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Design of ALES: a broad wavelength integral field unit for LBTI/LMIRcam

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ABSTRACT

The Arizona Lenslet for Exoplanet Spectroscopy (ALES) has been conceived of as an integral field spectrograph (IFS) that can be integrated with the existing 1-5 micron imaging camera LBTI/LMIRcam. Retrofitting an IFS to an existing camera poses interesting optical design issues. We have developed four reflective magnifier designs to create the proper scale for each spaxel of the IFS across the operational wavelengths of ALES. The lenslet design utilizes the flexible nature of silicon etching to provide aberration correction of images across the field of view that are introduced by inserting these magnifiers into the existing LMIRcam optical system. Finally, direct vision prism designs have been developed to provide suitable dispersion modes for the reference science cases of ALES.

Keywords: Adaptive optics, integral field spectroscopy, exoplanet imaging, exoplanet instrumentation

1. INTRODUCTION

Spectral characterization of exoplanet atmospheres is a powerful tool for constraining the physical characteristics of these objects. These observations potentially enable probing the composition, temperature, size of the planets, as well as the vertical structure of their atmosphere.

The Arizona Lenslet for Exoplanet Spectroscopy (ALES) was developed to enable observations at 3-5 microns, redder than other integral field spectragraphs (IFS). This capability is important for probing cooler and redder objects that have the majority of their flux being emitted at these longer wavelengths. ALES uses the existing LBTI/LMIRcam[1] infrastructure on the Large Binocular Telescope[2] to allow for an IFS with minimal new instrumentation needed.

The initial implementation of ALES has been successful in demonstrating the general approach. This proceedings describes the optical design of an improved implementation of ALES, to expand its wavelength coverage, range of magnifications, and image quality.

2. LBTI, LMIRCAM AND ALES

The Large Binocular Telescope Interferometer[3] (LBTI) is an instrument design to provide high spatial resolution imaging across the 1.5-13 micron wavelength band. LBTI can combine and phase the two telescope beam from the LBT, or carry out separated imaging observations. The LMIRcam instrument is one of the two imaging cameras for LBTI, providing Nyquist-sampled observations of the coherent LBTI PSF. LMIRcam has a reflective set of camera optics that provide two intermediate focal planes, and two intermediate pupil planes.

ALES is a retrofit of the LMIRcam instrument to enable integral field spectroscopy. A magnifier is placed just after the first pupil plane. A lenslet is placed at the second focal plane. Finally, a direct vision prism is placed near the second pupil plane. The resulting set of spectra produced by this series of optics can be reassembled into an image cube that spans the chosen spectral range.

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2.1 The ALES prototype

The first version of ALES was implemented and had first light in 2015.[4] The prototype ALES version had a refractive magnifier that was Keplerian (which rotated the image by 180 degrees, relative to the unmagnified image), with a magnification of 8.3.

A lenslet was manufactured by Jenoptik Optical Systems that had 50x50 360 micron spaxels and dispersed the light using an orientation such that a spectrum spanned 36 pixels. The aberrations introduced by the LMIRcam biconic limited the useful field-of-view to the central 30 spaxels.

A direct vision prism Zinc Selenide (ZnSe) and Sapphire doublet was used to acquire spectra over the range of 2.8-4.2 microns.

3. ALES OPTICAL DESIGN

The upgraded ALES design builds upon the lessons learned with the ALES prototype. In particular we have designed reflective magnifiers, for broader coverage, adopted aberration compensation in the lenslet array design, and developed higher dispersion prism dispersers.

3.1 Magnifiers

To allow for use over a broad range of wavelengths, the magnifiers are reflective. The basic design for each system is that of a Cassegrain type telescope, modified to work with a converging beam. Thus the first optic is concave and approximately parabolic, while the second optic is convex and has a hyperbolic aspheric shape. This basic approach works for a range of magnifications. The optical assembly is compact, allowing the magnifiers to be housed in a rotating wheel locate just after the first pupil plane of the LMIRcam optics. All of the magnifiers have the first element of the magnifier 48 mm after the pupil created by the first biconic mirror in the LMIRcam optics. The optical prescription for each magnifier is summarized in Table 1. Figure 1 Shows the optical ray trace of the 6, 12, 25, and 50 X magnifiers. A cartoon of the mechanical assembly is shown in Figure 2.

Table 1. ALES Magnifiers Optical Prescriptions.

Magnifier	Primary Radius	Primary Conic	Secondary Radius	Secondary Conic	Separation
6X	25.5	-1.199	4.244	-0.897	10
12X	35.414	-1.287	2.940	-0.669	15
25X	46	-1.419	1.808	-0.605	20
50X	1.808	-1.433	0.86	-0.885	20

3.1.1 Magnifier Alignment

The spacing of the two mirrors for each magnifier is critical for creating an assembly that is afocal. Because of this we setup a room temperature assembly to allow refinement of this spacing.

According to the nominal design, the first surface of all of the magnifiers should be 249 mm before focus. This is because the distance from biconic 1 to focus is 650 mm; the distance to the pupil image is 353 mm, and the magnifiers are placed 48 mm after the pupil plane.

We set up a lab source to simulate the LMIRcam beam. A fiber laser was used with a set of optics used to create an f/15 beam. An f=400 mm lens was used at 1:1 imaging. The location of focus was then measured by putting a small ccd camera (2.5 micron pixels) at the focus on a translation stage.

The diffraction spot size is $0.63*15 = 9.5$ μm or 4 pixels. Very roughly, can find the focus with an uncertainty that corresponds to a geometric beam size equivalent to twice the beam size. At f/15, the beam is 9.5 um wide when it is +/- 280 μm from best focus.

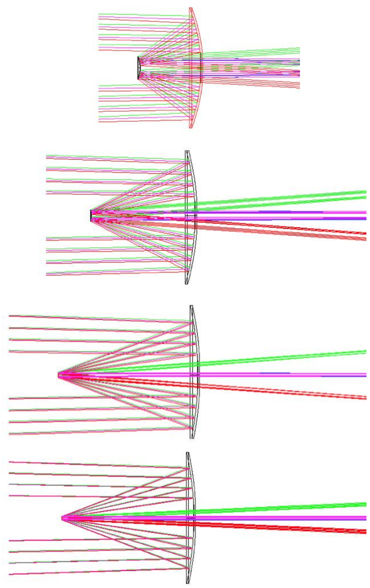

Figure 1. Ray Traces for the ALES Magnifiers. From top to bottom the magnifiers are for the 6, 12, 25, and 50 times magnifiers.

The next step was to insert the magnifier and measure the focal shift by translating the camera to find best focus. We could then adjust the mirror separation of the magnifier to minimize the focal shift with the magnifier inserted, relative to it not being present.

The final step was to build in the focus shift expected once cooled to cryogenic temperatures. For each magnifier we calculated the focal shift at room temperature that would result in an afocal system when at cryogenic temperatures, and aligned to this new position.

For refinement at cryogenic temperatures we relied on the feature that a movement of the whole assembly would result in a focal shift with a greatly reduced sensitivity. Thus the final set of several iterations done at cryogenic temperatures did not adjust the distance between each primary and secondary, but was a movement of each assembly to minimize the focal shift.

3.2 Lenslet array

The lenslet array is placed at the intermediate focal plane for LMIRcam. The device is designed to have lenslets which are 0.5 mm on a side. Since LMIRcam second biconic mirror reimages at a 1:1 magnification, this allows for 73 spaxels across the HAWAII H2RG detector. The lenslet is manufactured out of silicon by Jenoptik Optical Systems. Each lenslet shaped is created by an etching process that can create arbitrary and unique lenslet shapes. The prototype ALES lenslet included pinholes to reduce crosstalk between spaxels.

For the original ALES lenslet array, the LMIRcam second biconic mirror introduced astigmatism and defocus (Z4) for spaxels that were not on-axis. For the in-plane direction horizontal/vertical astigmatism (Z5) is introduced, while for the out-of-plane direction diagonal astigmatism (Z6) is introduced. In the new lenslet being fabricated, these values are applied to each lenslet, creating an astigmatic image for off-axis spaxels, that eliminates it in the final focal plane when used with the LMIRcam biconic mirror. Because of this change to the design, the pinhole mask was eliminated in the new ALES lenslet array, since the aberration would reduce the throughput of the pinholes significantly for spaxels at the edge of the field.

The focal ratio of the lenslet spaxels is f/15 (as measured on the side of the square aperture). In other words each lenslet has a focal length of 7.5 mm. This creates a diffraction-limited spot of 57 microns, or approximately 3 pixels at 3.8 microns wavelength. During the design of the lenslet array, we explored using a faster focal ratio to reduce this spot size, but the aberrations introduced by the second biconic mirror were then more severe, and

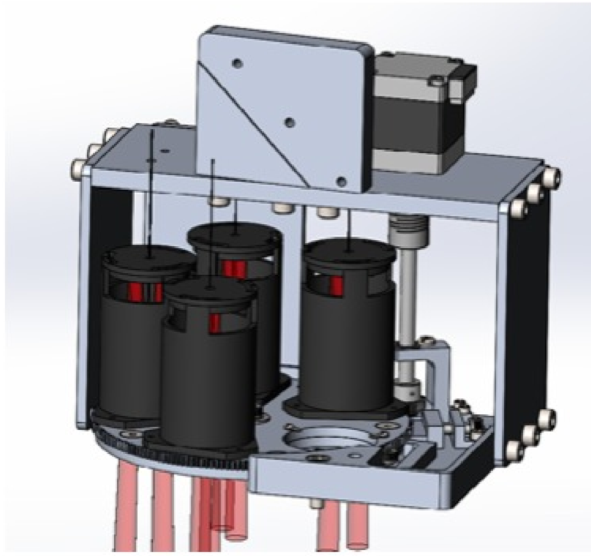

Figure 2. The ALES magnifier wheel assembly. A stepper motor adapted for cryogenic operation is used to drive a wheel that can insert any of the three magnifiers or allow for an unmagnified beam to proceed through to the detector.

had components of higher order aberrations. Slower focal lengths resulted in a diffraction-limited spot larger than 3 pixels. Because of these competing effects we adopted 7.5 mm as the focal length for the lenslets.

The defocus scales quadratically with the distance of the spaxel from the center of the field, while the vertical astigmatism is a linear function of the X position, and the diagonal astigmatism is a linear function of the Y position in the focal plane. By including the base radius of curvature of 18.2 mm for the center lenslet, one can write the lenslet shape as the sum of Zernike Fringe Polynomial therms Z4, Z5, and Z6:

$$Z4 = (1.0687 \times 10^{-5} \times R^2) + 0.013736 \tag{1}$$

$$Z5 = (-9.5285 \times 10^{-4} \times X) \tag{2}$$

$$Z6 = (-9.5285 \times 10^{-4} \times Y) \tag{3}$$

Where R, X, and Y are defined in millimeters away from the center of the lenslet array.

3.3 Dispersers

The dispersing elements for ALES need to be placed in an f/15 converging beam and are required to fit within the mechanical envelope of the existing filter wheels. For the prototype version of ALES, currently deployed, the geometry of the spectrum packing was to rotate the prisms such that the vertical distance between the edge of one spectrum and the next was 2-d, where d is the distance between spaxels (see Figure 4). Since the spaxel size was 40 pixels, the resulting spectrum can be no longer than 40 pixels (assuming a 4 pixel buffer between spectra).

For the new ALES lenslet array, the geometry we adopted was to orient the dispersion such that the vertical distance is 3-d between spaxels. This packs the spectra closer together, but allows for more pixels across each spectra. We also increased the spaxel size to 27 pixels, resulting in a maximum spectrum length of 80 pixels (again assuming a 4 pixel buffer between spectra).

We designed three dispersers of increasing spectral resolution (and decreasing spectral range) for use with ALES. All of the designs use a Sapphire-ZnSe-Sapphire arrangement of prisms to produce an undeviated beam

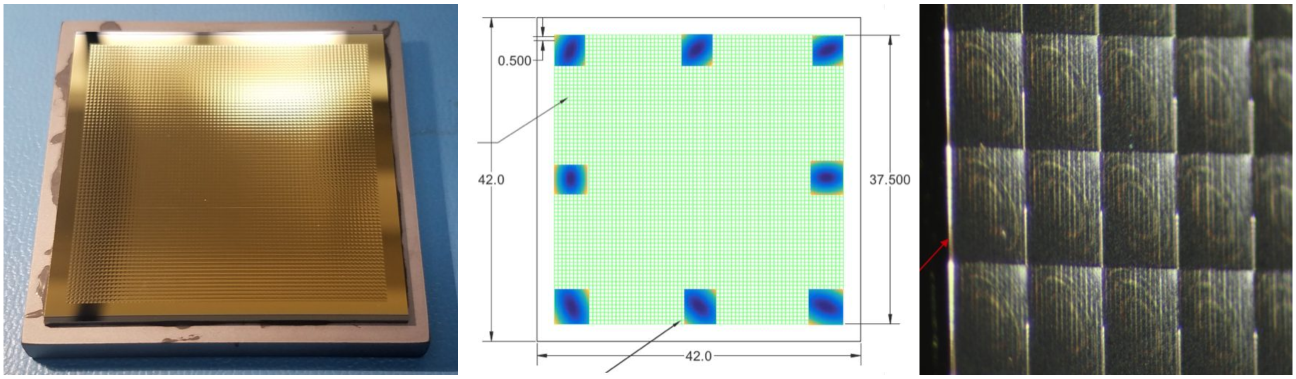

Figure 3. The lenslet array for the new version of ALES. Each lenslet has a shape that is unique for its location in the focal plane. The center lenslet has a spherical shape, while the off-axis ones have added astigmatism to correct for the second LMIRcam biconic. The left image shows the initial fabricated lenslet. The middle image shows the varying shape of sample lenslets at the edge of the array. The right image shows a closeup view of the lenslet where it is possible to discern their shape.

for the central design wavelength. Each prism is 15 mm in diameter. We have plans for a second "high" spectral resolution that covers the 2.0-2.3 μm region that is still in the process of being designed.

For each initial design prism set, a convex cylinder radius is polished into the first and second prism on their first surface. For the first prism the radius is in the plane of the biconic raytrace. For the second surface the radius is defined perpendicular to this. The prescription for the initial design is summarized in Table 2. Currently we have no plans to fabricate this design.

The initial design was discussed with vendors, and we found that the cylinder radius and the polishing of the convex shape on sapphire was either difficult or cost-prohibitive. Because of this we developed a revised design that avoided these.

The revised design maintains image quality across the field-of-view by use of a spherical convex shape on the first surface of the ZnSe prism. The prescription for the revised design is summarized in Table 3. The revised design is planned for fabrication.

The resulting spectral resolution for these dispersers will depend on the PSF width for each spectra. If we conservatively assume that the PSF width is 4 pixels, then there will be 20 resolution elements available for each disperser. The "low" disperser is design to work over 3-5 μm, for a spectral resolution of about 40. The "medium" disperser design will work over the 2.8-4.2 μm and the 2.2-3.7 μm region using two separate passband filters. These will provide spectral resolutions of 50 and 40 respectively. The "high" disperser design will work over the 3.1-3.5 μm region, resulting in a spectral resolution of 165.

Table 2. ALES Dispersers Optical Prescriptions - Initial Design. These designs have cylindrical radii on the first surface of the first and second prisms.

Dispersion	1st prism vertex angle	In-Plane Cylinder Radius (mm)	2nd prism vertex angle	Out-of-Plane Radius (mm)	3rd Prism vertex angle
Low	4.6	1844	4.6	3763	4.6
Medium	8.8	1518	8.8	2995	8.8
High	29	1433	29	2670	29

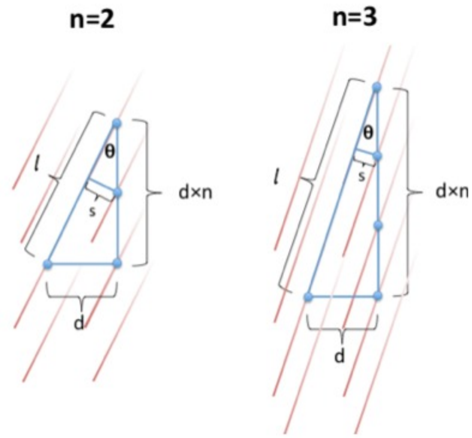

Figure 4. Geometry for packing the spectra for each spaxel onto the detector. The left cartoon shows the geometry adopted for the prototype ALES system, while the right cartoon shows the geometry planned for the new ALES lenslet.

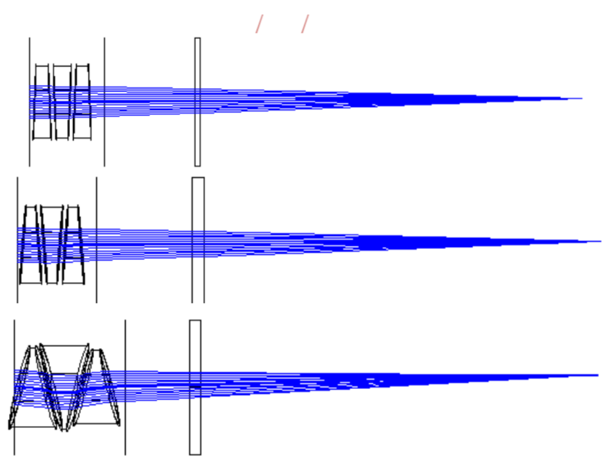

Figure 5. Dispersers for ALES. The figure shows the prisms for the low, medium, and high dispersers for ALES. The associated bandpass filter and the width of the filter wheel is also shown in each raytrace.

Table 3. ALES Dispersers Optical Prescription - Revised Design. These designs have a convex spherical shape for the first surface of the second prism.

Dispersion	1st prism vertex angle	2nd prism vertex angle	Radius (mm)	3rd Prism vertex angle
Low	4.6	4.6	3751	4.6
Medium	8.8	8.8	3004	8.8
High	26	25	2775	26

4. STATUS

The prototype of the ALES IFU has been in use for 2015 through the 2018 observing season. This summer we plan to upgrade to the version of ALES described in this proceedings.

The 6X, 12X, and 25X magnifiers were installed in summer 2017. We iterated on the minimum focus shift for each magnifier. The 50X magnifier will be installed in August 2018.

The lenslet array was manufactured in 2017, but an error in coordinate systems caused the first version to be fabricated with incorrect aberration correction. The process did verify the ability to correct the aberration in one axis, but resulted in an increasing aberration in the orthogonal direction. A corrected version of the lenslet array is currently being fabricated by Jenoptik and will be ready for installation in August 2018.

The first medium disperser system has been fabricated and is being planned for testing in July 2018.

We plan to commission this new version of ALES in fall 2018. Since the prototype version of ALES has been in regular use, we anticipate the main effort in commissioning will be in characterizing the new optics and refining observing procedures to use the system efficiently. The deployment of this new version of ALES provides a unique observing capability within the exoplanet community.

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