Zerodur. The secondary mirror (M2) has an optical diameter of 952 mm, f-ratio of 4, 120 mm thickness, and cast in Astro-Sitall. The telescope has three Cassegrain ports with a back focal distance of 2.5 m. The main axial port has a science field of view of 30′ diameter whereas the side ports provide a 10′ diameter. The as-specified optical image quality E80 is less than 0″.45 for wavelengths less than 1500 nm. The active optics system (AOS) controls the alignment of M1 and M2 using pneumatic actuators and a hexapod mechanism, respectively. The corrections can also be applied in a closed loop using data from the Shack-Hartmann wavefront sensing system. The vital characteristics of the telescope are given in Table 2.

The telescope was fully assembled in early 2012 in the workshop of Advanced Mechanical and Optical System (AMOS; Liège, Belgium). The first integration was accomplished using dummy mirrors M1 and M2 and thereafter engineering tests were conducted. Later on, the actual uncoated M1 and coated M2 mirrors were integrated. Some verification tests on telescope were performed in the integration hall of the AMOS workshop with a small sky window of 15 square degree and a Full

Table 1: Key parameters of the Devasthal site.

Parameters	**Value**
Location	Alt: 2424 ± 4 m; Long: $79°41'04''$ E; Lat: $29°21'40''$ N
Seeing (Ground level)	$1''.1$ (median); $0''.75$ (median of 10 percentile values)
Wind	<3 m/s for 75% of time
Air temperature	21.5°C to −4.5°C (variation during year) ≤ 2°C (variation during night)
Rain	2 m (average over year, 80% during June to September)
Snowfall	2 ft (average; during January and February only)
Clear nights	Out of 208 spectroscopic nights, 175 are photometric
Sky Transparency (mag/airmass)	Average: $k_U = 0.49 \pm 0.09$; $k_B = 0.32 \pm 0.06$ $k_V = 0.21 \pm 0.05$; $k_R = 0.13 \pm 0.04$ $k_I = 0.08 \pm 0.04$ Best: $k_U = 0.40 \pm 0.01$; $k_B = 0.22 \pm 0.01$ $k_V = 0.12 \pm 0.01$; $k_R = 0.06 \pm 0.01$
Relative humidity	$\leq 60\%$ during spectroscopic nights Much higher during July to September

Width at Half Maxima (FWHM) seeing of about $2''$. The initial results on the performance of the telescope viz, pointing, tracking, and image quality were found to be satisfactory. The AOS function tests were successful. These results are described by Ninane, Flebus & Kumar (2012) and references therein. The M1 and M2 manufacturing and as-built optical quality of the mirrors are described by Semenov et al. (2012).

2.1 Instrument Envelope

The telescope provides three Cassegrain ports for mounting instruments. The main axial port is designed for mounting instruments weighing 2000 kg. Any axial port instrument can be mounted with the telescope interface plate (TIP; diameter 1500 mm, thickness 30 mm) and it can occupy a cylindrical cum conical space of 1.8-m height below the TIP (see Fig. 2). A constant cylindrical diameter of 3 m from TIP to 0.8 m and a decreasing conical diameter from 3 m to 1 m corresponding to the distance below the TIP from 0.8 m to 1.8 m. The center of gravity (CG) of the axial port instrument is 800 mm below the TIP. The positioning of the CG for any instrument is very critical: a shift of 1 cm of the CG position in the vertical axis will create a torque of 200 Nm which is close to the altitude bearing friction. The telescope has the capacity to bear an imbalance of 2000 Nm on the altitude axes and of 400 Nm on the rotator axes. Imbalances are adjustable using motorised weights on the altitude axes and fixed weights on the rotator axes. The axial port instruments are required to have a first eigen frequency of more than 20 Hz. The side port instruments can have a weight of 250 kg each with a CG of 620 mm away from the TIP. The parameters of the side-port instrument envelope are given in Table 2.

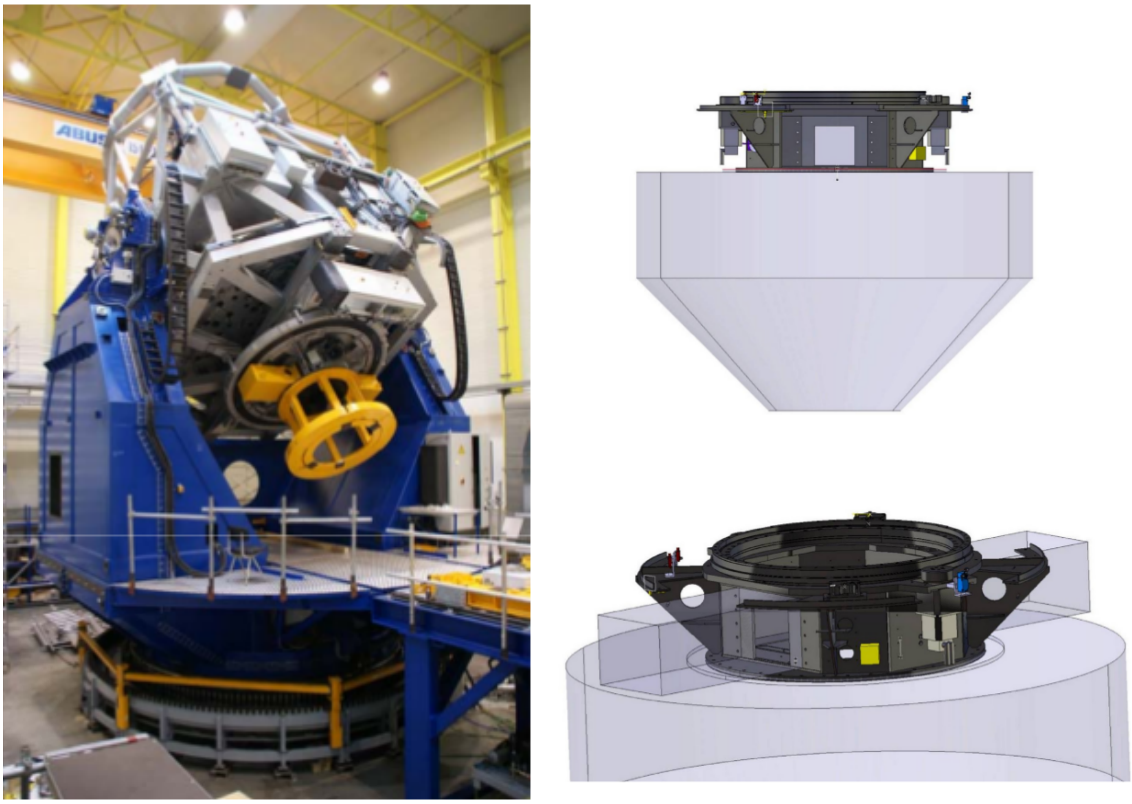


Figure 2: Left: Picture of the fully assembled telescope at the AMOS workshop in Liège (Belgium). The telescope is pointing at a 55° elevation. The dummy instruments are shown in yellow. The axial-port instrument weighs 2000 kg and the side ports weigh 250 kg each. Right: The instrument envelope for side ports and main port instruments is shown.

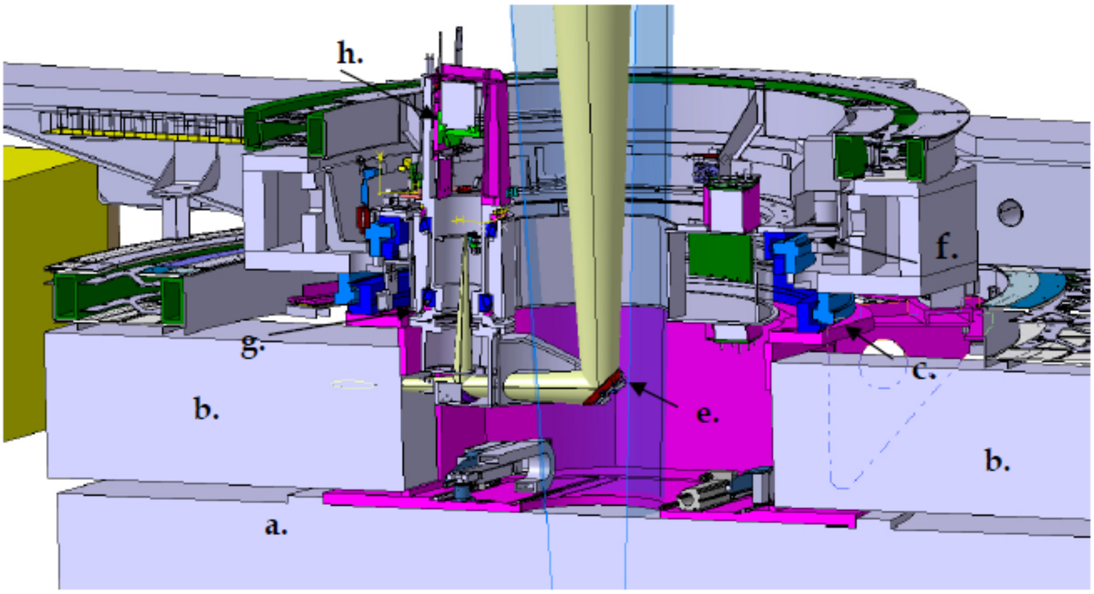


Figure 3: The Adapter Rotator Instrument Support Structure (ARISS) with main instrument envelope (a), side-port instrument envelope (b), rotator bearing (c), pick-off mirror (e), adaptor bearing (f), turn table (g), and optical bench with guider camera and wavefront sensor (h).

Table 2: Key characteristics of telescope

Parameters	**Value**
Primary Mirror clear aperture	3.6 m
Focal ratios	Primary: F/2; Effective: F/9; Plate Scale: $6''.366$ /mm
Back focus distance	2.5 m
Science Field of View	$10'$ on side ports, $30'$ on axial port; ($35'$ for the AGU)
Operational waveband	350 nm to 5000 nm
Mounting	Alt-azimuth
Sky coverage	15° to $87^{\circ}.5$ in elevation
Optical image quality	- Encircled Energy Diameter 50% (E50) $< 0''.3$, - Encircled Energy Diameter 80% (E80) $< 0''.45$, - Encircled Energy Diameter 90% (E90) $< 0''.6$, For the wavelength range from 350 nm to 1500 nm and without corrector for $10'$ Field of view.
Pointing accuracy	$< 2''$ RMS (Root mean squared)
Tracking accuracy	$< 0''.1$ RMS for 1 minute in open loop, $< 0''.1$ RMS for 1 hour in close loop, $< 0''.5$ Peak for 15 minutes in open loop.
Cassegrain-end Instruments	1 main axial port instrument: - maximum mass: 2000 kg - instrument flange: 40 cm before the focus. 2 side port instruments: - maximum mass: 250 kg per instrument - allocated room: 0.5 m × 0.5 m × 0.7 m (H × W × L) - instrument flanges: 10 cm before the focus.

2.2 Acquisition and Guiding Unit

The acquisition and guiding unit (AGU) measures the telescope wavefront errors and the tracking errors during operation. A pick-off mirror can be aligned on a guide star located at the edge of the field of view ($30'$ to $35'$ annulus). The guide star light beam is then directed towards an optical bench equipped with a wavefront sensor and a guider camera (see Fig. 3). The pick-off mirror is positioned on the guide star using the movements of the adapter and turntable. The centroid of the star on the guide camera (550-750 nm sensitivity) is used to correct the tracking errors while the wavefront sensor camera (400-550 nm and 750-900 nm) measures the wavefront errors which are used to modify the force distribution of the M1 axial actuators and make all the corrections relating to the telescope optics. Focus and coma are corrected using the hexapod mechanism of M2. The main axial and two side port instruments are fixed to the Adapter Rotator Instrument Support Structure (ARISS) including a rotator that derotates the image of the sky. The Side Port Fold Mirror (SPFM) is also located in ARISS. The AGU, rotator, and SPFM are nested at the rear of M1, just above the instrument.

3 The Telescope Enclosure and Auxiliary Systems

The telescope enclosure building is designed to house a pier, a telescope, and a mirror coating unit. Considering the limited space available at site, a very compact building has been designed and built. The enclosure is designed to support the installation of four overhead cranes so that the installation of the entire telescope could be done inside the enclosure. The dome of the telescope is off-centered from the telescope. A 3.7-m coating unit has been installed in the enclosure. The technical requirement and the design stage planning of the enclosure is described by Pandey et al. (2012). Recently, a cable anti-twister has also been designed and developed to meet the requirement of proper routing of delicate instrument cables (e.g. optical fibers) from the Cassegrain end of the telescope to the telescope control room. A brief account on the completion of these facilities is given in the following subsections.

3.1 Telescope Enclosure

The 3.6-m telescope enclosure building is a custom-built system of great complexity. The enclosure involves structural (concrete and steel), mechanical, and electrical engineering. The telescope enclosure building has three parts: the rotating dome, the stationary dome-support structure, and an auxiliary building. The entire building is made of steel. The dome is a cylindrical insulated structure with pitched roof having diameter of 16.5 m and height of 13 m. The dome has a 4.2 m wide opening slits and a wind screen. The telescope floor is at 11-m level and a total of 12 ventilation fans are installed on the dome support structure for thermalisation of the telescope building at the start of observations. A ventilation duct has also been provided to flush hot air out of the technical room. The dome building is also equipped with a 200 kg lift which is used to transport instrument components from the ground to the telescope floor. The auxiliary building is equipped with a coating plant unit. Due to heavy precipitation at the Devasthal site ($\sim$2 m of rain from June to September and $\sim$2 ft of snowfrom January to February), it was extremely difficult to mobilise the manpower and resources for the construction of this complex building. The construction work finally got completed in 22 months and the enclosure was put into regular use in June 2014. A few snapshots during construction are shown in Fig. 4.

3.2 Telescope Pier

The telescope enclosure building houses a pier which is a hollow cylinder made up of M25 grade concrete (Fig. 5). The top of the pier is 8.26 m above the ground and its foundation is completely isolated from the building. The as-designed natural frequency of the pier is 25.44 Hz. The horizontal natural frequency of the as-built pier has been measured using 3C geophones and piezoelectric sensors (Gatkine & Kumar 2014). A mean value of 22±2 Hz is obtained, which is consistent with the as-designed value. The telescope is designed to have natural frequency of 7.4 Hz.

3.3 Overhead Cranes

The customized cranes were essentially required inside the building as there were (1) space constraints around the telescope building for operating big external heavy duty cranes from outside and (2) transportation constraints for bringing heavy weight cranes (altitude of observatory and sharp bends in the road to the site). To meet the challenge of the telescope installation from inside the telescope building by lifting components through its hatch, two Single Girder cranes in the extension building and two Under-Slung cranes in the dome of 10 MT capacity each were specifically designed and developed.

Figure 4: Snapshots of telescope enclosure building at Devasthal are shown since the beginning of construction in September 2012 till its completion for telescope installation in June 2014, respectively left to right.

All the four overhead cranes were custom built to achieve the objective of handling the telescope mirror and its various components during installation and assembly. Overhead cranes were installed in the limited available space inside the building and tested as per IS 3177. Cranes were equipped with features like variable voltage variable frequency drive compatibility, provision to move two cranes in tandem, digital load display, anti-collision mechanism, electrical interlocks, radio remote, low hook height, and compact carriage for the telescope integration at site. A detailed technical paper on the successful utilization of these overhead cranes during installation of telescope is written by Bangia et al. (2016). A picture of the Under-Slung crane is shown in Fig. 5.

3.4 Dome control system

The position of the 3.6-m telescope is separated by 1.85 m from the dome centre at an angle of 255 degrees with respect to the north. This posed a serious challenge in synchronizing the dome slit with the telescope. A synchronization algorithm was developed in-house and implemented in the dome control system (DCS). An absolute multi-turn encoder is mounted with one of the dome wheels to fetch the dome azimuth position. A photoelectric sensor is also mounted to get the homing position and error correction for dome. A microcontroller based interface card is used to interface amongst hardware and DCS using an ethernet converter. The DCS is developed in Python. The full set-up was tested and made ready by February 2015. The complete description of the DCS is given by Gopinathan et al. (2016). A snapshot of the DCS Graphics User Interface (GUI) window and the fully aligned dome and telescope are shown in Fig. 6.

Figure 5: Left: A picture of the 3.6-m telescope pier. The pier is a hollow cylinder with an inner diameter of 5 m, an outer diameter of 7 m, and a top slab with a thickness of 1 m. The height of the pier from the ground is 8.26 m. Right: A picture of the dome overhead cranes.

3.5 Coating unit

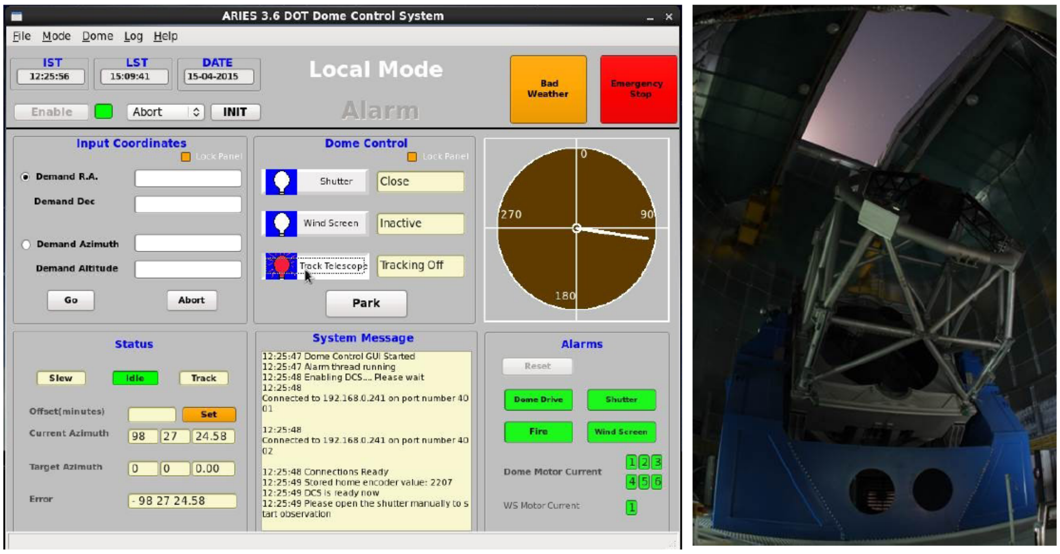
Initially the primary mirror of the 3.6-m DOT is uncoated polished Zerodur glass. In order to do the Aluminum (Al) coating on M1, a coating plant along with a washing unit was installed in the extension building. The magnetron sputtering technique is used for the coating (Pillai et al. 2012). Several coating trials are done and samples are tested for reflectivity, uniformity and adhesivity. A detailed description of the coating plant installation, M1 cleaning and coating procedures and the testing results of the samples are given by Reddy et al. (2016). M1 was cleaned before applying a reflective Al coating on it in February 2015 by using the coating unit at Devasthal. A mean reflectivity of about 86% over 400 to 1000 nm was achieved. M2 was coated with Al along with a protective layer deposition of Silicon dioxide (SiO_2) in September 2010 at Lytkarino Optical Glass Factory (LZOS), Russia. The reflectivity was measured on one sample coated along with M2 and a mean reflectivity of 87% was achieved in the wavelength range from 400 nm to 1000 nm. Fig. 7 shows the coating plant at Devasthal and the reflectively of the freshly coated M1 and M2 of telescope.

3.6 Cable anti-twister

It was envisaged to develop a cable anti-twister to facilitate delicate instrument cables through a hole provided in the pier of telescope. The critical cables such as helium supply, Cryoline, optical fibers used in the Faint Object Spectrograph and Camera (FOSC), the TIFR-ARIES Near Infrared Spectrograph (TANSPEC) and other instruments will be routed through the anti-twister. The weight of the hanging structure on telescope is expected to be below 350 kg after finalisation of the drawings and selection of materials.

4 Commissioning and initial performance

The integration of the telescope was accomplished in the period from October 2014 to February 2015. The mechanical integration of the telescope was achieved using overhead cranes installed in



IST 12:25:56

LST 15:09:41

DATE 15-04-2015

Abort

● Demand R.A.

Demand Dec

○ Demand Azimuth

Demand Altitude

Shutter: Close

Wind Screen: Inactive

Track Telescope: Tracking Off

Offset(minutes)

Current Azimuth: 98 27 24.58

Target Azimuth: 0 0 0.00

Error: - 98 27 24.58

```
12:25:47 Dome Control GUI Started
12:25:47 Alarm thread running
12:25:48 Enabling DCS.... Please wait
12:25:48
Connected to 192.168.0.241 on port number 40
01

12:25:48
Connected to 192.168.0.241 on port number 40
02

12:25:48 Connections Ready
12:25:49 Stored home encoder value: 2207
12:25:49 DCS is ready now
12:25:49 Please open the shutter manually to s
tart observation
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Figure 6: The software to synchronise the telescope with the off-centered dome was designed and developed by ARIES. Left: The graphics user interface of the dome conrol system. Right: The telescope in synchronised position with telescope.

the telescope building. These cranes can lift telescope parts with a hoist speed as slow as 3 mm s^{-1}. They also have provision to move in tandem. The telescope came in parts. The maximum weight of a single part was 14 MT. The whole telescope of 150 MT was installed successfully on top of the pier using these overhead cranes.

The freshly coated M1 was integrated with the telescope in January 2015. The telescope was fully assembled and was made ready for tests in March 2015. A set of about 75 engineering verification tests were performed during mechanical, electrical and optical integration of the telescope. The on-sky tests were also performed from March to May 2015. The synchronization of the dome motion with the telescope has also been successfully achieved. The analysis of these tests were in conformity with those achieved at the factory. A picture of the as-built telescope is shown in Fig. 8.

Rigorous on-sky tests of the telescope were performed from October 2015 to February 2016. In particular, a set of four system level tests: pointing accuracy, tracking accuracy, optical quality, and AGU guider sensitivity. The AGU sensitivity also defines the sensitivity of the wavefront sensor used for the Active Optics. A set of four instruments were used for the purpose of tests, i.e. a test-camera and test-Wave Front Sensor (WFS) which were used at the Cassegrain port of the telescope, and the AGU-camera and the AGU-WFS which are part of the telescope.

An air-cooled Microline ML 402ME CCD with 9 μm pixels and a chip size of 768×512 pixels is used both as test-camera and as AGU-camera. They have a plate scale of $0\farcs06$ pix^{-1} and $0\farcs166$ pix^{-1}, respectively. A Microline ML4710-1-MB with 1024×1024 size and 13 μm pixels was used both as test-WFS and as AGU-WFS, though they used a lenslet array of 33×33 and 11×11, respectively. A comprehensive set of data was collected and analysed. The test procedures and results were put in the form of a professional technical report. The performance results were evaluated by a high-level technical committee.

The image quality of the telescope was found to be consistent with the specifications. The as-built specifications of four system level parameters as well as results of tests are listed in Table 3. A total of six measurements resulted in E50 of $0\farcs15\pm0\farcs03$, E80 of $0\farcs26\pm0\farcs04$ and E90 of $0\farcs37\pm0\farcs07$. These are better than the specifications of $0\farcs3$, $0\farcs45$ and $0\farcs6$, respectively. The pointing accuracy was found to be well within the specifications. Some tracking measurements are marginally above the specification as these are very sensitive to seeing conditions (particularly at low elevations) and local

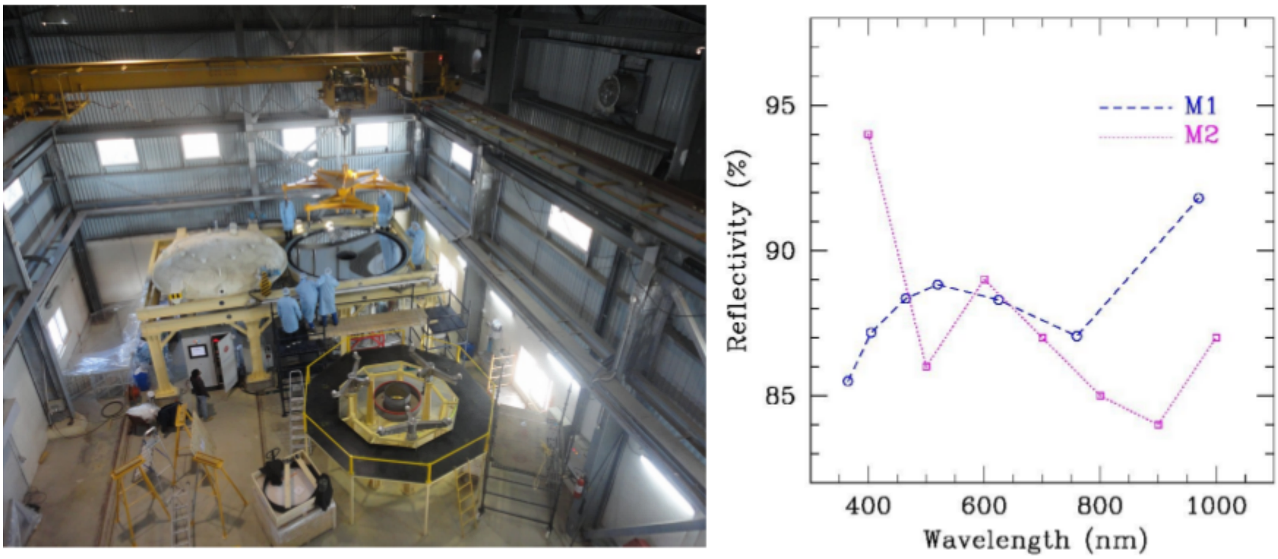

Figure 7: The coating plant at Devasthal. Reflectivity of M1 and M2 is shown in the right panel.

weather disturbances (e.g. strong winds, passing clouds) which may affect the centroiding of stars.

4.1 Images of Celestial sources

Images of a few binary stars with known separation were observed on different nights during November-December 2015 using the test-camera. Stars having a separation of sub-arcsec were observed and they were clearly resolved. In the night of 30 November 2015, a binary with known angular separation of about $0\farcs4$ was resolved in one of the observations (Fig. 9). The point spread function of a star has three main contributions, i.e. seeing, tracking, and optical quality. It has been observed that the optical quality of the telescope can be maintained at the level of $0\farcs2$ FWHM as M1 is about 15 m above the ground level and the seeing contribution at this level is reduced to about $0\farcs2$. Hence, considering the tracking accuracy results, it is expected that the telescope can deliver FWHM images of celestial sources as good as $\sim 0\farcs4$.

5 Summary and future events

The 3.6-m Devasthal Optical Telescope has been successfully installed at Devasthal. The first aluminisation of the primary mirror has been accomplished using a newly commissioned coating facility inside the telescope enclosure building. The algorithm and control software for synhronization of the dome motion with that of telescope has been designed, developed and tested. The engineering performance of the telescope was tested comprehensively at the site. A rigorous on-sky performance of the telescope was tested using a test-WFS and test-camera. The telescope was accepted for science observations in February 2016. The first light instruments, i.e. a 4K×4K Imager and the Faint Object Spectrograph and Camera (FOSC), are being tested at the moment. It is likely that the telescope will be released for science observations as soon as the test runs with the instruments are completed. The telescope was technically activated jointly by the Prime Ministers of India and Belgium on 30 March 2016 in the presence of the Minister of Science and Technology, Government of India.

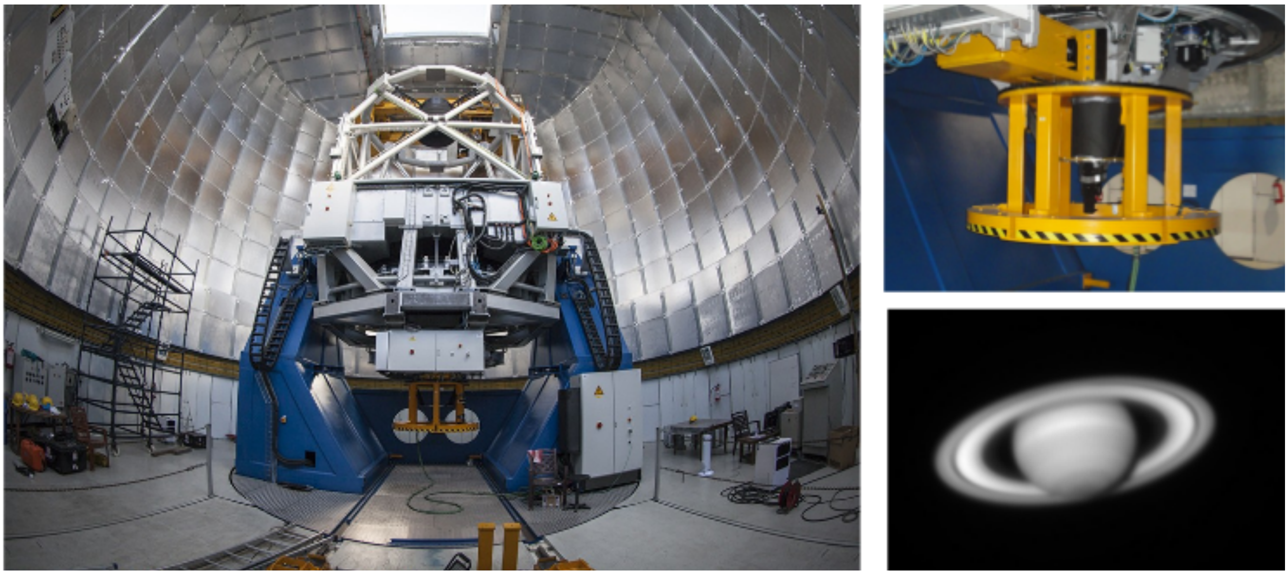

Figure 8: Left: Picture of the as-built telescope at the Devasthal site. Right: The test-camera was installed at the main port of the telescope and a picture of Saturn was obtained during the first night. The seeing of this image was close to 1″.

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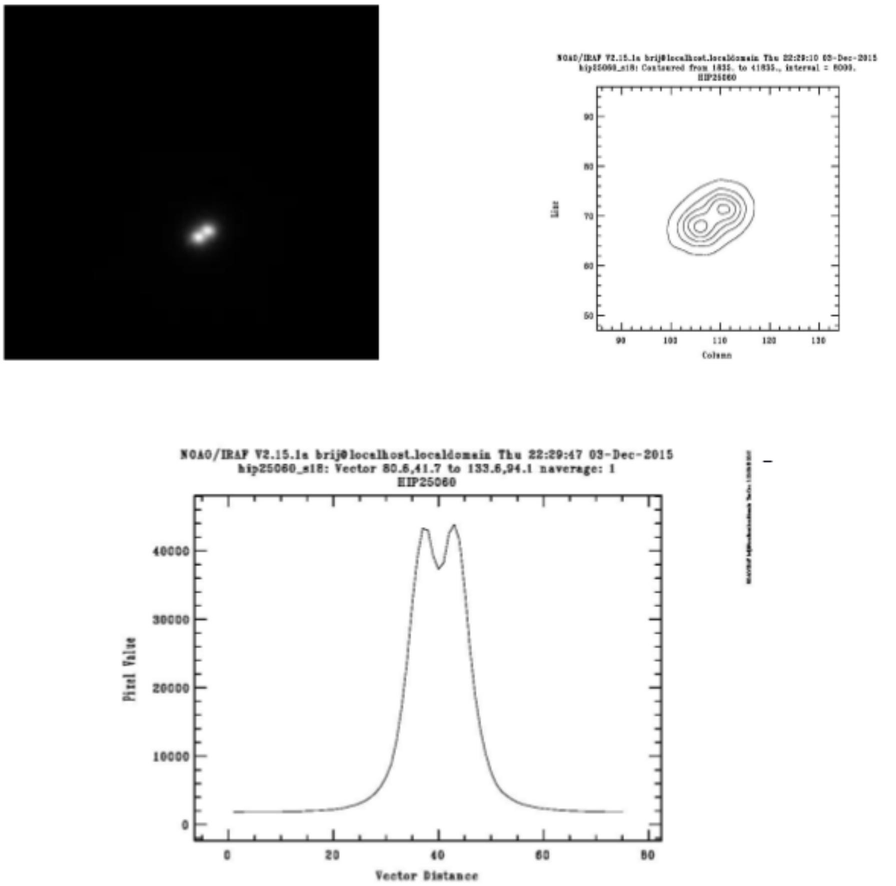

Figure 9: Observation of HIP 25060 by using a broad band visible filter. The peak-to-peak separation is 6 pixels (≈ $0\farcs34$). The elongation seen in the image/contour is due to atmospheric differential refraction. The exposure time was 1 second.

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Table 3: As-built key characteristics of the telescope

Parameters	Value
Pointing Accuracy	Specs: less than $2''$ RMS Results (RMS): $1''.1$, $1''.3$ and $1''.2$ for side-port-1, side-port-2 and main-port respectively.
Tracking Accuracy Open-Loop (without guider):	Specs: $< 0''.1$ RMS for 1 minute Results ($''$): 0.06, 0.08, 0.08, 0.08, 0.09, 0.09, 0.10, 0.12, 0.12, 0.14. Mean: $0''.08 \pm 0''.03$ Specs: $< 0''.5$ PEAK for 15 minute Results ($''$): 0.16, 0.22, 0.24, 0.24, 0.25, 0.32, 0.34, 0.35, 0.36, 0.42.
Tracking Accuracy Close-Loop (with guider):	Specs: $< 0''.11$ RMS for 1 hour Results ($''$): 0.07, 0.07, 0.08, 0.09, 0.09, 0.09, 0.10, 0.10, 0.10, 0.11, 0.13, 0.13. Mean: $0''.09 \pm 0''.02$
Optical Image Quality	Specs (diameter): E50 $< 0''.3$; E80 $< 0''.45$; E90 $< 0''.6$ Results ($''$): E50 values are 0.19, 0.13, 0.13, 0.12, 0.18, 0.14; E80 values are 0.37, 0.27, 0.23, 0.25, 0.33, 0.23; E90 values are 0.49, 0.36, 0.31, 0.32, 0.42, 0.30.; Note: E50, E80 and E90 values are inferred from analysis of aberrations of optics with the mean of $0''.15$, $0''.26$ $0''.37$ respectively.
AGU Guider Sensitivity	Specs: V mag of about 13 mag Results: 12.85 mag star tested successfully