GPI Calibrations

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GPI Instrument Capabilities

High contrast imaging
- 10^{-6}, 1-sigma, 1-hour for bright targets

Lenslet based integral field spectrograph
- 2.4 x 2.4 arc sec field of view
- Nyquist image sampling at 14 mas per lenslet
- Operation in *YJHK (K split into K1 and K2)*
- *R* ≈ 40 spectroscopy in *H-band*
- ~36000 microlens spectra over the field of view

Polarimetry
- Dual channel polarimeter (full IFS field)

Milli-arc second astrometry
- 1mas accuracy

Non-redundant Mask (Sparse Aperture Masking)

Always mounted on the up-looking port
- *Instrument flexes with telescope movements*

GEMINI OBSERVATORY

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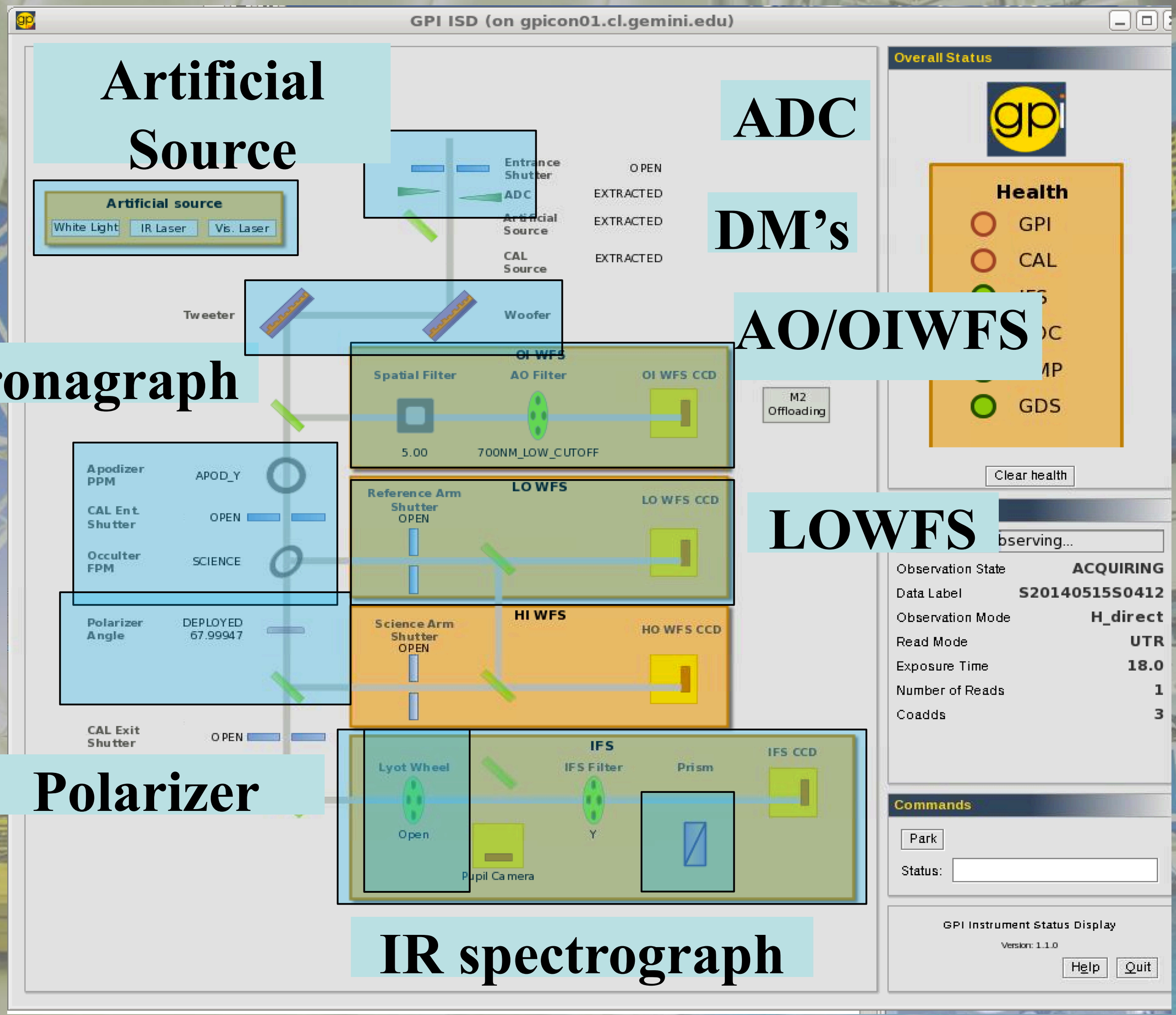
GPI Instrument Layout

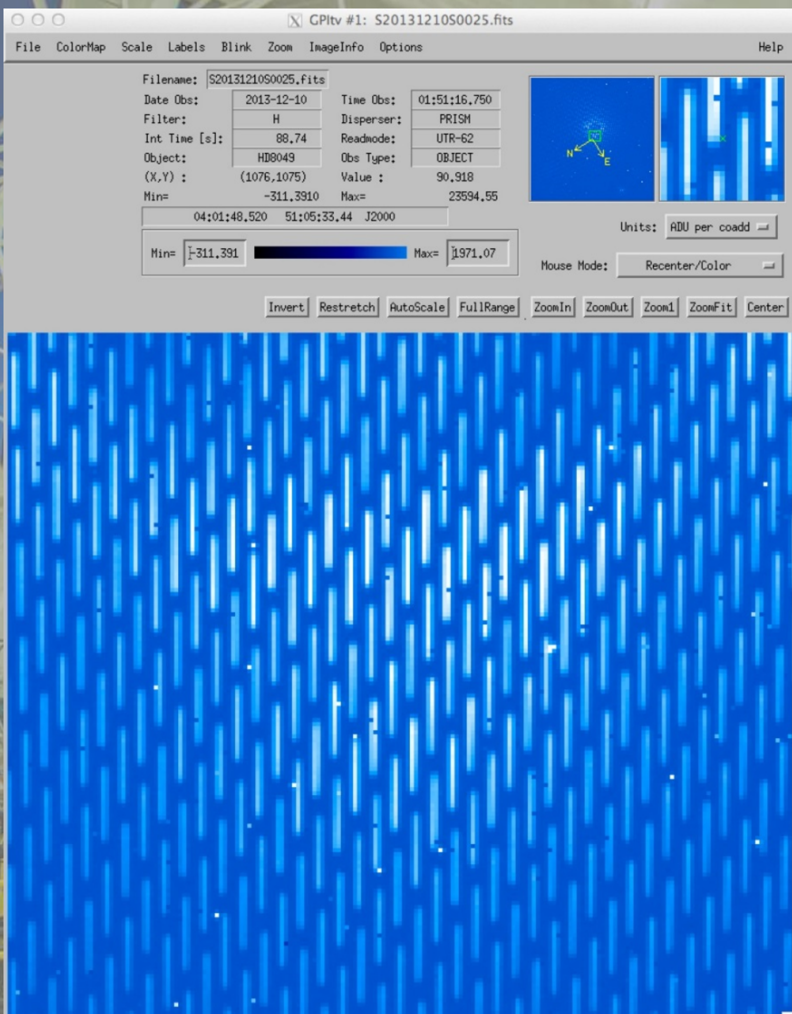


GPI IFS Detector

- ✓ HgCdTe HAWAII-2RG (H2RG)
- ✓ 2048×2048 pixel with 18 μm pixel pitch
- ✓ Wavelength coverage over 0.9-2.5 μm (Y, J, H, K)
- ✓ 32 readout channels
- ✓ Up-the-ramp (UTR) mode for all observations,
- ✓ Pixels are clocked out at 100 kHz
- ✓ Shortest exposure time, 1.45479s per full frame readout
- ✓ Sub-arrays available but gives no gain in readout time except for smallest sizes due to using only 1 amplifier.

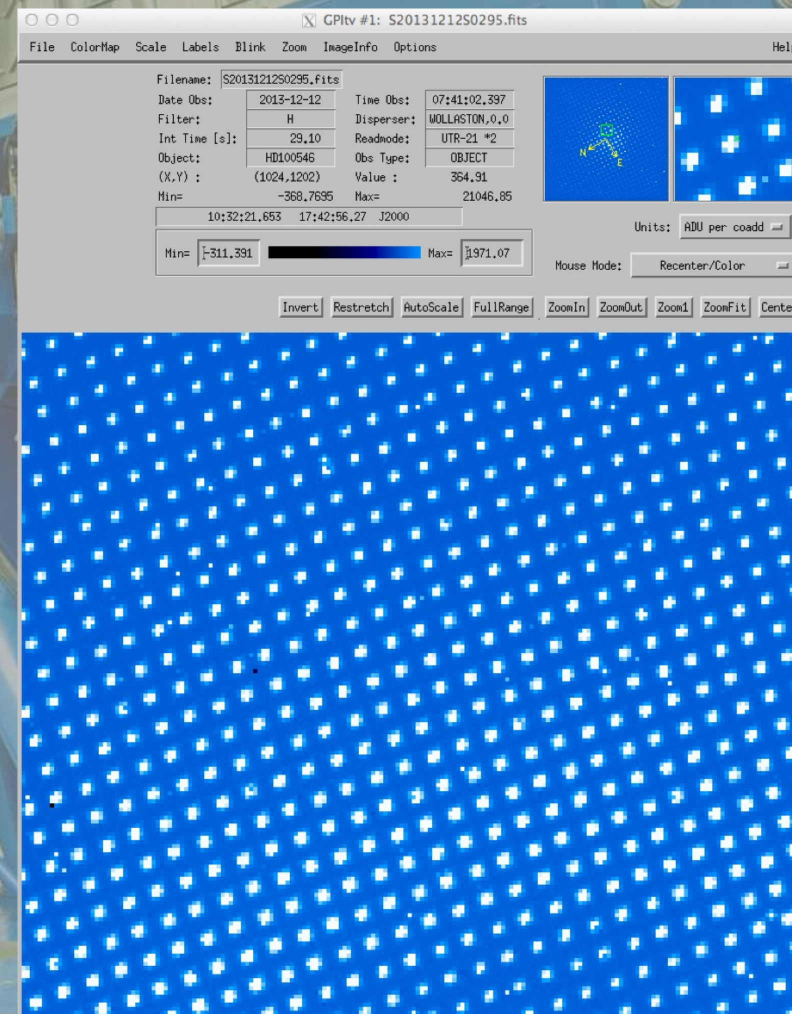
Raw Spectroscopic Data

Each lenslet is represented by **one** spectra



Raw Polarimetric Data

Each lenslet is represented by **two** spots as a pair



Distortion

- Distortion was characterized with an illuminated square pinhole grid at the testing facility at Santa Cruz.
- The residual vectors with an average vector length is 0.26 spaxels.
- After a 5th order polynomia fit, the average positional residual drops from 0.26 spaxels to 0.04 spaxels.

The lenslet s

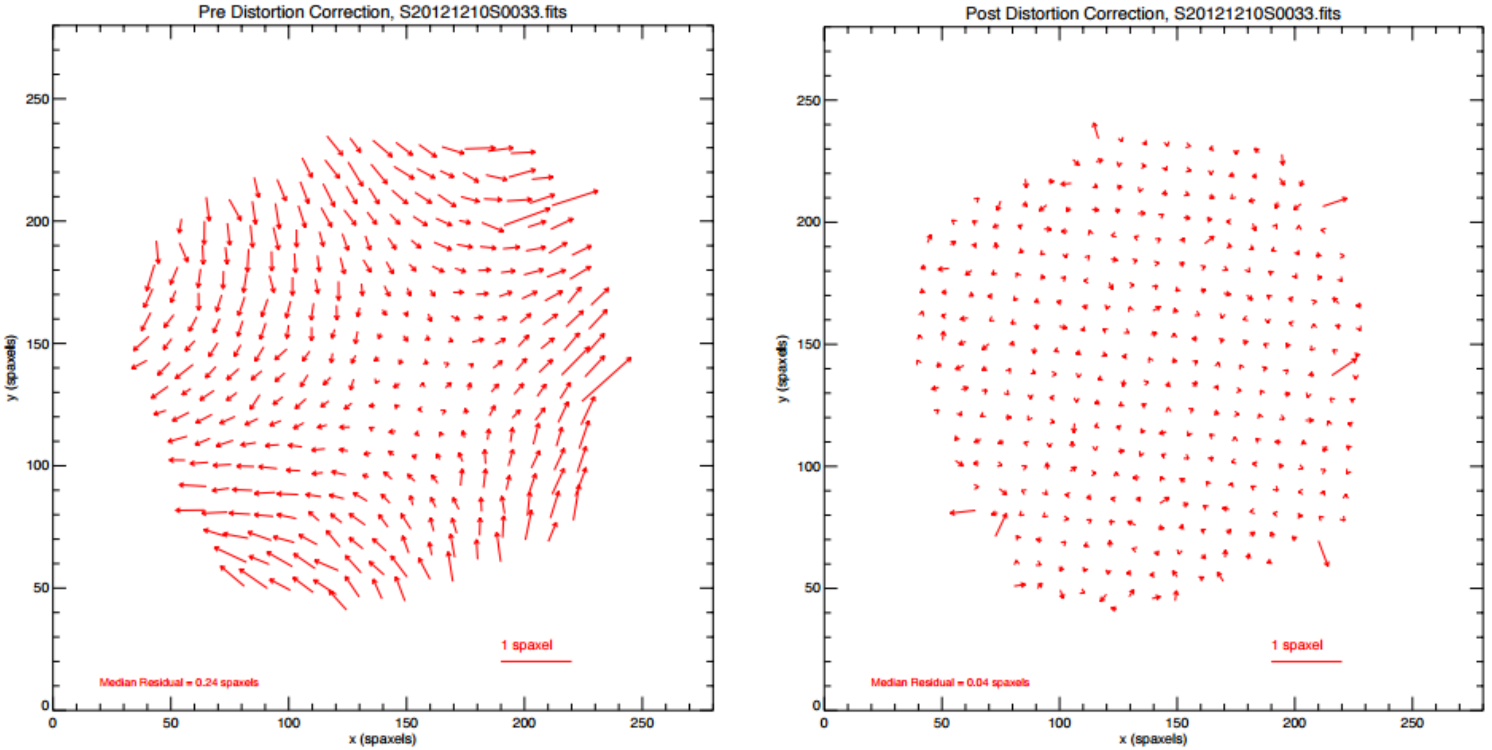
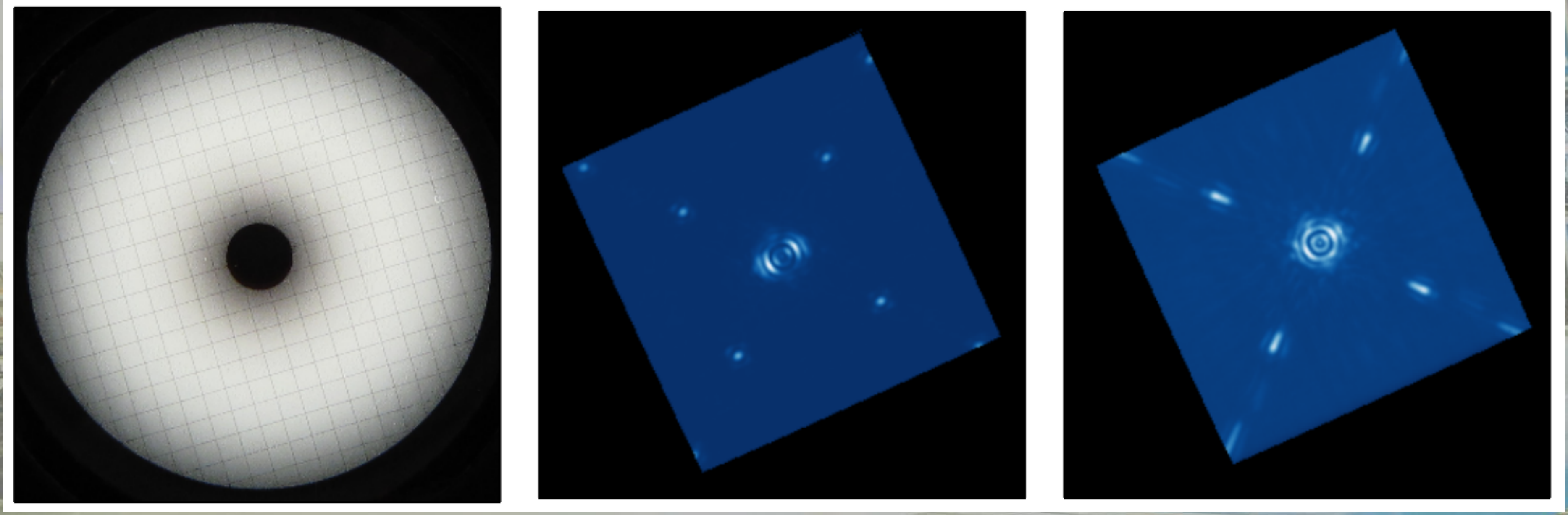


Figure 8: Positional residuals for an example IFS wavelength channel pre and post-distortion correction (left and right, respectively). Vectors are magnified by a factor of 30. The median drops from 0.24 pixels to 0.04 pixels when the correction applied. Large vector "outliers" are likely due to poor centroid measurements for an individual spot in one frame.

Satellite Spots I

- Coronagraphic observations blocks the light of the primary and thus cause a problem for differential spectrophotometry and astrometry of an exoplanet relative to its primary.
- GPI includes a square grid superimposed on the pupil apodizer.
- Diffraction of starlight from this grating injects first-order diffraction spots into the field of view for a given wavelength.
- In each wavelength channel in spectral mode, this creates reference spots named ***satellite spots***.
- In broadband polarimetry mode, the satellite spots become streaks extending radially outward from the location of the star.



Satellite Spots II

The satellite spots are then used to:

- Determine the location of objects in the field relative to the central star with a 1 mas accuracy
- Determine the relative flux of the blocked central star with a 2% accuracy.
- When stacking observing sequences the central reference point is determined from the satellite spots.

Position accuracy in Spectroscopy

- In the current GPI pipeline, the central star is located by taking a simple mean of all 4 × 37 satellite spot positions. We rely on the fact that after distortion correction, opposite pairs of satellite spots are displaced equally and in the opposite direction in both x and y from the central star.

- Positional accuracy is 0.05 pixels (or ~ 0.7 mas) in the central star position for an H-band datacube along one axis.

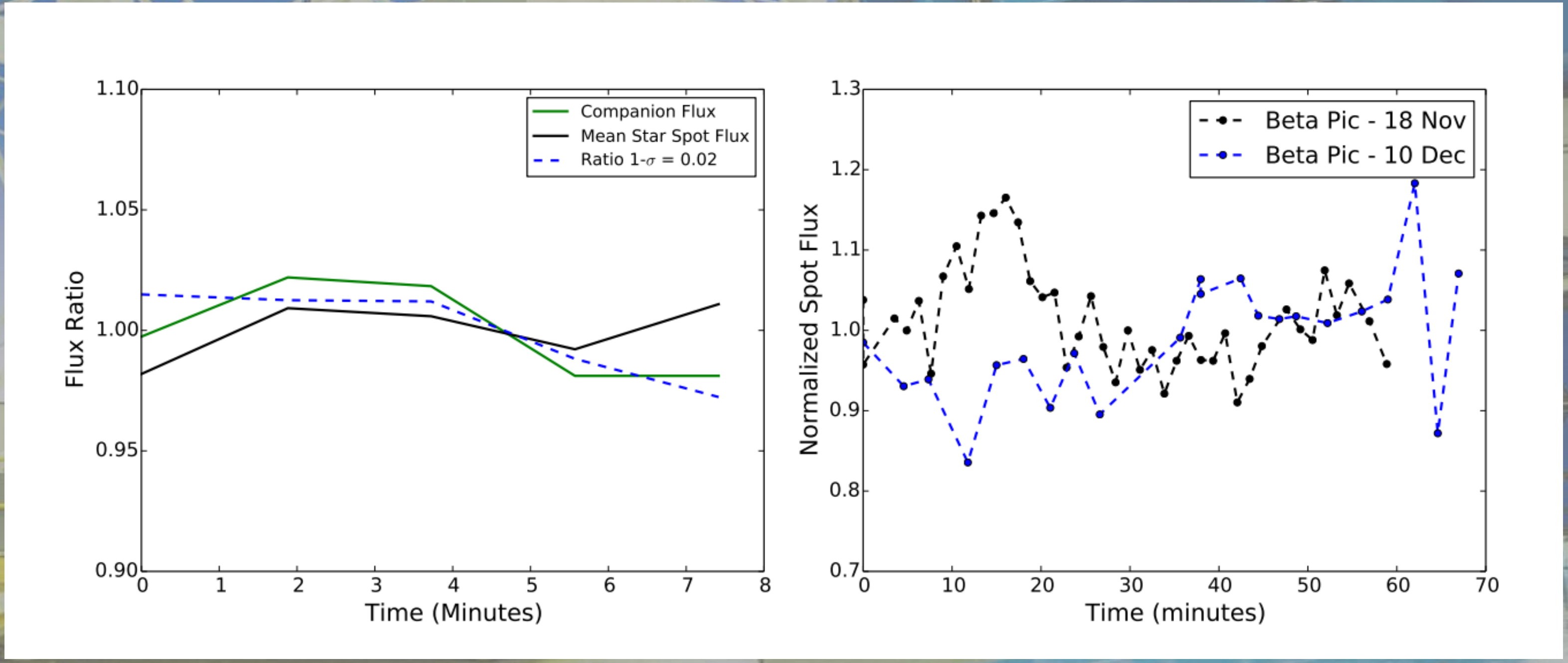
Position accuracy in Polarization

- Using the Radon transform technique to find the occulted star, the measured separation and error is comparable to the spectral data.

Flux Calibration using the satellite spots

- Using the relative flux determined in the satellite spots one can scale this to the blocked central star with a 2% accuracy

- In the figure below shows the normalized flux of the satellite spots compared with the measured flux of an unblocked binary companion.



POSITION ANGLE

- The orientation of the instrument on the sky depends both on rotation of the coordinate frame within GPI and the orientation of GPI on the Instrument Support Structure (ISS).
- We observed various binaries with concurrent measurements from Keck.
- The difference between the *"true"* north position from Keck and the position from GPI is the north offset that must be applied to GPI astrometry.
- Combining all measurements via weighted average gives a final value of -1.00 ± 0.03° for the GPI north offset consistent over several months and dismounting the instrument from the telescope.

Object	Date Observed	GPI Measured Position Angle (deg)	Implied North Offset (deg)
HIP 43947B	14 May 2014	261.85 ± 0.02	-1.03 ± 0.04
HIP 44804A	14 March 2014	307.239 ± 0.002	-0.92 ± 0.04
"	14 May 2014	307.22 ± 0.19	-0.90 ± 0.19
HIP 80628	14 March 2014	44.89 ± 0.12	-1.27 ± 0.12
"	11 May 2014	44.75 ± 0.08	-1.13 ± 0.08

Detector Calibrations - Daytime

There are a set of calibrations that should ideally be taken during the day over the weekend so that they are completed without interruption.

The calibrations are used by the pipeline for proper:

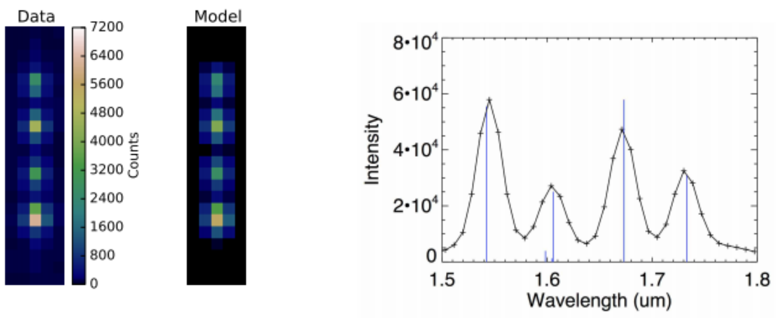
- ❑ Wavelength calibration
  - ❑ Arcs
- ❑ Correction of detector cosmetics (hot, cold, and warm pixels)
  - ❑ Flats (polarization and spectral)
- ❑ Background (light leaks), bias and dark current subtraction
  - ❑ Darks (also used to identify “hot” pixels)
  - ❑ Thermal darks (shutters open up to the GCAL) for K1 and K2

Daytime Calibrations – Telescope Constraints

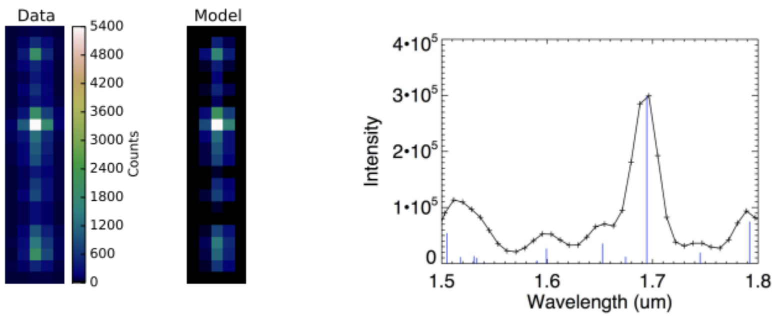
Name of group	Frequency	Requirements	Time	Bands
Arc	Weekly (weekend)	**NO** telescope movement and **NO** Lights on Telescope at Zenith **NO** movement of the science-fold and changes in GCAL Movement in the dome is **OK** with flashlights	4.0h	All
Spectral Flats	Weekly (weekend)	**NO** telescope movement Telescope at Zenith **NO** movement of the science-fold and changes in GCAL Lights on and movement in the dome is **OK**	1.25h	All
Polarization Flats	Weekly (weekend)	**NO** telescope movement Telescope at Zenith **NO** movement of the science-fold and changes in GCAL Lights on and movement in the dome is **OK**	1.25h	All
Darks	Weekly (weekend)	There are **NO** constraints, on GCAL, telescope or external	6.5h	One

Wavelength Calibration using the ARCs

- Using the weekly arcs the procedure fits all the peaks in the lenslet spectrum simultaneously, and with increased sub-pixel sensitivity. The new algorithm uses a least squares fitting approach to compare an individual lenslet spectrum in the 2D detector plane to a modeled spectrum.



(a) H band Xe Arc Lamp



(b) H band Ar Arc Lamp

Band	Pixel Offset	$\Delta\lambda\,(\mu m)$	$\Delta\lambda/\lambda$ %
Y	0.096	0.0013	0.14
J	0.084	0.00068	0.054
H	0.032	0.00049	0.032
K	0.095	0.0014	0.07

Detector cosmetics correction (FLATs)

The purpose of the flats is to perform standard detector corrections to determine the hot, cold and warm pixels. The linearity correction has been done at UCLA previous to installation of the lenslet array.

- The main issue faced with FLATs in GPI is that light always goes through the lenslets and thus there is NO way of getting a simultaneous uniform illumination of all the detector pixels.
- The above is compounded by the subpixel shifts of the microspectra and thus science data may fall on pixels that do not have a measured flat.

- By adding together many flat field exposures taken using several different filters it is possible to illuminate (albeit non-simultaneously) all of the pixels on the detector.
- This illumination pattern is very structured and not a uniform illumination, therefore we refer to this as a “multi-filter pseudo-flat”.
- We then take advantage of the translational symmetries inherent in the lenslet array to build up a reference image that retains the spectral structure from the illumination pattern but is smoothed over several detector pixels.

Detector cosmetics correction (FLATs) II

- By comparing individual pixels to this reference image, we can identify those that lack sensitivity.
- The selection criterion to flag cold pixels is any pixel having a less than 15% normalized response, as measured from the multi-filter pseudo-flat. The GPI detector has ~2500 cold pixels.
- The hot pixels are easily identifiable from the long dark exposures.
- The non-linear pixels can be detected using a series of flat-fields taken while the detector was in “write-all” mode. This mode writes each individual detector read in up-the-ramp mode to disk.
- Examining the pixel response in each individual read allows identification of the non-linear pixels. The number of non-linear pixels is ~1,000 and is not a significant contribution to the total number of bad-pixels.
- An overall bad pixel map is generated by combining all three bad pixel types into a single boolean (1 or 0) image.

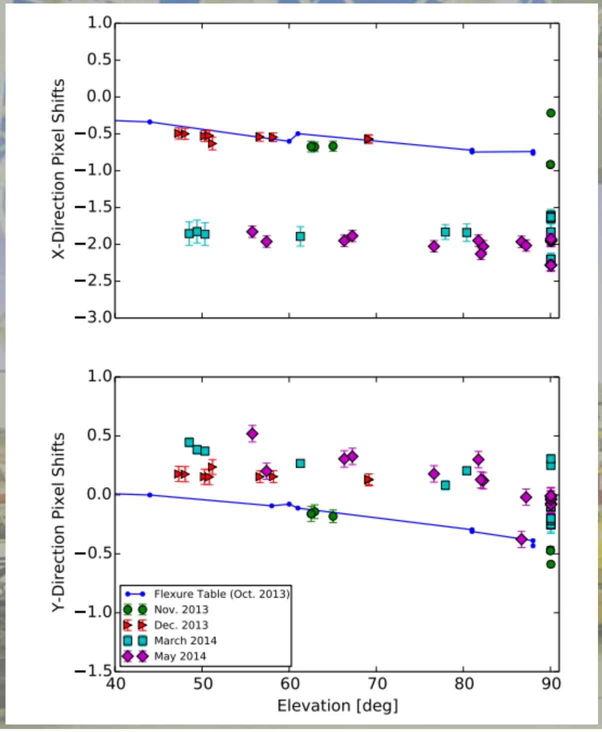
FLATs open issue

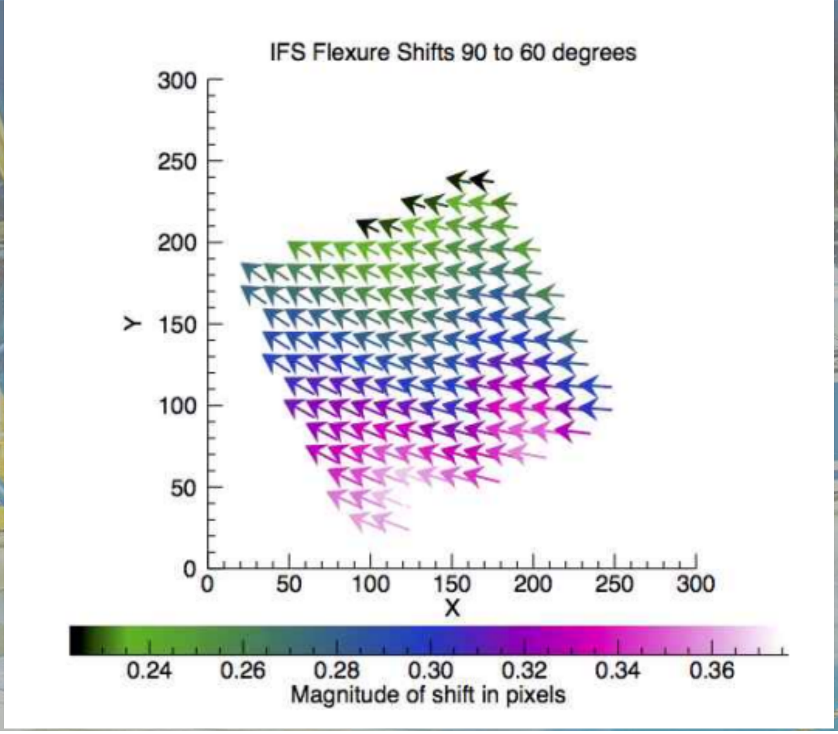
The multi-filter pseudo-flat technique described earlier works to locate grossly low QE pixels but is not precise enough to measure smaller QE variations between good pixels.

Given the presence of flexure continuously changing the registration between lenslets and the detector it is not sufficient to take day calibration flats while the telescope is parked at zenith, since slightly different sets of pixels will be illuminated at night. Improved calibration methods to deal with this situation are under investigation.

Detector Calibrations - Nighttime

- With almost all detector calibrations taken during the day there is only one single set of detector/IFS calibrations taken during the night.
- Due to subpixel shifts in the lenslets with respect to detector caused by telescope movement and changes in elevation one must accurately calibrate the exact positions of the spectra on the detector to properly extract the spectra.
- It should be note that the shift varies in magnitude and direction over the full detector.





Flexure Calibration

- Determining the flexure is difficult in the actual science data is difficult due to the faintness of the spectra and to some degree no knowledge of the exact shape of the spectra.
- To determine the sub-pixel shifts of the microlens spectra from the flexure model a short 30s ARC is taken after every slew.
- The same spectra is also used to determine the exact start and end of the science spectra.
- Using the same wavelength fitting technique the global shifts of the ARC spectra are determined and then applied to the extraction of the science data.

CORRELATED NOISE REMOVAL

Beyond the Gaussian read noise, the GPI detector is subject to three known independent sources of correlated noise.

- Vertical striping,
- Horizontal striping
- Microphonics noise.

The GPI pipeline includes primitives that derive noise models based on nonilluminated pixels and use them to attenuate all three sources of noise in both dark and science frames.

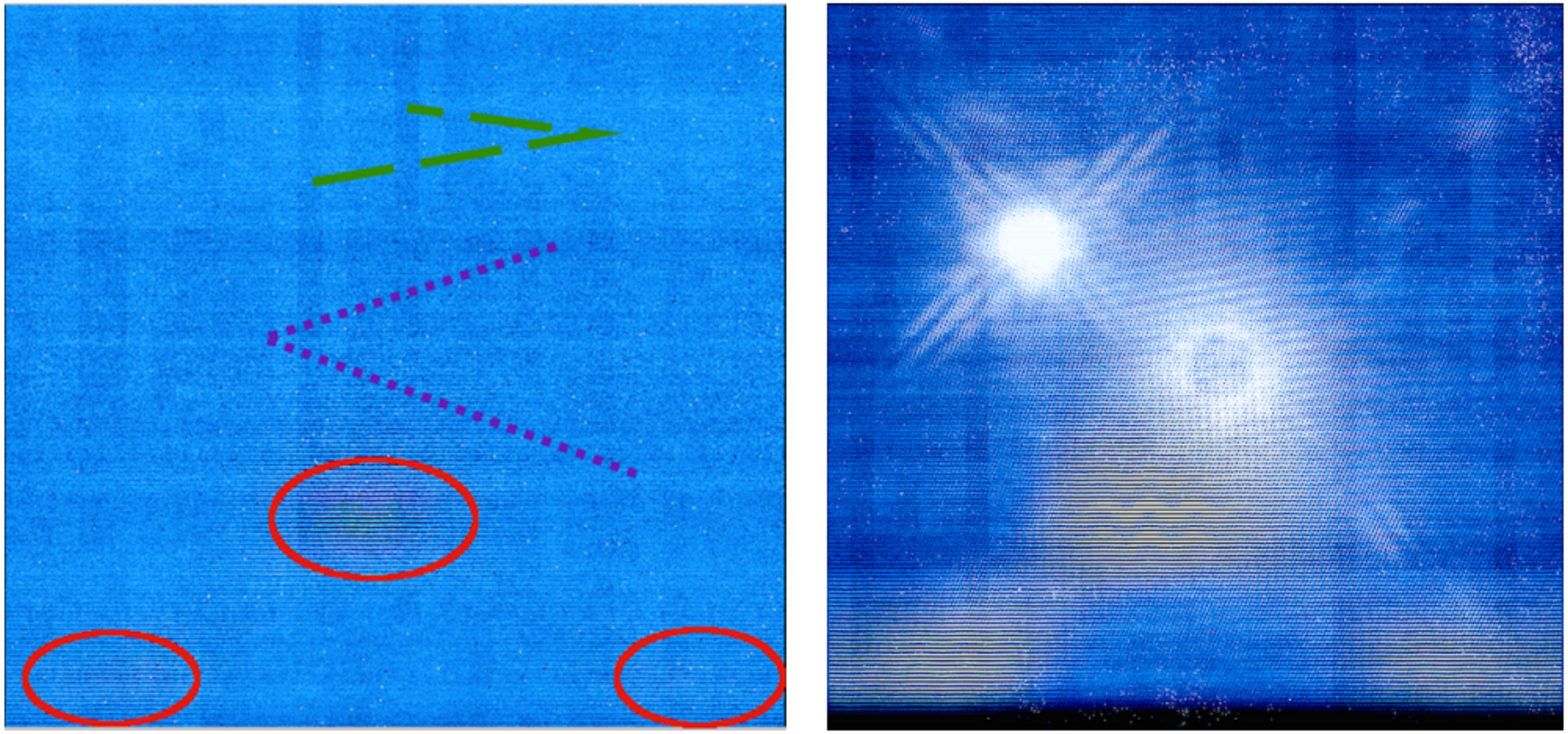


Figure 2. **Left:** A 1.5 second GPI dark frame shows the three independent sources of correlated noise. The red circles indicate sections of the detector heavily affected by the microphonic noise. The purple dashed lines indicate regions of horizontal detector striping and the green dashed lines indicate example of the vertical striping. **Right:** 10 coadds of a 1.5 second short exposure coronagraphic image exhibits similar features, but are much harder to identify. This image is heavily stretched to make them visible.

CORRELATED NOISE REMOVAL II

- For a dark frame, no flux is present, and therefore the pipeline utilizes the entire image to derives a high-fidelity noise model.

- For the more complicated case of science exposures which have complex patterns of microspectra or polarization spots over much of the detector, the illuminated pixels must be masked out such that only the un-illuminated pixels are used to derive the correlated noise model.

- With the exception of the masking, the algorithms to determine the noise model are similar between the dark and science image cases.

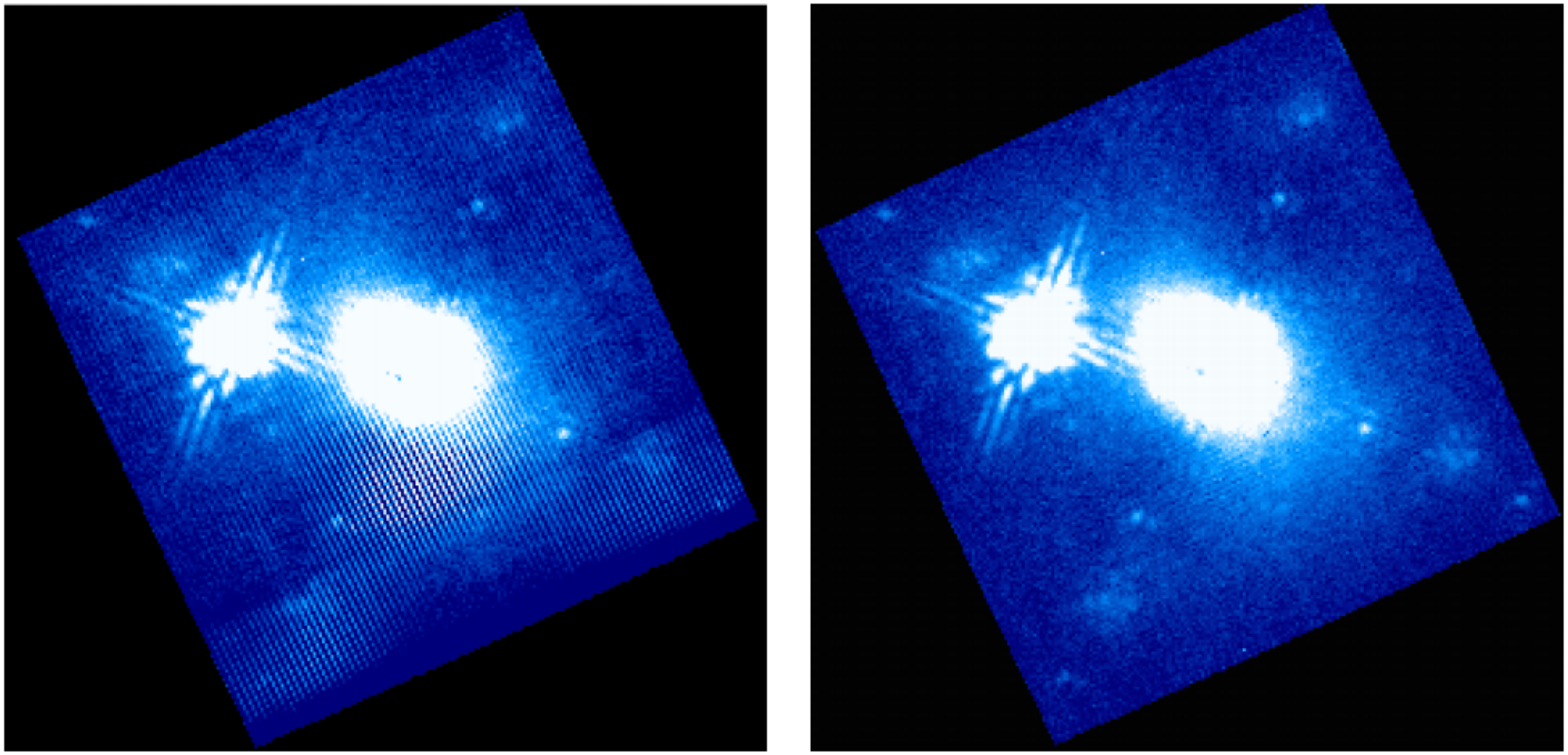


Figure 3. **Left:** A quicklook reduced cube consisting of 10 coadds of a 1.5 second image which has heavily stretched to show the result of the correlated noise in reduced science images. **Right:** The same cube after running the destriping primitive (same image stretch).

AO Calibrations

Calibrations related to the AO system can be split into:

- Daytime calibrations, which are done by executing an IDL script are performed by the day crew in the afternoon after the telescope checks.
- The nighttime calibrations are performed automatically as part of the acquisition step after every slew.

Daytime AO Calibrations

The IDL script does the following calibrations:

- Takes AOWFS darks for dark current subtraction
- Alignment of MEMS to AOWFS
- Spatial filter alignment
- New DM flats (optional)
- LOWFS (CAL) darks
- Apodizer and Lyot alignment

All alignment steps produces logfile entries and images for trending purposes.

Nighttime AO Calibrations

Automatically as part of the acquisition sequence, the following calibrations are executed:

- ❑ Takes AOWFS darks for dark current subtraction
- ❑ Alignment of MEMS to AOWFS
- ❑ Apodizer and Lyot alignment

All alignment steps produces logfile entries and images for trending purposes.

Standards

- An astrometric standard is taken every time GPI mounted on the telescope. This is used to check the astrometry, mostly using Orion and Baade's window.
  - Staggered so that ideally both standards taken at least once during the same telescope mount period.
- Polarimetric and telluric standards every month in open loop, during the first year of operation. Lately descoped to yearly as no significant improvement in post-processing from having these standards.
- PSF standards only taken by user request.
  - Difficult as AO performance varying faster than time between standard and science.
  - Standard in Direct mode and thus limited magnitude range and highly likely with different read-out.

Open Issues

- ✓ Getting around the microlens spectra and flats
  - ✓ ??? Suggestions
- ✓ Automatic evaluation of daytime calibrations
  - ✓ Scripts exists but pending full automation
- ✓ Better long term stability monitoring of calibrations.
  - ✓ Currently resource limited
- ✓ Can the number of night and daytime calibrations be decreased?
  - ✓ In particular standards?
- ✓ Implementation of faster Speckle nulling techniques
  - ✓ In development externally
- ✓ Take PSF standards with the new ND filter installed, filter was installed for engineering and internal calibration purposes but could be used to make the Direct mode usable on brighter targets w/o saturating the IFS.