PMAS: The Potsdam Multi-Aperture Spectrophotometer. II.
The Wide Integral Field Unit PPak

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ABSTRACT. PPak is a new fiber-based integral field unit (IFU) developed at the Astrophysical Institute of Potsdam and implemented as a module into the existing Potsdam Multi-Aperture Spectrophotometer (PMAS) spectrograph. The purpose of PPak is to provide an extended field of view with a large light-collecting power for each spatial element, as well as an adequate spectral resolution. The PPak system consists of a fiber bundle with 331 object fibers, 36 sky fibers, and 15 calibration fibers. The object and sky fibers collect the light from the focal plane behind a focal reducer lens. The object fibers of PPak, each 2.7 mm in diameter, provide a contiguous hexagonal field of view of 74" x 64" on the sky, with a filling factor of 60%. The operational wavelength range is from 400 to 900 nm. The PPak IFU, together with the PMAS spectrograph, are intended for the study of extended, low surface brightness objects, offering an optimization of total light-collecting power and spectral resolution. This paper describes the instrument design, the assembly, integration, and tests, the commissioning and operational procedures, and presents the measured performance at the telescope.

Online material: color figures

1. INTRODUCTION

Three-dimensional spectrographs, or integral field units (IFUs), exist at many observatories, providing spectra for a large number of spatial elements ("spaxel") within a two-dimensional field of view, rather than only along a traditional one-dimensional spectrograph slit. Depending on the instrument, up to hundreds or even thousands of spectra are recorded simultaneously in any single exposure. While the instrumentation suite is diverse and based on various principles of operation (image slicers, lens arrays, fiber bundles, or combinations of these), compromises with respect to field of view, spatial sampling, wavelength coverage, and spectral resolution have to be made, due to the limited detector space.

Since its commissioning in 2001 May, the Astrophysical Institute Potsdam (AIP) has successfully operated PMAS, the Potsdam Multi-Aperture Spectrophotometer, at the Calar Alto Observatory 3.5 m telescope in southern Spain (Roth et al. 2004; Kelz et al. 2003a). An overall description of the PMAS instrument is given by Roth et al. (2005, hereafter Paper I). While PMAS is a unique spectrophotometer, covering a wide wavelength range from 350 to 900 nm, its standard IFU, a fiber-coupled lens array, provides 256 spectra and is limited to a maximum integral field of view of 16" x 16" on the sky.

Driven by the “Disk Mass” project (Verheijen et al. 2004), which requires imaging spectroscopy of nearby face-on galaxies (with typical sizes of 1”) at an intermediate spectral resolution (of $R \geq 8000$), a science case was put forward to develop a larger IFU for PMAS. Based on the experience with the SparsePak bundle, which was constructed and commissioned for the 3.5 m WIYN telescope at Kitt Peak (Bershady et al. 2004, 2005), the PPak (PMAS fiber Package) fiber bundle was designed and built at the AIP in 2003 as part of the ULTROS project (ultradeep optical spectroscopy with PMAS). This new IFU was produced on a short timescale of approximately 6 months, and with a budget of less than €20,000 for the hardware components (mainly lenses, filters, and fibers). PPak was successfully integrated within PMAS in 2003 December and was commissioned in spring 2004. The PPak mode of PMAS is now fully operational and is routinely employed.
for the Disk Mass project, as well as for a variety of other common-user programs that require large integral field spectroscopy.

As a bare fiber bundle IFU, PPak is based on earlier developments, such as DensePak (Barden & Wade 1988), INTEGRAL (Arribas et al. 1998), and SparsePak (Bershady et al. 2004). Like these instruments, PPak uses rather large fibers that cannot properly sample the (seeing-limited) image, but instead collect more flux and allow for wide fields. PPak and SparsePak span $74' \times 64'$ and $72' \times 71'$ on the sky, respectively, and provide the largest fields of view of any IFU available worldwide (see Table 1). In addition, a single PPak fiber with 5.7 arcsec$^2$ on the sky collects twice the amount of light at the 3.5 m telescope than a single spatial element, which effectively limits the fiber core diameters. Around 400 of these fibers can be accommodated at the spectrograph slit, which effectively limits the fiber core diameters. Around 400 of these fibers can be accommodated at the spectrograph slit, which allows for wide fields. 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### Table 1: Selected IFU Instrumental Parameters with Corresponding Spectral Capabilities

| Instrument | Telescope Diameter (m) | FOV (max.) (arcsec) | Spaxel Size (arcsec) | Spaxel Number | Filling Factor | Range (Å) | Resolution (Å/Å) | Specific Grasp (arcsec$^2$m$^2$) | Total Grasp (arcmin$^2$m$^2$) |
|------------|------------------------|---------------------|---------------------|---------------|---------------|-----------|-----------------|-------------------------------|-----------------------------|
| PMAS PPak  | CA 3.5                 | 74 × 64             | 2.68 circular       | 331 ± 36      | 0.60          | 400       | 8000            | 47                            | 4.23                        |
| SparsePak  | WIYN 3.5               | 72 × 71             | 4.69 circular       | 75 ± 7        | 0.25          | 260       | 12,000          | 138                           | 2.87                        |
| DensePak   | WIYN 3.5               | 45 × 30             | 2.81 circular       | 91 ± 4        | 0.42          | 260       | 20,000          | 49                            | 1.25                        |
| INTEGRAL   | WHT 4.2                | 34 × 29             | 2.70 circular       | 115 ± 20      | 0.67          | 360       | 4200            | 73                            | 2.32                        |
| VIMOS      | VLT 8.2                | 54 × 54             | 0.67 × 0.67         | 6400          | 1.00          | 350       | 220             | 23                            | 40.50                       |
| SAURON     | WHT 4.2                | 41 × 33             | 0.94 × 0.94         | 1577          | 1.00          | 540       | 1250            | 11                            | 4.77                        |
| SPIRAL     | AAT 3.9                | 22 × 11             | 0.7 × 0.7           | 512           | 1.00          | 330       | 7600            | 5.4                            | 0.77                        |
| PMAS LARR  | CA 3.5                 | 16 × 16             | 1.0 × 1.0           | 256           | 1.00          | 700       | 6000            | 8.2                            | 0.58                        |
| OASIS      | WHT 4.2                | 17 × 12             | 0.42 hexagonal      | ~1100         | 1.00          | 370       | 2650            | 2.3                            | 0.71                        |
| GMOS       | Gemini 8.1             | 7 × 5               | 0.2 hexagonal       | 1000 + 500    | 1.00          | 280       | 1700            | 1.8                            | 0.49                        |

a Corresponding value for the maximum FOV may depend on foreoptics magnification.
b Dedicated sky spaxels are listed separately.
c Bare fiber bundles (first four rows); lens array types (bottom six rows)
d Selected values only; may span a wide range, depending on configuration and wavelength.
e Specific grasp = telescope area (m$^2$) × spaxel size (arcsec$^2$).
f Total grasp = telescope area (m$^2$) × spaxel size (arcsec$^2$) × number of spaxels.
g PPak IFU and PMAS spectrograph with second-order gratings.
h SPIRAL with Littrow spectrograph (decommissioned).
i Lens array IFU and PMAS spectrograph with first-order gratings.

This paper is organized as follows. Section 2 presents the instrument and its optomechanical design. Section 3 summarizes the manufacture, assembly, and integration of the PPak components. Section 4 describes the operational procedure during observation, the data reduction, and the visualization tools. The instrument performance at the telescope and the test results are given in § 5.

### 2. INSTRUMENT DESCRIPTION

The baseline parameters for the development of PPak were to provide a contiguous sampled field of view of at least 1' across, with high specific grasp per spaxel and adequate resolution at the spectrograph. PPak needed to be designed as an unforeseen add-on module to the existing Cassegrain-mounted PMAS instrument. Therefore, certain space constraints dictated the overall design. Likewise, the PMAS spectrograph hardware and performance had to be taken as given. The existing PMAS grating set (see Table 2 of Paper I) includes gratings with 300, 600 and 1200 lines mm$^{-1}$, of which two can be used in the second spectral order. Taking advantage of anamorphic de-
magnification (see § 5.4), spectral resolutions of $R \sim 8000$ can be achieved with the I1200 and J1200 gratings if the pseudoslit width of the PMAS spectrograph does not exceed 150 μm, which effectively limits the fiber core diameters. Around 400 of these fibers can be accommodated at the spectrograph slit, with acceptable separations and cross talk. The PMAS spectrograph accepts an F/3 beam, which implies that allowing for some focal ratio degradation, the fibers can be fed with up to F/3.3 in the focal plane, which sets the plate scale and fiber grasp. The purchase of even higher line density or holographic
reflection gratings was not considered at the time of PPak’s development.

Figure 1 illustrates the principle of operation for both the preexisting lens array (LARR) IFU and the new PPak IFU. For the lens array mode, the telescope focal plane image is magnified by a foreoptics (dashed outline; Roth et al. 2003), then spatially sampled by a lens array and reconfigured by an optical fiber module (Kelz et al. 2003b).

PPak, on the other hand, is equipped with a focal reducer lens (FORED) in front of the telescope’s focal plane, which maximizes the field of view and provides the required plate scale and F-number. The subsequent fiber bundle (solid line) bypasses the foreoptics and lens array and bridges the distance of around 3 m to the spectrograph. Additional fibers (dashed-dotted line) connect the spectrograph to a dedicated calibration unit. At the spectrograph entrance, the fibers from both the lens array and the PPak IFU form two parallel slits, of which only one is active during observing. The PPak IFU is placed 6’ off-
axis so as not to obstruct the existing field for the direct-imaging camera. This allows the use of the acquisition and guiding optics (A&G; dotted outline) for target acquisition and guiding in both the PPak and lens array IFU mode. The various components are described in more detail in the following subsections.

### 2.1. Focal Reducer Lens

The focal reducer lens, which is located immediately in front of the fiber bundle, reduces the focal length of the Calar Alto 3.5 m telescope from 35,000 to 11,550 mm, changes the plate scale from 5\,\mu\text{m} to 17\,\mu\text{m}, and converts the telescope F-number from F/10 to F/3.3. The focal reducer is a four-lens system consisting of a triplet and a thick singlet lens (see Fig. 2), which creates the required telecentric exit rays. The system has four glass-to-air interfaces, which are treated with antireflective coatings. The individual lenses of the triplet are made of LF5, BaK1, and LF5, respectively, while the fourth lens is made of BaK1. The thickness of the triplet is 28 mm, and that of the single lens is 64 mm, while their diameters are 50 mm. The lenses are optimized for a wavelength interval between 400 and 850 nm; i.e., neglecting the blue part of the spectrum that otherwise is accessible with the PMAS spectrograph. The image quality that the focal reducer provides was optimized to match the fiber size of 150\,\mu\text{m} and does not deteriorate the point-spread function (PSF) beyond the typical seeing (see spot diagrams in Fig. 3).

Since the light is coupled to optical fibers, telecentric exit rays are required. The focal reducer lens creates a telecentric field 7 mm (125\,\mu\text{m}) in diameter. The system can also be placed up to 65 mm off-axis, which is necessary due to space constraints within the existing PMAS instrument. The off-axis position of the focal reducer causes a small telecentric offset of 0\,\mu\text{m}. While in principle this offset could be compensated for completely with a tilt correction of the entire fiber array, it was considered a small and negligible change in terms of the incoming F-number (see Fig. 12 of Bershady et al. 2004).

A common, compact, and stiff mount for the focal reducer and the PPak IFU was designed in order to make sure that the fiber bundle is firmly attached to the focal reducer image plane, which is located 6 mm behind the lens (see Fig. 4). This mount also allows the insertion of bandpass or interference filters (with diameters of 50 mm, or 2 inches) in front of the lens. Any mechanical flexure due to a changing gravity vector was calculated to be 4\,\mu\text{m} (≈0\,\mu\text{m}) in the worst case. In the spatial direction, this is much smaller than the fiber sampling size (of 150\,\mu\text{m}) or effects caused by seeing (0\,\mu\text{m} ≈ 30 \,\mu\text{m}). In terms of focal accuracy, this amount of flexure is negligible. Note that due to the limited pointing accuracy of the telescope, it is practically impossible to measure flexure effects of this magnitude, if present at all.
Fig. 4.—Three CAD views of the mount that holds the focal reducer lenses, the fiber head, and optional filters. Due to space constraints, the fibers bend 90° below the IFU and exit sideways. A flexure analysis of the mount stability vs. inclination yields a maximum deformation of 4 μm at the top part with respect to the fixed mount plate. (Mechanical design by S. M. B.) [See the electronic edition of the PASP for a color version of this figure.]

2.2. PPak IFU

The final PPak design features 331 fibers in a densely packed hexagonal grid with a maximum diameter of 74", while each fiber projects to 2'68" in diameter on the sky. The fiber-to-fiber pitch is 3'6. The projected fiber area, with 5.7 arcsec², is comparable to that of DensePak or INTEGRAL, but is smaller than for SparsePak. However, the larger number of fibers allows the observer much freedom to apply adaptive binning of spaxels to increase the signal-to-noise ratio (S/N).

An additional 36 fibers are distributed among six “mini-IFUs” and are placed 72" away from the center to sample the surrounding sky (see Fig. 5). Not shown are 15 extra fibers that are not part of the IFU, but are connected to a calibration unit. These calibration fibers can be illuminated with light from spectral-line lamps during the science exposures. This provides a synchronous spectral calibration and keeps track of any image shifts at the spectrograph detector (see § 4.9 of Paper I).

A fair number of additional fibers (shown in black) are placed around the active (white) fibers to serve as protective buffers and to avoid increased FRD (focal ratio degradation) edge effects (see Figs. 8 and 9 in Bershady et al. 2004) of the outer science fibers. These buffer fibers are ~70 mm long and terminate inside the mount, just below the IFU head. Table 2 gives a summary of the total fiber breakdown.

2.3. Fiber Slit

The output ends of the fibers are placed side-by-side to form a long fiber slit. For practical reasons and to assist with data reduction, the overall fiber slit is divided into 12 blocks (called slitlets). A slitlet is 7.5 mm wide and features 32 V-grooves with a spacing of 0.234 mm (see Fig. 6, right). Given a spectrograph magnification of 0.6 and 15 μm pixel⁻¹, a fiber core projects to 6 pixels at the detector, with a pitch of 9.4 pixels. The chosen spacing is a trade-off to minimize cross talk and the overall slit length, because of edge vignetting.

![Focal Reducer Lens](Image)

![IFU](Image)

![Mount plate](Image)

![Table 2](Image)

| Fiber Type      | Active | Buffer | Total |
|-----------------|--------|--------|-------|
| Object          | 331    | 216    | 547   |
| Sky             | 36     | 186    | 222   |
| Calibration     | 15     | 22     | 37    |
| Total           | 382    | 424    | 806   |

Fig. 5.—Layout and dimensions of the PPak IFU. The central hexagonal is made up of 331 object fibers surrounded by six sky IFUs. Note that only the white circles represent active fibers, while the black ones are protective buffers. Each circle represents the combined fiber core, cladding, and buffer material. While the physical size of the central IFU is just 4 mm, its coverage on the sky is more than 1'. [See the electronic edition of the PASP for a color version of this figure.]
In contrast to other IFUs that are add-on units to existing spectrographs, PMAS features a designated fiber spectrograph (see Paper I). The spectrograph collimator is an $f = 450$ mm, F/3 system, and therefore the optics accepts the whole fiber output cone, without the need of additional beam-converting microlenses. The spectrograph optics require a curved fiber slit that directly couples to the first lens of the collimator. The fibers are mounted parallel to each other but terminate at different lengths to form a curved focal surface (see Fig. 6, left).

2.4. Slit to Sky Mapping

The focal plane geometry of the PPak IFU was largely determined by the Disk Mass project. The arrangement of the fibers in the focal plane, and how they map to the slit, follows a quasi-random fashion. The central IFU can be divided into five main segments (see Fig. 7). The central segment, with fibers numbered 148 to 184, maps to the central part of the slit. The fibers in the two intermediate segments of the IFU (1–66 for the northern part, and 266–331 for the southern part) map to the edges of the slit. The fibers in the two outer IFU segments (67–147 for the northern part, and 185–265 for the southern part) terminate halfway between the center and the edges of the slit (see Table 3). One reason for this arrangement was that for typical targets, such as galaxies, the surface brightness falls off rapidly away from the center. Since the outer fibers carry the weaker signals, any additional vignetting or aberration effects, predominantly at the edge of the slit, are thus avoided. Care was taken that fibers that are adjacent in the focal plane are well separated in the slit. The aim was to minimize any systematic effects that purely depend on the location of fibers within the spectrograph. Note that this approach is opposite to that of other instrument layouts, such as SPIRAL (Lee & Taylor 2000), in which fibers adjacent at the sky remain adjacent at the slit.

Also note that the central row at the IFU, starting in the east with fiber number 185 and ending in the west with number 92, contains fibers from all five segments. This ensures that drifting a star across the central row produces 21 spectra distributed over the entire CCD, nearly sampling the full range of optical paths through the spectrograph.

Each slitlet carries three sky fibers distributed in three non-adjacent sky IFUs. In this way, each triplet of sky fibers on a slitlet spans a triangular area on the sky around the main IFU. In other words, the sky is sampled symmetrically around the object and is well distributed within the slit, again to avoid any instrumental biases. This scheme results in 36 sky fibers altogether, which is twice the “optimum” number of dedicated sky fibers as calculated by Bershadly et al. (2004, Fig. 3), but helps to limit systematic errors in the sky subtraction.

2.5. Fiber Loop Box

Stress on optical fibers increases the FRD, with consequences for the overall optical system performance (see Barden 1998; Parry & Carrasco 1990; Ramsey 1988; and Schmoll et al. 2003, and references therein). To minimize FRD and therefore the loss of information, the fibers are inserted into protective, friction-free, three-layer furcation tubings, and are only bent at tolerable radii. Roughly 2 m behind the IFU and some 40 cm in front of the fiber slit, the protective tubing is interrupted to allow the fibers to form a loop. The fiber loops are placed inside an enclosed $30 \times 30$ cm box, where they are kept in groups of 32 and placed into separate sections divided by Teflon sheets (see Fig. 12). The loop box serves two functions: first, any pull on a fiber results in a change of the individual loop diameter, which prevents the fibers from being torn. Second, the loops provide a reservoir of extra fiber length, which is needed during assembly and integration. Note that both the IFU and the spectrograph are mounted at the Cassegrain station and remain fixed with respect to each other. Therefore, no stress-relief cabling, as used for bench-mounted instruments with long (>10 m) fiber lengths, is required.

2.6. PPak Calibration Unit

Fifteen fibers that are distributed along the fiber slit are diverted from the rest of the fiber bundle, as their input ends are not placed at the telescope focal plane, but are connected to the PPak calibration unit (PPCU). This unit is made from standard OVIS laboratory equipment and consists of five liquid-light guides (Lumatec, Germany), a white diffuser screen, a relay lens, and the calibration fibers themselves (see Fig. 8). Four liquid-light guides illuminate the diffuser screen with light from the various calibration lamps (such as halogen continuum, mercury, neon, and thorium/argon). A fraction of the light is picked up by the relay lens and focused onto the calibration
Fig. 7.—Diagram of the mapping scheme at the IFU. In the focal plane, five main segments map to distinct regions along the slit (see Table 3). North is up and east is left. The orientation is fixed on the sky, as the instrument cannot be rotated. Note: image not to scale; artificial gaps added.
fibers, using the same F-number as for the science fibers, and
with an object distance at infinity. As the lamps are placed
within electronic boxes and feature individual shutters, any
combination of calibration light (and the respective exposure
times) can be fed into the calibration unit. The calibration fibers
can be illuminated separately from or simultaneously with the
object fibers, allowing the observer flexibility with respect to
calibration strategy and needs. Finally, a change of lamps or a
swap to a spare lamp is easily done by reconnecting the light
guide(s), without any changes to the calibration unit itself.

3. MANUFACTURE, ASSEMBLY, AND INTEGRATION

3.1. Lens Optics

The fabrication of the focal reducer lens was contracted to
Präzisionsoptik Gera (Germany), based on specifications from
the optical design calculations by U. L. (see § 2.1). These
calculations were repeated as soon as the glasses were procured
from Schott (Germany), and the index of refraction was mea-
sured at the design wavelengths in order to optimize the design.
Note that due to its thickness, the fourth lens was made from
two pieces. The individual lenses were cemented together using
optical compound K57, produced by Carl Zeiss Jena (Ger-
many). All glass–air surfaces were treated with a Balzers broad-
band antireflection coating, yielding a transmission of
$98\%$ across the design wavelength range.

The first lens of the spectrograph collimator (diameter
$D = 100\, \text{mm}$, curvature $R = 218\, \text{mm}$), to which the fiber slit
connects, was produced by Carl Zeiss Jena.

3.2. Fiber Cables

After tests in the AIP laboratories, we selected silica/
silica step-index fibers with core/cladding buffer diameters of
$150/165/195\, \mu\text{m}$, low-OH cores, and NA (numerical aperture)
$= 0.22$, of the FIP150165195 series from Polymicro Tech-
nologies, LLC. (US; see Fig. 9). The fiber bundle was man-
Fig. 8.—PPak calibration unit. Liquid-light guides illuminate a white diffuser screen from which the light is reflected backward. A relay lens couples the light with the correct F-number into the calibration fibers. An optional filter can be inserted. Up to five light guides offer the possibility to combine the light from different lamps.

Manufactured as follows. First, the fibers were cut to a length of 3.5 m, and one end was polished manually (smallest grain size = 0.3 μm). The exit surfaces were polished at this early stage because the assembled fiber slit is curved and therefore difficult to polish. At the input end, the fibers were first assembled into the IFU head and polished afterwards. Copying parts of the SPIRAL-B design (Lee & Taylor 2000), a three-layer polypropylene-Kevlar-PVC furcation tube from Northern Lights Cable (US) was cut to length and fitted with connector screws on both ends. Altogether, 367 fibers were inserted into 12 protective tubings, each tube carrying the object and sky fibers from one slitlet. The 15 calibration fibers were put into an additional tube.

3.3. Fiber-Slit Assembly

The polished ends of the fibers were glued onto the 12 slitlets using EPO-TEK 301-2 nonshrinking two-component epoxy from Polytek. Each slitlet typically holds 28 object fibers, 3 sky fibers, and 1 calibration fiber (see Table 3 for details). The outermost calibration fibers (C1 and C2 at one end of the slit, and C15 at the other end) are separated from the object fibers by one empty groove. Three sky fibers (from three different sky IFUs) are distributed uniformly among the 28 object fibers. To ensure a correct and repetitive fiber alignment, an assembly jig was produced that holds both the fibers and the slitlet in place and allows an accurate end termination of each fiber against a dummy surface with the correct curvature. After the correct alignment was controlled visually, the fibers were clamped temporarily and then glued onto the slitlet block. Given that the V-grooves are 100 times longer than a fiber diameter, and manufacturing tolerances of <0.01 mm were achieved, the alignment and the end positioning of the fibers were done to an accuracy of within a few microns. Altogether, 12 slitlets, each carrying 31 or 32 fibers, were mounted side-by-side on a common stage, creating a fiber slit 94 mm long in total. The slitlets can be moved and locked individually. In this way, any length variations between slitlets are irrelevant, as each slitlet can be brought forward until the fibers touch the collimator lens surface. The overall unit includes mounts for the cables, the fiber slit, and the collimator lens, as well as protective covers (Fig. 6, left).

The fibers were repeatedly cleaned with methanol and water in an ultrasonic bath prior and after the assembly, to remove any contamination from the surfaces. The quality was controlled by inspections of the fiber ends using a video microscope. Illumination of individual fibers yielded their positions within each slitlet, and the fibers were labeled according to a predefined position table (see Fig. 7).

3.4. Fiber-Head Assembly

At the input (i.e., the IFU) side, the individually labeled object and buffer fibers were ordered and preassembled row-by-row on a piece of sticky tape. No additional glue was applied at this stage. A mount was manufactured at the AIP workshop; it features a central hexagonal opening and precision steps to aid the correct fiber alignment. The milling precision was on the order of 1/100 mm (=5% of a fiber diameter), which was more than adequate to ensure that the fibers form a densely packed arrangement. The main IFU was built up by inserting each row of fibers (27 rows in total) into the hexagonal mount, with the fibers extending ≈5 mm beyond the mount surface. For practical reasons, this was done separately for the two
halves (see Fig. 10), which were put together and locked mechanically thereafter. In fact, it was the added tolerance on the size of the overall number of fibers, and not the precision of the mount manufacture, that limited the correct alignment. The maximum deviation from a regular hexagonal grid occurs for the outermost row and was measured to be of the order of 10% of a fiber diameter, corresponding to a misalignment of approximately $0.07\,^\circ$.

Six additional circular drillings around the central opening accommodate the sky-fiber IFUs. The assembly of the sky IFUs was similar to that of the main IFU, using the row-by-row approach. Each sky IFU consists of 6 sky fibers and 31 short buffer fibers (Fig. 5), which form a dense pack 7 fibers across. This was inserted into a steel ferrule with a matching inner diameter of 1.4 mm. Subsequently, the ferrules were glued into the holes drilled in the mount (Fig. 11, left). After assembly, the IFU mount was pointed downward, and the extending fibers were immersed in a bath of epoxy that worked its way upward in between the fibers and through the mount by means of capillary force. In this way, the fibers are glued together and to the metal mount, without introducing additional stress. After the epoxy had cured, the entire fiber head, including the six sky IFUs, was polished using a custom-made polishing stage (as described in Kelz et al. 2004). Polishing sheets from Newport and Data Optics were used, featuring grain sizes from 30 to 0.3 μm. The surface quality was inspected regularly during the polishing process using a video microscope with 4× to 16× magnification (Fig. 11, right). This allowed the projection of highly magnified fiber images onto a monitor. In conjunction with a variety of viewing angles and illuminations, scratches on the order of 1 μm were visible and could be polished out. The end requirements were to have no obvious surface defects, such as partial breakages of core or cladding material, no scratches larger than 1% of the fiber diameter ($\leq 1.5\,\mu m$), and a visually flat and perpendicular end surface.

### 3.5. Integration of PPak into PMAS

Optical gel from Cargille Laboratory (code 0406, $n = 1.46$) was applied between the spectrograph collimator lens and the fiber slit(s) to match the refractive indices. The loop box was filled and closed (see Fig. 12), and all 13 PPak cables were inserted into a common flexure tube. Inspections revealed that no fibers were broken or damaged during the process of manufacture, assembly, and integration.
During the construction and initial commissioning, the PPak bundle was a single entity from end to end. This implied that the existing lens array fiber module needed to be dismounted from the PMAS instrument to make space for the PPak module. As this is a time-consuming and potentially hazardous undertaking, both fiber modules (i.e., the fiber slits and loop boxes) were merged into a single unit (called a double IFU) in 2004 October. The double slit consists of two parallel rows featuring the 256 lens array fibers and the 382 PPak fibers (see Fig. 13). The spacing between the slits is approximately 2 mm. The foreoptics and the two IFUs remain as physically separate units. While both IFUs cannot be used simultaneously, it is easy and safe to change the configuration during the day. A change of modes between the lens array IFU and the PPak IFU involves a hardware switch to select a different shutter, to reconnect the internal lamps to the respective calibration units, and to cover the IFU that is not in use.

4. OPERATIONS

4.1. Calibration

While the entire lens array IFU can be illuminated from a deployable internal calibration unit, the position of the PPak IFU, which is off-axis and in front of the telescope focal plane, is outside the optomechanical range of the original calibration unit. Therefore, PPak calibrations must be performed instead with dome or sky flat-field exposures. Flat-field exposures with external light sources (continuum and arc lamps) yield the fiber-to-fiber responses, wavelength calibration, and position information required to accurately trace and subsequently extract the spectra from a recorded image. These calibration images should be obtained at least once per night and for each grating setting.

The best spectrograph focus is found by illuminating the calibration fibers only, using the internal spectral line lamps. This will yield well-separated emission spots across the entire CCD chip. Preferably, the calibration fibers should always be illuminated by a spectral line lamp while a science exposure is taken. This allows for the tracing of any image shifts or spectrograph defocus during the data reduction for each science frame (see Fig. 14).

4.2. Instrument Control Software

The AG-OPTICS system for acquisition and guiding is described in Paper I. Unlike the lens array IFU, which is positioned at the center of the A&G field of view (of 3'.2 × 3'.2), the PPak IFU is located off-axis, 295'' to the south and 206'' to the west. Since the offset is known to the instrument control software, the basic functionality for field acquisition and guiding remains unchanged. The A&G instrument control software (pics_ag) has an option to overplot the PPak outline or even the position of the 331 fibers to a freshly obtained acquisition frame, and allows for an offset pointing to center the object of interest onto the PPak IFU. The position of a guiding box around a guide star on the A&G frame can be stored and recalled. This allows for the accurate repositioning of a guide star on subsequent nights to within 0'.2. Note that this procedure has been successfully applied using the finer sampling lens array IFU, which, due
to its distance, is more likely to be subject to relative flexure than the closely mounted PPak unit (see Fig. 1).

The IDL-based PMAS instrument control software (PICS) includes some additional features for PPak operations, namely the option to include calibration light within the science frames (e.g., $5 \times 10$ s of ThAr distributed equally within an overall exposure time of 30 minutes) and to center, offset, or mosaic-point the PPak IFU.

Note that the nod-and-shuffle (or beam-switching) mode that is available for the lens array IFU is possible with PPak too, but at the cost of a higher level of cross talk, as the spacing between the PPak spectra on the detector is smaller.

### 4.3. Data-Reduction Software

Based on the P3d data-reduction software package (Becker 2002; see Paper I), an adapted version for PPak (PPAK_online) was written by T. B. The program can be used for a quick-look inspection of the data quality and for a reconstruction of maps, while observing at the telescope. The code is written in IDL and allows the user to process the raw data and to eliminate the specific instrumental signature. The subroutines include bias and dark subtraction, cosmic cleaning, spectra tracing, flexure compensation, spectra extraction, flat-fielding, and wavelength calibration. The full P3d package also allows for CCD pixel-to-pixel response variation, stray-light modeling, and wavelength-dependent fiber response calibration. There are also various custom-made IDL utilities for the visualization of stacked spectra, maps, and individual (or co-added) spectra (see Fig. 15). These utilities are available within GUIs and from the IDL command line, supporting the use of scripts. It is also possible to call the E3D visualization tool from within PPAK_online, providing further features, such as interpolated maps, line fitting, etc. (see Sánchez 2004; Sánchez et al. 2004). PPak data were also successfully reduced using the Hydra package within IRAF.

### 5. PERFORMANCE

#### 5.1. Throughput

The instrumental throughput was obtained using two methods. First, the observed flux of spectrophotometric standard stars was compared to tabulated values from the literature. Second, the relative throughput of dome flat exposures for the lens array IFU and the PPak IFU was determined. The reason for the second approach is that often the actual atmospheric conditions at Calar Alto are either nonphotometric or not known well enough to unambiguously determine the true instrumental response. However, the instrumental efficiency using the lens array IFU has been well established previously (see Paper I), and therefore a relative response measurement can yield the PPak throughput.

Figure 16 plots the directly measured PMAS+PPak efficiency. The lower (dotted) curve gives the total throughput, from top of the atmosphere to the detector. It was obtained by comparing the flux of the spectrophotometric standard star BD +75 325, observed on 2004 November 20 at an air mass of 1.3, to the expected flux as given by Oke (1990). This total efficiency $\eta$ includes the instrument $\eta_{\text{inst}}$, the atmosphere $\eta_{\text{atm}}$, and the telescope $\eta_{\text{tel}}$. The middle (dashed) curve represents the efficiency from the top of the telescope to the detector; i.e., taking atmospheric extinction and air mass into account. The atmospheric extinction coefficients for each wavelength were calculated by
scaling typical extinction tables for Calar Alto (Hopp & Fernandez 2002) to $k_{es} = 0.14$ mag and $\eta_{ext} = 0.85$, which was the measured extinction in the $V$ band during the night. The top (solid) curve is the pure instrumental throughput $\eta_{intr}$, from the telescope focal plane to the detector. The instrumental configuration included the PPak IFU without any filters, and the spectrograph with the V300 grating in first order (300 lines mm$^{-1}$, blaze angle = 43°, $\alpha = 16\degree$, $\lambda_{cen} = 542$ nm). The throughput of the primary mirror was derived from reflectivity measurements obtained routinely at Calar Alto. Assuming a similar value of 75% for the secondary reflectivity, the telescope efficiency was estimated to be $\eta_{tel} = 0.57$ in $V$ at the time of observation.

Note that the plots in Figure 16 present lower limits, in that the flux lost outside the finite aperture of a single fiber was neglected. Applying an aperture correction (along the lines of CCD aperture photometry techniques; e.g., Howell 1989) based on the measured seeing FWHM of 1.1 in $V$, and assuming a Gaussian approximation to the PSF, we estimate a correction factor of 1.15; i.e., a peak efficiency of 31%.

This value agrees reasonably well with the comparison of dome flat exposures taken with both the lens array and the PPak IFU, while the spectrograph setup with a V300 grating remained unchanged. The PPak configuration was found to have a throughput 1.5 times higher than the lens array IFU, resulting in a peak efficiency of 30%, compared to 20% for the lens array IFU. As the coupling of both fiber slits toward the spectrograph is similar, and since the difference in length between the lens array and PPak fibers is only 1.5 m, we attribute this difference in efficiency to the foreoptics and input coupling in particular. As shown in § 4.3 of Paper I, the lens array IFU throughput suffers from two effects: first, from light losses caused by the extended parts of the lens array PSFs (i.e., stray light and diffraction spikes), and second, from the median misalignment between the micropupil images and the fiber cores. Both these problems are not present in the PPak design, so a bare fiber bundle fed by a large foreoptics lens is more efficient.

Instrumental throughput estimates for other PMAS gratings were bootstrapped from the lens array IFU efficiency data, as shown in Figure 15 of Paper I. Using a grating blazed in $R$ (600 lines mm$^{-1}$, blaze angle = 139°, $\lambda = 530$–810 nm), the instrumental efficiency peaks at 36% between 600 and 700 nm. Note that the PPak configuration has not been optimized in the blue, and that both the image quality of the focal reducer lens and the transmission of the fibers and the lenses rapidly decrease below 400 nm. The groove density of the gratings (e.g., 300, 600 or 1200 lines mm$^{-1}$) only has a minor effect on the efficiency. Those gratings, which are used in second order (11200 and J1200), show a significantly lower efficiency, due

to intrinsic grating effects and a geometrical overfill of the grating at large tilt angles (see § 5.4).

5.2. Fiber Response and Cross Talk

Visual inspection of either the forward- or backward-illuminated fiber bundle yielded an apparent uniform fiber response across the slit and the IFU. This was confirmed by sky and dome flat exposures taken at the telescope. Figure 17 shows a cross-dispersion cut at roughly 500 nm through a raw dome flat exposure with the illuminated 331 object fibers and 36 sky fibers. The vignetting of the spectrograph optics toward the edges, and the degree of flatness of the fiber-to-fiber response, can be judged from this plot. Note that there is an overall slope in the intensity level, which is believed to result from two effects: the slit is not perfectly centered on the optical axis of the spectrograph, and the undersized flat-field screen in the dome does not in fact provide a uniform and flat illumination across the field. Figure 18 is a zoomed version of the previous image, showing a central slitlet only. The maxima of the normalized intensities range between 0.89 and 0.98. In zeroth order, the fiber core projects to 6 pixels on the CCD. The pitch between individual fibers is 9.4 pixels, resulting in moderate cross talk and a typical interorder minimum intensity of 20% of the peak level.

The final amount of cross talk not only depends on the instrumental performance, but also on the actual data reduction. A profile-fitting extraction method is capable of allocating the overlapping wings of the flux distribution toward the individual spectra. In this way, cross talk can be disentangled better than using an extraction scheme with fixed pixel numbers (see Becker 2002). Apart from spectra extraction, other parameters, such as the option to use on-chip binning in the spatial direction, or the (sagittal and tangential) focus setting of the spectrograph, will result in different levels of cross talk. Whether or not these are of concern, and what level of cross talk is acceptable, will depend on the particular science case.

5.3. Scattered Light

Scattered light effects mainly depend on the selected grating, wavelength range, and order (i.e., the grating position). In particular, ghost images were noticed at certain second-order wavelength settings, where the grating is overfilled and its mount is highly inclined toward the incoming beam. The exact origin of these ghost images is the subject of further investigation.

In addition to ghost images, most complex optical systems show extended wings of the PSF at low intensity levels, which are generally attributed to “scattered light,” although the precise physical origin of this “halo” around the PSF core is difficult to assess. The relatively large separation of the PPak calibration fibers allowed us to obtain high-S/N cross-dispersion profiles from well-exposed continuum lamp calibration exposures, and to map the scattered light level, as illustrated in Figure 19. The overlapping individual scattered light halos from these cali-
Fig. 17.—Cross-dispersion cut through a raw dome flat exposure featuring all 367 spectra that belong to the PPaK IFU (the calibration fibers were not illuminated). Note the gaps between the 12 slitlet blocks.

Fig. 18.—Typical fiber-to-fiber throughput variation (zoom of Fig. 17). Cross-dispersion cut of one slitlet is shown, containing 31 spectra that are well separated down to 20% of the peak value.

Fig. 19.—Normalized average of 100 columns in the cross-dispersion direction near the center of the CCD. Only the 15 calibration fibers are illuminated with halogen light, while the 367 IFU fibers are dark. This allows the measurement of the extent of the wings of the flux distribution to low light levels.
from the integrated scattered light can be on the order of 8%–14%. This value highly depends on the assumed width of a spectrum, the position of the spectrum on the chip, and the wavelength.

Becker (2002) has implemented in the P3d data-reduction package a profile-fitting extraction method that is based on empirically determined cross-dispersion profiles as a function of wavelength for each spectrum; however, it is currently only available for data obtained with the PMAS lens array IFU. The iterative scheme of this code is capable of (1) measuring and eliminating the cross talk between adjacent spectra (on the order of 0.5% for the lens array), and (2) simultaneously solving for a model of diffuse scattered light over the face of the detector (less than 1% of the average peak intensity). While this level was considered negligible for normal PMAS data, the application of the scattered light model to data from the Multipupil Fiber Spectrograph (MPFS) at the Selentchuk 6 m Telescope, which does have significant stray-light patterns, proved to be essential to eliminating systematic errors (Becker 2002). Implementing a profile-fitting extraction routine for PPAK data, as well as a thorough characterization of cross talk and stray-light properties for the various grating setups at different grating tilts, is a goal of a future upgraded version of the P3d software.

5.4. Use in the Second Spectral Order

PMAS was initially designed and built as a spectrophotometer for low/medium spectral resolution imaging, with the goal of maximizing wavelength coverage rather than spectral resolution. More recently, the main science driver for retrofitting PMAS with the PPAK IFU demanded that $R \approx 8000$ (Verheijen et al. 2004), which could not be satisfied with the current fiber size (i.e., pseudoslit width) and any of the standard gratings in first order. However, a test with two gratings in second order (I1200: blaze angle = $37^\circ$, 1200 lines mm$^{-1}$, and J1200: blaze angle = $46^\circ$, 1200 lines mm$^{-1}$) yielded satisfactory results in the wavelength region near 520 nm. Figure 20 illustrates that not only the roughly twofold increase of linear dispersion, but also the effect of anamorphic demagnification, helps to improve the spectral resolution (e.g., Schweizer 1979). Considering the basic grating equation $\sin(\alpha) + \sin(\beta) = n g \lambda$, where $\alpha$ and $\beta$ are the angles between the grating normal and the incident and diffracted beams, respectively, $n$ is the spectral order, $g$ the groove density in (lines mm$^{-1}$), and $\lambda$ the wavelength, the anamorphic (de)magnification $r$ of the slit width is given by

$$r = \frac{\cos(\alpha)}{\cos(\beta)}.$$

For a typical setup in first order, $r$ is close to unity, and the effect is often negligible. In second order, however, the grating tilt is more extreme, so that $r$ becomes significantly different from 1. The top left panel of Figure 20 shows a small central region of a raw CCD frame from a sky flat-field exposure that was taken on 2004 November 8 using the V600 grating in first order, with a grating tilt of $\alpha = 15^\circ$. The anamorphic magnification of this setup is $r = 1.08$. Therefore, the two rows of calibration spectra with ThAr emission lines present a close to perfect round spot appearance. The corresponding plot with emission-line profiles reveals a FWHM of $\approx 3$ pixels (from a $2 \times 2$ binned CCD frame), exactly matching the expected width of 6 unbinned pixels.

The bottom panel shows the same situation for a setup with the J1200 grating in second order, mounted in the “backward” orientation (see Paper I); i.e., the grating normal facing the camera, and a grating tilt of $\alpha = 63^\circ$. This sky flat-field exposure was obtained on 2005 May 4. In contrast to the V600 exposure from above, the emission-line spots are now significantly compressed in the dispersion direction, and the line profiles are extremely sharp, with a FWHM of $\approx 1.5$ pixels ($2 \times$ binned). The anamorphic magnification is $r = 0.49$. The resolving power obtained in this configuration with the 150 $\mu$m PPAK fibers is $R \approx 7900$. Note that in order to maintain sharp images and this relatively high spectral resolution, careful focusing, the restriction of exposure times, and the avoidance of hour angles with adverse flexure effects (see Paper I) are of utmost importance.

The use of the high-resolution mode comes at the expense of a lower throughput. Table 4 lists the relative efficiencies $T_{\text{rel}}$ (in ADU s$^{-1}$ Å$^{-1}$) of the I1200 and J1200 gratings in second order.
order, forward (fwd) and backward (bwd) oriented, respectively, with reference to the V1200 grating in first order.

6. SUMMARY

A new integral field unit based on the fiber-bundle technique, providing high grasp and a large field, was developed and successfully commissioned for the existing PMAS three-dimensional instrument. The central PPak IFU features 331 object fibers, projected by the 3.5 m Calar Alto telescope, that span a hexagonal field of view of $74'' \times 64''$, with a filling factor of 60%. The individual spaxel (fiber) size is $2.7''$ across, yielding a total grasp of $15,200$ arcsec$^2$ m$^{-2}$ at this telescope. An additional 36 fibers are distributed over six sky IFUs that surround the main IFU at a distance of $72''$ from the field center, allowing a good coverage and subtraction of the sky background. For calibration purposes, 15 fibers can be illuminated independently with arc lamps during a science exposure and can keep track of spectral resolution and image shifts. A summary of the technical parameters is given in Table 5. Further details regarding the PPak spectrograph, the available gratings, and the filters are given in Paper I and can be found online.\(^6\)

The combination of spaxels with high grasp and the PMAS spectrograph, which has high efficiency and wide wavelength coverage, makes PPak a powerful tool for the study of extended low surface brightness objects, which require a high light-collecting power and a large field of view. Figure 21, gives an example of the galaxy UGC 463, which was observed for the Disk Mass project. Despite the rather crude sampling of the fibers, the basic morphological structures of the galaxy seen in the POSS-II image (spiral arms, stars clumps, etc.) are clearly visible in the PPak reconstructed image. Apart from the ability to create mono- and polychromatic images from the resulting data, one exposure with PPak yields 331 spatially resolved spectra of the target. The high number of fibers at the outer and fainter parts of the galaxy gives the observer the option to adaptively bin spaxels in order to further increase the S/N.

During 2004, PPak was available on a shared-risk basis, as its usage involved a complex changeover between the lens array and PPak fibers, which had to be done by AIP staff. With the integration of the two parallel fiber slits, the PPak IFU was permanently installed and was offered as common-user instrument, beginning in 2005. Two further upgrades are scheduled: a new mount to ease the exchange of order-separating filters, and adjustments to the PPak data-reduction software. Since its commissioning, PPak has attracted considerable interest from several observers, with the result that nine observing runs for a total of 26 nights, plus nine “service buffer A” nights, were granted to PMAS-PPak within its first year by the Calar Alto telescope allocation committee. In 2005, approximately 50% of the allocated time for PMAS has been used with the PPak IFU. Throughout these runs, the PPak module has worked without failure.

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\(^6\) See http://www.caha.es/pmas.
Fig. 21.—Comparison between the POSS-II R-band image (left) and the PPak reconstructed image of the galaxy UGC 463 (right). The PPak data were obtained using the V300 grating centered at ≈5300 Å. Once reduced, the reconstructed image was created using E3D (Sánchez 2004): a three-dimensional cube was created by adopting a natural neighbor interpolation scheme to a common grid of 1.35 pixel. After that, a two-dimensional image was produced by co-adding the flux in the wavelength range between 4500 and 6000 Å.

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