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# WEAVE: Commissioning Milestones and Current Status

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## Abstract

WEAVE, a powerful new multi-object spectrograph, was in June 2022 mounted on the 4.2-m William Herschel Telescope (WHT) at the Roque de Muchachos Observatory on La Palma. Scientific observations kicked off in October 2023, and will transform the scientific productivity of the WHT, with a combination of Open Time observations and a series of high-impact surveys, all carried out in queue mode.

We aim to provide an overview of the WEAVE project, highlighting key achievements and addressing significant challenges encountered during the commissioning of various subsystems. An update on the current status of the instrument will be shared.

## 1 WEAVE Overview

WEAVE is the wide field multi-object spectrograph, which was installed at the prime focus of the WHT in June 2022. It began its commissioning phase in the summer of the same year, with science observations initiated in October 2023. The instrument has been described at [1] and [2], but the most updated description of the as-built instrument, at the time of integration at the telescope, pre-commissioning, can be found at [3]. There is also an updated description that is being maintained at the Isaac Newton Group (ING) web page [1].

The instrument can be used in any of 3 focal-plane modes: MOS (multi-object spectroscopy), mIFU (mini integral-field units) and LIFU (large integral-field unit).

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[1] `https://www.ing.iac.es//Astronomy/instruments/weave/weaveinst.html`

In MOS mode, up to $\sim$ 1000 individual fibres can be positioned anywhere within the field of view, with each fibre having a diameter of 1.3 arcsec. There are actually two sets of MOS fibres, one for plate A (960 fibres) and another for plate B (940 fibres), and WEAVE is designed so that two robots configure one of the two sets of fibres (e.g. for plate A) while the 1-hour observation with the other set is taking place (e.g. on plate B). Then the tumbler is rotated by 180 deg so that plates A and B swap positions.

The mIFU mode offers up to 20 fibre bundles (each $11 \times 12$ arcsec$^2$ on the sky), which can be positioned anywhere within the field of view, plate B only. For any given observation, the MOS and mIFU modes cannot be observed simultaneously.

In LIFU mode, a single IFU is positioned at the centre of the field of view. The hexagonal array of 547 fibres provides a (hexagonal) field of view of $78 \times 90$ arcsec$^2$.

WEAVE features a dual-arm spectrograph (blue and red), housed on a single Nasmyth platform. This design maximizes efficiency by allowing simultaneous observations over a range of wavelengths. A 5900 Å dichroic splits incoming light between the blue and red arms of the spectrograph, enabling optimized spectral coverage. WEAVE supports two resolutions, low (LR, R = 5000, 2500 for MOS/mIFU and LIFU respectively) and high (HR, R = 20000, 10000 for MOS/mIFU and LIFU), using five volume phase holographic gratings (VPHs) in red and blue arms, enhancing its versatility in conducting a wide range of observational campaigns.

## 2 WEAVE Commissioning Strategy

The commissioning phase of WEAVE aims to ensure that the integrated system meets both scientific and operational requirements for each observing mode: MOS, mIFUs, and LIFU. During this phase, the performance of the system is evaluated, and any unexpected features are identified to optimize WEAVE operation.

Key subsystems have been assessed to confirm that the system functions optimally in its different observing modes (MOS, mIFUs, LIFU). These subsystems include the focal plane, the calibration unit, fibre positioning and target acquisition, the spectrograph, science detectors, end-to-end throughput, observatory control system, and data system.

The strategy for planning commissioning tests takes into account that some tests, such as those for the focal plane and detectors, will be relevant to all three observing modes (MOS, mIFUs, LIFU). However, most subsystems require specific tests tailored to each mode, as they operate differently depending on the observing mode. Tests were prioritized in a specific order, as certain tests (e.g., fibre positioning) needed to be completed before others (e.g., target acquisition).

Testing for all three observing modes commenced early in the commissioning phase to avoid delays in evaluating the instrument performance across all modes. However, priority was given to the LIFU mode, as it was simpler than the others and provided a faster route to early science observations.

This strategic approach ensures that all subsystems were thoroughly evaluated.

## 2.1 Focal Plane

The main results from the focal plane commissioning are summarized below:

- The optical quality at the focal plane is excellent. Shack-Hartmann tests indicate that the prime-focus corrector delivers a well-rounded point-spread function (PSF) with full width at half maximum (FWHM) 0.25 arcsec. The on-sky FWHM are consistent with the independently-measured atmospheric seeing.
- The Atmospheric Dispersion Corrector (ADC) has also been thoroughly tested and is confirmed to perform as expected.
- Comprehensive characterization of the telescope focus has been conducted for all WEAVE modes.
- The astrometric mapping of the focal plane has been characterized. This is essential for commissioning, as it defines the link between the x, y coordinates on the focal plane and their corresponding positions in the sky. Accurate mapping is crucial for precise fibre positioning, minimising loss of light at the fibre aperture.

## 2.2 Calibration Unit

The calibration unit has undergone comprehensive testing, and the results demonstrate that it performs according to specification, ensuring that the instrument can maintain high precision in both mechanical and spectroscopic aspects.

- The mechanical operation of the unit has been verified, ensuring the correct operation of critical components such as the lamp switching mechanism and the alignment of the lamps.
- The calibrations lamps, Quartz-Tungsten-Halogen (QTH) for fibre-flats and Thorium-Argon-Chromium (ThArCr) for arcs, provide illumination that it is adequate, stable and repeatable, ensuring consistent calibration performance over time. Furthermore, the illumination covers the entire WEAVE field of view, a crucial requirement for precise and uniform calibration across the entire observational area.
- There is an illumination mismatch between the calibration lamps and the sky due to the different f-ratios of the calibration unit and the sky light. This results in a narrower spatial profile in calibration frames compared to science frames. However, this mismatch can be corrected with twilight sky observations.
- An issue with the ThArCr arc lamp is that there is a global shortage, making them increasingly difficult to obtain. As a result, the ThArCr lamp is currently being operated at a lower current to extend its lifespan, which has led to longer exposure times. In the search for an alternative to ThArCr, we have tested a new Cerium-Argon (CeAr) lamp, which has shown promise as a potential replacement for calibration purposes.

### 2.3 Target-Acquisition and Guiding: LIFU

The performance of the LIFU system has been thoroughly tested. The acquisition accuracy is consistently below 0.3 arcsec in $\sim 99\%$ of cases, demonstrating high reliability and repeatability. Guiding measurements show an RMS of approximately 0.3 arcsec for integration times of up to one hour. This guiding accuracy ensures that the target remains precisely centred during long exposures, which is critical for obtaining high-quality spectral data.

This level of precision has been possible thanks to the LIFU system being equipped with a powerful tool that allows effective target acquisition and guiding. A sophisticated algorithm calculates the necessary offsets to position the guide star at an estimated (x, y) location within the acquisition and guiding camera. This offsetting ensures that the science target is accurately centered on the focal plane, precisely at the central spaxel of the LIFU head.

### 2.4 Fibre-Positioning and Target Acquisition: MOS

Commissioning the positioner requires verification of both performance (described in this section), and reliability (in Sec. 2.4.1).

The main function of the positioner is to ensure that most of the light from the astronomical targets gets into the science fibres. From our error budget, the key requirement for the MOS mode is positioning fibres with an accuracy no worse than RMS $\sim 0.2$ arcsec (11.2 $\mu$m), which might degrade to a measured $\sim 0.3$ arcsec when adding the effects of guiding. To give an idea of the importance of the requirement, note that for fibre offsets $\sim 0.5 - 0.7$ arcsec the loss of collected light from the target is $\sim 30 - 60\%$.

To evaluate the positional performance, we carried out 'raster tests'. These involve configuring MOS mode with fibres centred on 200-300 stars distributed across the field of view. The telescope is then dithered in small offsets, typically following a spiral pattern: once the field is acquired and guiding is established, the telescope is moved to each position on a $5 \times 5$ rectangular grid.

The resulting data are analyzed to produce an intensity map for each star and its corresponding fibre, generated from the intensity measurements at each dither position. By locating the maxima in these intensity maps, we can estimate the offset between the required and actual fibre positioning (see Fig. 1) as a function of position in the focal plane. The test requires stable seeing of better than 0.9 arcsec and no cirrus clouds, as these factors can adversely affect the test results and their interpretation.

Campaigns of positioning accuracy measurements began in August 2023, and the first results showed an accuracy RMS $\sim 0.5 - 0.7$ arcsec. The accuracy has noticeably improved when including adjustments for tilt of the robot rotation axes, more accurate precision of robot calibration grid measurements, corrections for subtle temperature effects, and fixes of a few bugs in the positioner code. By September 2024, fibres were being positioning with RMS accuracy $\sim 0.3$ arcsec in the best cases, which matches the requirement, although there are still some excursions in behaviour that are under investigation. Reaching the desired accuracy is an iterative process which continues as of this writing.

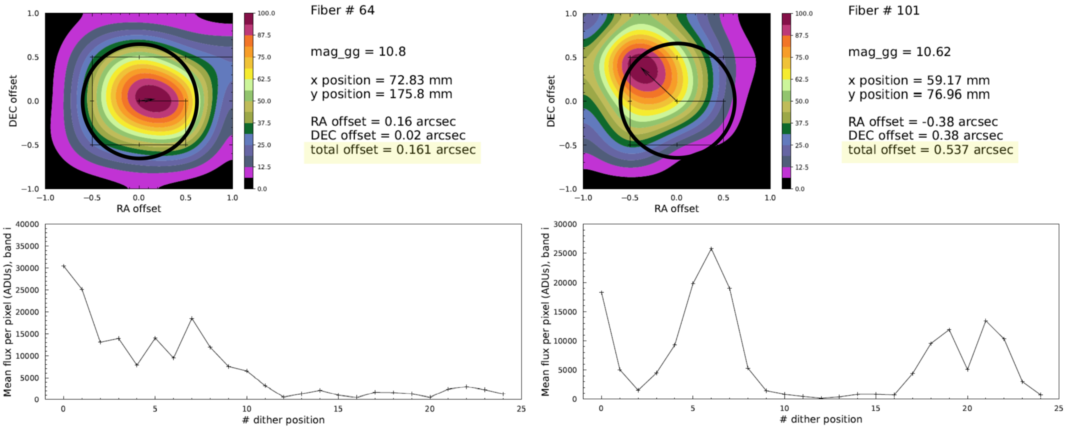

Figure 1: Intensity map obtained for two science fibres from a 5 × 5 spiral raster test. The estimated target-to-fibre offset for the case at left is 0.16 arcsec, which meets the requirement, but is 0.54 arcsec for the case at right, implying a target flux loss of ∼ 30%.

### 2.4.1 Fibre-Positioning: Reliability

In the summer of 2023, we conducted a campaign to assess the failure rate of the positioner in setting MOS fibre configurations. This analysis was crucial for understanding the operational challenges and reliability of the system during scientific observations.

During this campaign, approximately 2.5 hours were lost each night due to positioner-related issues, with only 40% of the MOS configurations successfully completed without problems. This highlighted the significant impact of positioner failures on the overall efficiency of the observing program.

Common problems encountered during the deployment or parking of fibres included fibre loops, loss of magnets, twisted prisms, and ferrule or prism losses, which typically require physical access to the positioner for repair. There are also other issues that can be resolved through the Positioner PLC.

In response to these challenges, numerous fixes were implemented to address bugs within the positioner code, alongside enhancements in the physical recovery procedures. These efforts have resulted in a remarkable reduction in failure rates. Currently, less than one hour is lost on average each night due to positioner issues, and over 80% of configurations are completed without any problems.

## 2.5 Spectrograph

For various reasons, verification of the WEAVE spectrograph upon delivery to the telescope was only partially completed, with several key tests being left for the commissioning period. Measurements during commissioning of the LIFU mode demonstrated performance close to specification and sufficient to start science observations. In contrast, commissioning of the MOS mode revealed that accurate focusing of this mode was limited by astigmatism, suggesting a misalignment within the spectrograph itself. This aberration had a very small effect on the spectrograph performance with LIFU fibres owing to the larger diameter of the latter fibres, but prevented the science requirements (tracing; spectral resolution) being met for MOS and mIFU fibres.

A plan is in place for a joint NOVA–ING team to fine-tune the optical alignment during the autumn-winter of 2024.

## 2.6 Science Detectors

The WEAVE system uses two $6276 \times 6192$ pixel CCDs in each arm (blue and red), each with four amplifiers for simultaneous readout. Each amplifier segment has unique bias, gain, and readout-noise characteristics.

The read noise, gain, and dark current were found during commissioning to meet the scientific requirement: $< 3\ e^-$ RMS, $\sim 1\ e^-/ADU$, and $< 6$ counts/hour, respectively. The red-arm CCD remained stable during commissioning, consistently meeting performance requirements. However, the blue-arm CCD displayed initial instability in one of the two CCDs, with enhanced noise levels that raised data reliability concerns. To address the blue-arm CCD noise, a pre-amplifier was replaced in May 2023, significantly improving noise levels.

## 2.7 End-to-End Throughput

The end-to-end throughput measurements are a valuable check of the performance of the optical system across various configurations, enabling the identification of any discrepancies with predicted throughput.

We have conducted several throughput measurements across all LIFU spectrograph modes. The results are reasonably consistent with predictions; however, a final analysis will be performed once the spectrograph alignment is fully resolved

## 2.8 Observatory Control System

The Observatory Control System (OCS) is essential to the WEAVE project, integrating and managing all observatory operations efficiently. During commissioning, the OCS software has been rigorously tested and refined. The OCS comprises several key modules: the Scheduler optimizes observations by priority and conditions, the Sequencer automates observation sequences, the Positioning interface manages fibre positioning, the Observing Block (OB) Database and OB manager that, respectively, stores and organizes the observing blocks, and interfaces for the Spectrograph, Calibration Unit, and Telescope Control System allow control of these subsystems. Acquisition and guiding modules ensure accurate targeting and guiding.

The OCS has proven to be highly effective, with all software components functioning smoothly and reliably. Observers have provided valuable feedback which has driven iterative improvements, resulting in an efficient, user-centred system.

### 2.9 Data System

The WEAVE Data System is a vital infrastructure that supports efficient data management, processing, and accessibility for the astronomical community. It includes several key components, each with specific roles in the data workflow, from raw data ingestion to delivering final products to Principal Investigators (PIs).

- Operational Repository (OR): Functional for both LIFU and MOS modes, providing essential data access for scientific analysis.
- WEAVE Automated Submission Platform (WASP): Allows PIs and survey teams to submit their observing blocks in XML format for verification prior to their ingestion into the OB database via the OCS (see Section 2.8).
- Quick Look (QL), L0 pipeline: Operational at the telescope, providing real-time feedback on data quality.
- Core Processing Software (CPS), L1 pipeline: Successfully operational for LIFU, with data processed since May 2023 available in the OR. All science data are currently being re-processed with version 2, and will be available at OR by mid-December 2024. The MOS version is now complete, including the successful stacking of multiple observations of targets on different nights with different fibres, to stress-test deep observations. Pending spectrograph realignment and re-calibration.
- Advanced Processing Software (APS), L2 pipeline: Extracts astrophysical parameters from reduced spectra. The software is now fully operational for LIFU and MOS. Currently all science data are being re-processed with version 2, and will be available at the OR by mid-December 2024.
- WEAVE Archive Software (WAS): it is ready to ingest raw data for engineering access and currently, by December 2024, it is starting to transfer data from CPS and APS.

The Data Flow for LIFU is functional, but integration between the OR and WAS is still in progress. Tests of the MOS data flow are ongoing.

Each component of the WEAVE Data System is crucial for managing the extensive data generated during observations. As the system evolves, continuous testing and improvements will further enhance its effectiveness for researchers in the field.

## 3 Current Status

### 3.1 LIFU comissioning and Science Verification (SV)

Commissioning of the LIFU mode[2] was completed in early 2023, marking a significant milestone for the WEAVE project, though some caveats remain.

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[2] `https://weave-project.atlassian.net/wiki/spaces/WEAVEDEV/pages/25664739/LIFU+commissioning+summary+table`

The throughput measurements so far are roughly consistent with prediction, a final analysis will be performed once the spectrograph is aligned. Additionally, the dataflow through the CPS, APS, and WAS has not been fully tested due to certain required functionalities still being in development. It will be necessary to re-measure the low-resolution (LR) and high-resolution (HR) spectral resolution, traceability, and crosstalk after alignment of the spectrograph.

LIFU SV observations were conducted from mid-May to mid-July 2023, successfully completing 84 SV OBs in both low and high resolution modes.

Science observations with LIFU, including both survey and open-time programmes, began in the last trimester of 2023 (2023B2). They were interrupted in September 2024 for the spectrograph-alignment standdown.

Additional details on SV and science observations are available in this volume at [4].

### 3.2 MOS/mIFU Commissioning

The commissioning of the MOS and mIFU modes[3] is currently in progress, in parallel with the ongoing LIFU science observations.

Key outstanding issues include: fine-tuning the fibre positioning errors, speed of convergence and failure rates of the fibre positioning; misalignment of the spectrograph; throughput measurement in MOS mode (although confident predictions can be made on the basis of measurements in LIFU mode); and insufficient testing of the complete data flow in the MOS mode.

Once the above issues are resolved, rapid progress in the commissioning of the MOS/mIFU modes is expected, leading to the start of SV observations, marking an important milestone in validating the scientific capabilities of these modes.

It is also worth noting that two extensive sets of MOS science data, comprising a total of 47 OBs, were already collected in April and August 2024 to assist in the development of the L1/L2 pipelines.

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[3] `https://weave-project.atlassian.net/wiki/spaces/WEAVEDEV/pages/25819518/MOS+commissioning+summary+table`

the European Commission, and the University of Pennsylvania. The WEAVE Survey Consortium consists of the ING, its three partners, represented by UKRI STFC, NWO, and the IAC, NOVA, INAF, GEPI, INAOE, Vilnius University, FTMC – Center for Physical Sciences and Technology (Vilnius), and individual WEAVE Participants. The WEAVE website can be found at [4] and the full list of granting agencies and grants supporting WEAVE can be found at [5].

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[4] `https://weave-project.atlassian.net/wiki/display/WEAVE`

[5] `https://weave-project.atlassian.net/wiki/display/WEAVE/WEAVE+Acknowledgements`