PINES: First Year Operations and Photometric Performance

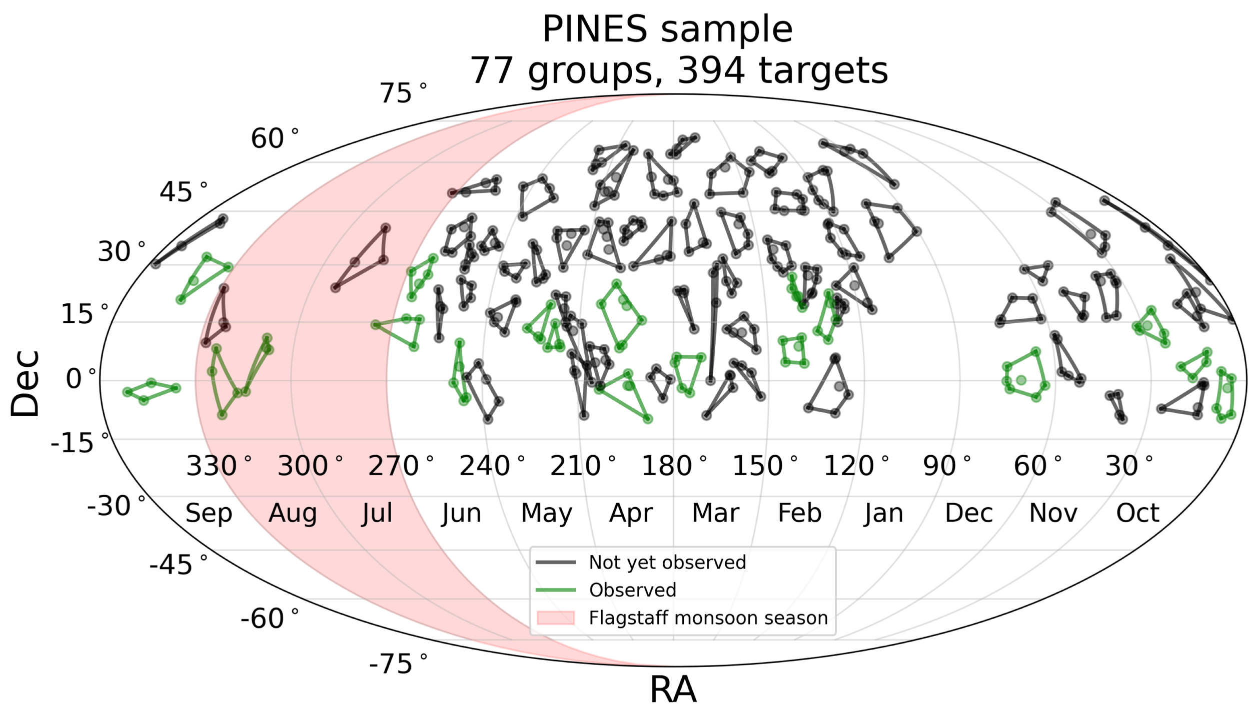
Patrick Tamburo[1], Philip Muirhead[1], Allison McCarthy[1], Murdock Hart,[2] Julie Skinner[1], Johanna Vos[3], Daniella Bardalez Gagliuffi[3], Jacqueline Faherty[3], Eric Agol[4], Christopher Theissen[5]

[1]Boston University, [2]Perkins Telescope Observatory, [3]American Museum of Natural History, [4]University of Washington, [5]University of California, San Diego

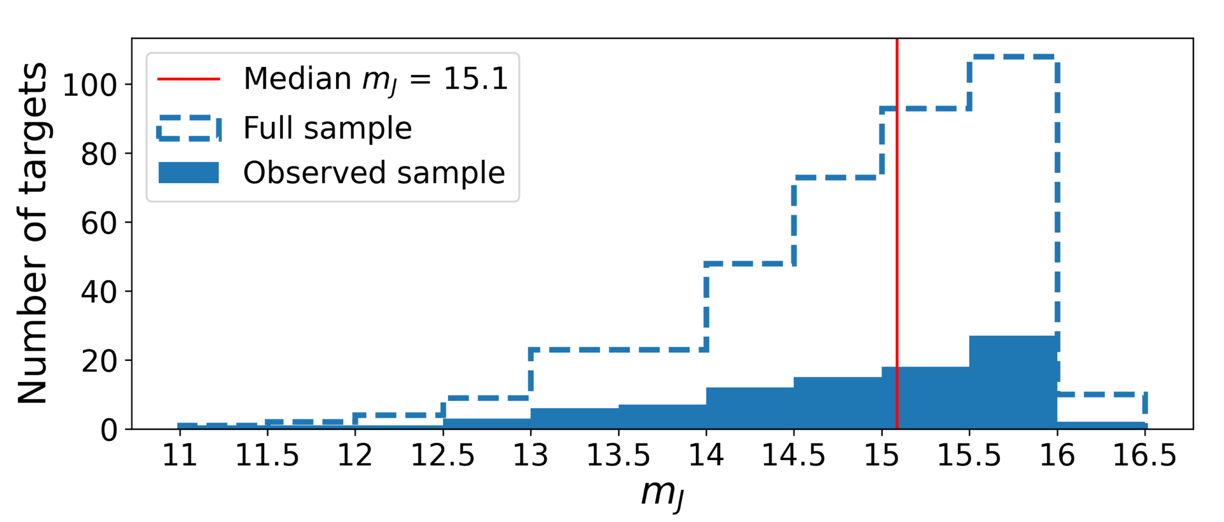
The Perkins INfrared Exosatellite Survey (PINES) is a program to search for transiting short-period exosatellites around a sample of almost 400 spectroscopically confirmed L and T dwarfs with Boston University's 1.83-m Perkins Telescope near Flagstaff, AZ. The survey operates at near-infrared wavelengths (*J*- and *H*-bands) in order to obtain the highest precision possible on optically faint L and T dwarfs, **spectral types whose short-period satellite population is currently unconstrained.** Depending on their mass, L and T dwarfs can be either stars, brown dwarfs, or planetary-mass objects. For this reason, we refer to their orbiting companions as "exosatellites", instead of the less general term "exoplanets".

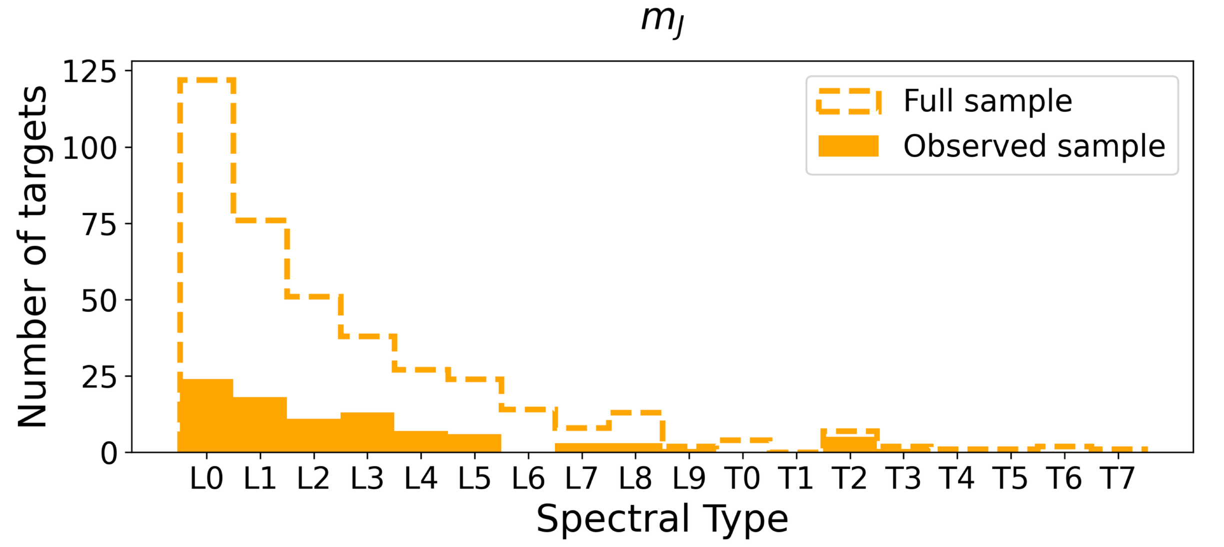
Following the survey design of Tamburo & Muirhead (2019), PINES has been operational for over a year, and has targeted 93 L and T dwarfs during that time. A custom photometric pipeline has been developed for the reduction and analysis of PINES data, and while the observed photometric precision is worse than was simulated in Tamburo & Muirhead (2019), **the detection of satellites in the super-Earth size range and larger will be possible around the majority of the survey's 394 target sample.**

Survey Sample



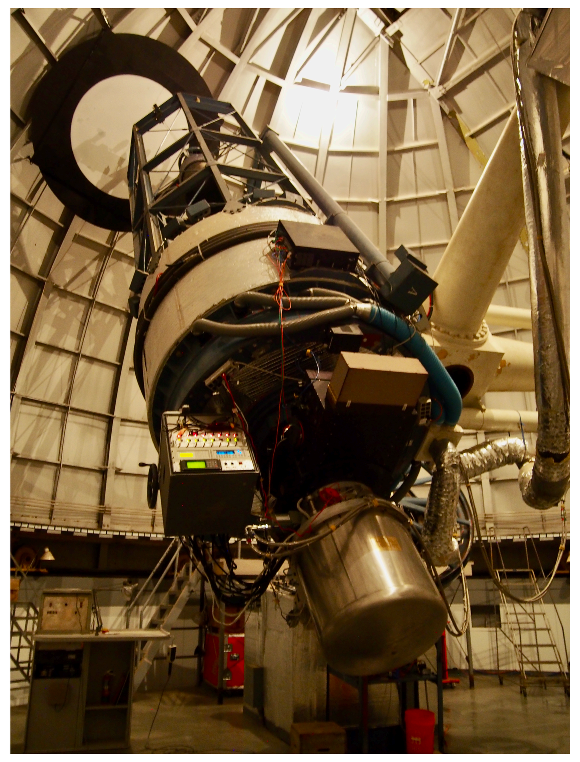
Sky map of the PINES sample, **consisting of 394 spectroscopically confirmed L and T dwarfs** split into 77 groups. Groups of 4-7 targets are observed for five nights at a time. Groups that have been observed in the first year of PINES operations are shown in green.





Top: Histogram of target *J*-band magnitudes. The median magnitude of the sample is denoted with a red line. *Bottom*: Histogram of spectral types for the full and observed samples. **PINES is a magnitude-limited survey with a *J*-band cutoff of 16.5, which biases the sample to early L dwarfs.**

Observing Facility and Instrument



Left: Dome enclosure for Boston University's Perkins Telescope Observatory (PTO) at Anderson Mesa Station, near Flagstaff, Arizona. *Right*: Interior of the PTO, showing the 1.83-meter Perkins Telescope with the Mimir instrument (Clemens et al. 2007) mounted on the back. **PINES uses Mimir in its wide-field (10'x10') *J*- and *H*-band imaging modes.**

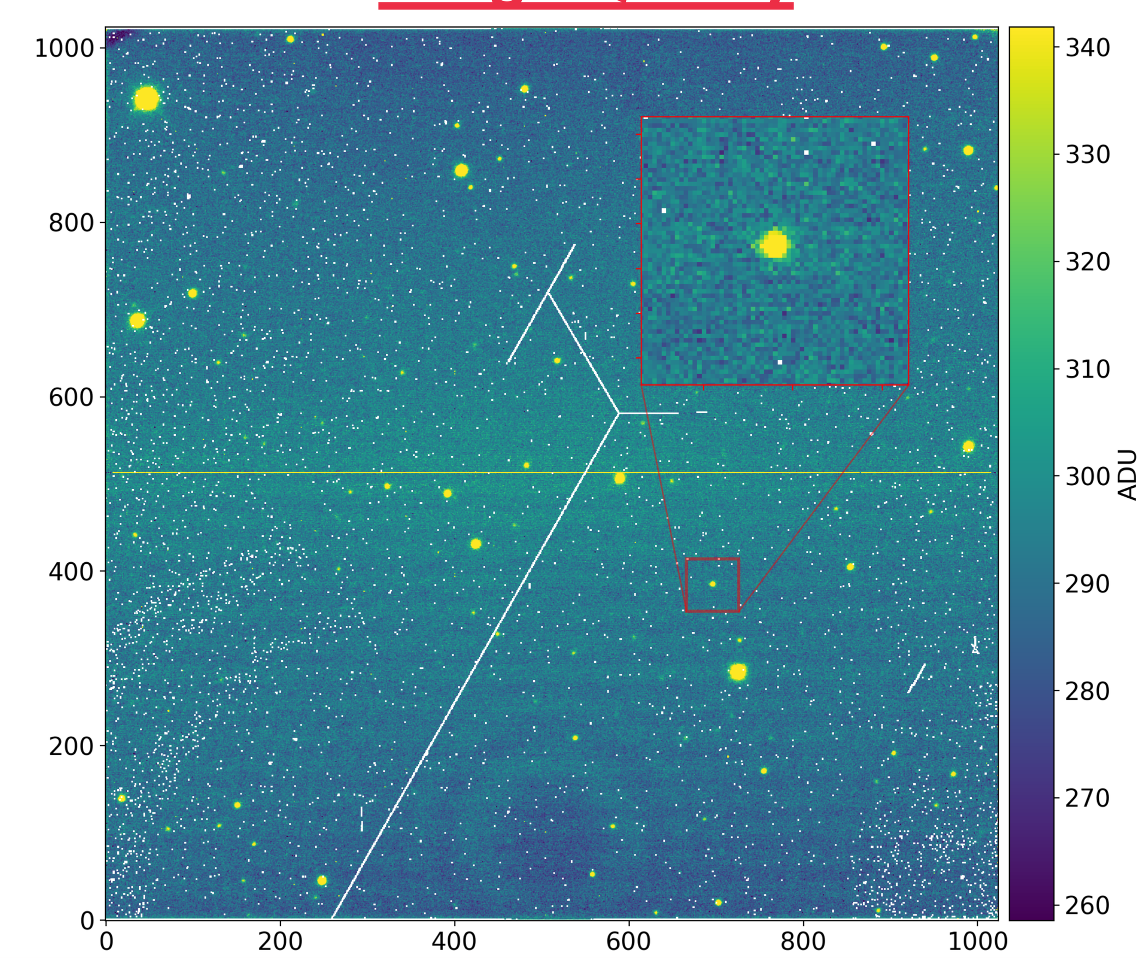
PTO Specifications	Value	Mimir Specifications	Value
Longitude	111° 32' 09.3"	Detector type	ALADDIN III InSb
Latitude	+35° 05' 48.6"	Format	1024 x 1024 pix
Altitude	2206 m	FOV	10' x 10'
Primary Diameter	1.83 m	Plate Scale	0.579" pix^{-1}
Secondary Diameter	0.41 m	Gain	8.21 e^- ADU^{-1}
F/#	17.5	Read Noise	18-20 e^- rms
Remote Capable?	No	Dark Current	22.65 t^{-1} e^- pix^{-1} s^{-1}

Year 1 Statistics

Parameter	Value
Number of Observing Runs	12
Targets Observed	93
Number of Nights Assigned	109
Number of Nights with Data	63
Loss Rate (Weather, COVID, etc.)	42%
Average Seeing	2.6 ± 0.5"
Quantity of Data Acquired	317.5 GB
Suitable Reference Stars per Field	≥ 5

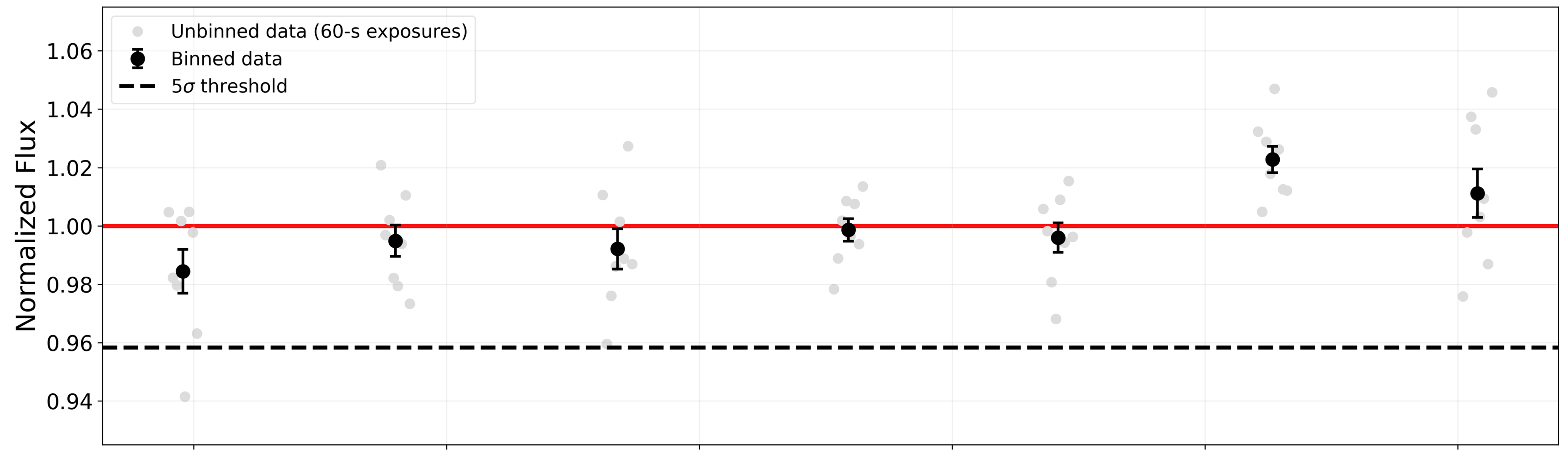
Statistics from the first year of PINES operations. **The project has remained on-schedule despite the COVID-19 pandemic.**

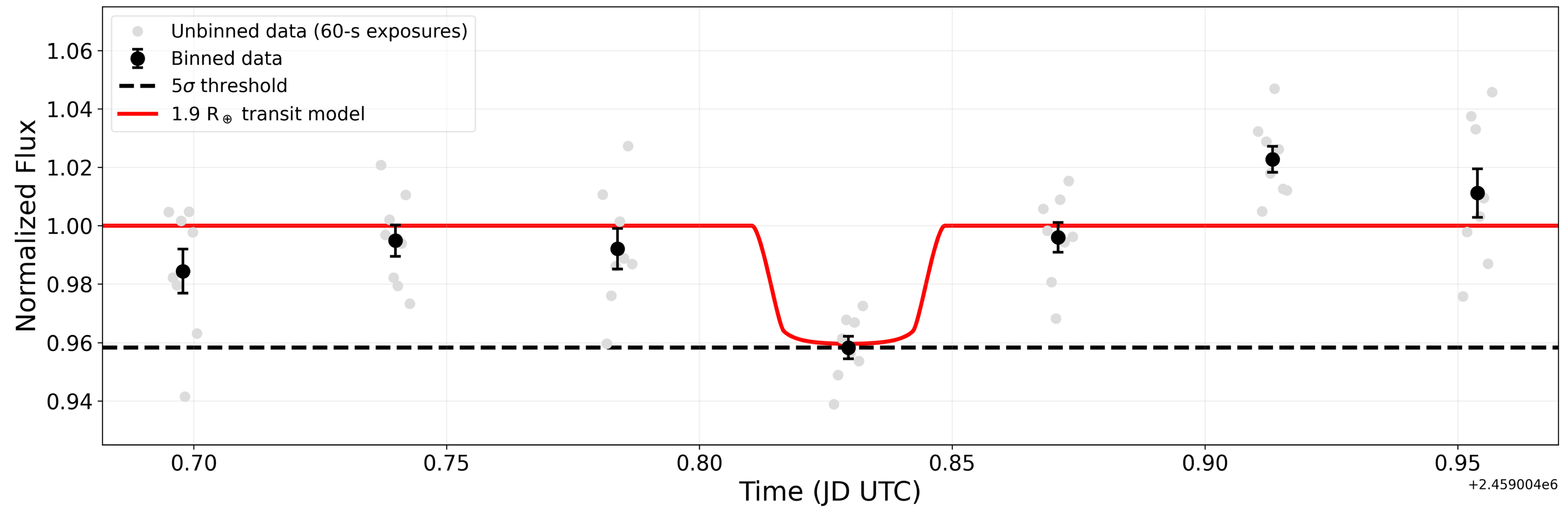
Image Quality



A reduced PINES field taken in *J*-band with Mimir, with bad pixels represented in white. The region surrounding the target L dwarf is shown in the inset. **Mimir data has a number of cosmetic issues**, including a crack in the detector running from the lower left to the middle of the image. **Bad pixel values are corrected if they fall within a target or reference aperture in the PINES Analysis Toolkit.**

Typical Planet Detection Sensitivity

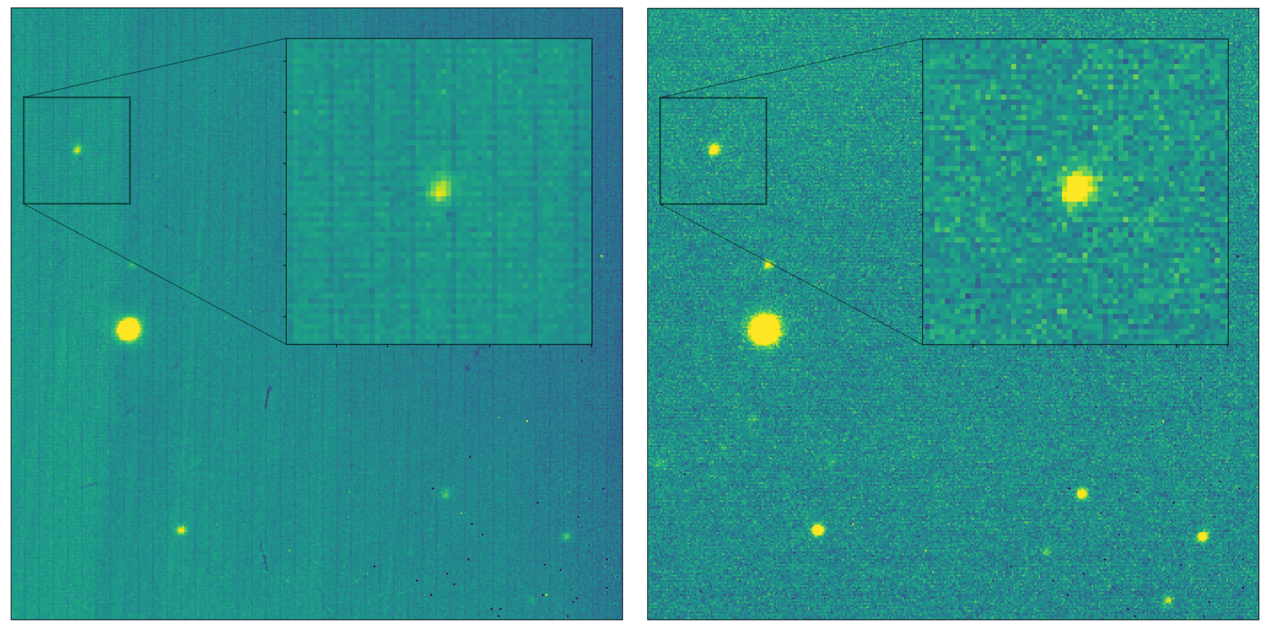




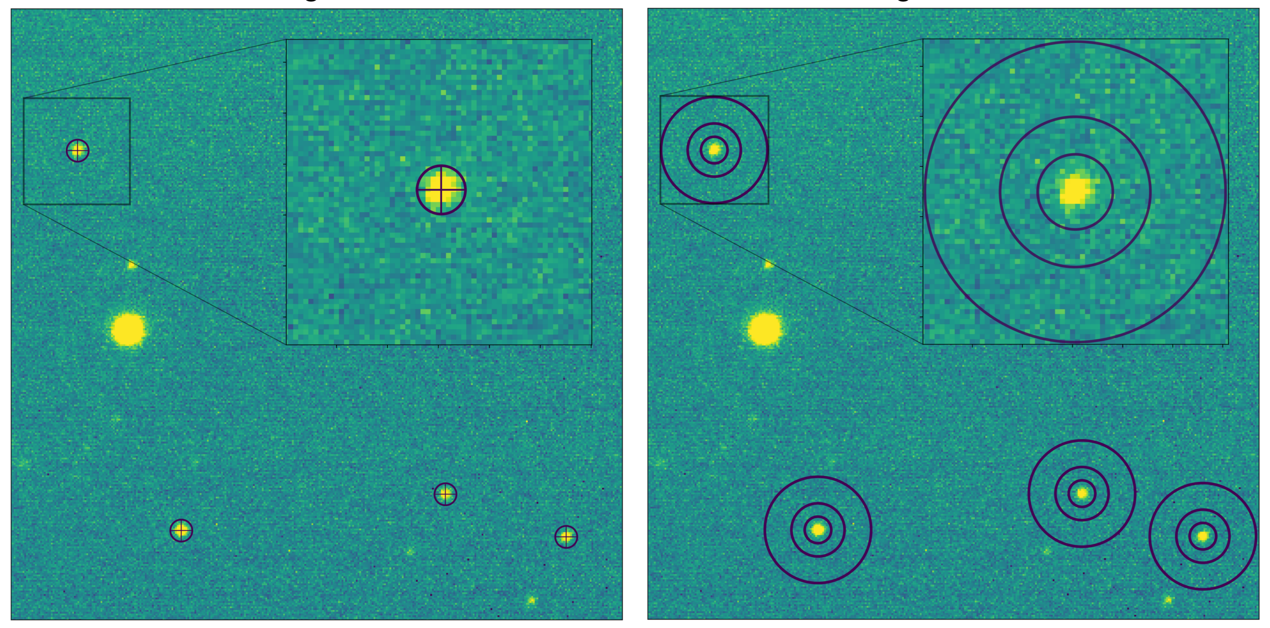
PINES observes groups of 4-7 L and T targets on each observing night in a cycling pattern, where each target in the group is observed for about 10 minutes every hour. This strategy maximizes the likelihood of observing partial transit events (Tamburo & Muirhead 2019), which can then be followed up in later observing runs, but results in non-continuous time coverage for any individual target. *Left, top*: **One night** of *J*-band PINES data for a m_J = 14.94 L1 dwarf, observed using the PINES cycling strategy in June 2020 and analyzed with the PINES Analysis Toolkit. *Left, bottom*: The same lightcurve with the injected transit of a 1.9 R_{Earth} planet around a typically sized L dwarf. The depth of this simulated transit event is significant at the 5σ level. **This target is near the median brightness of targets in the PINES sample, and is thus representative of the typical planet detection sensitivity of the survey.**

The PINES Analysis Toolkit

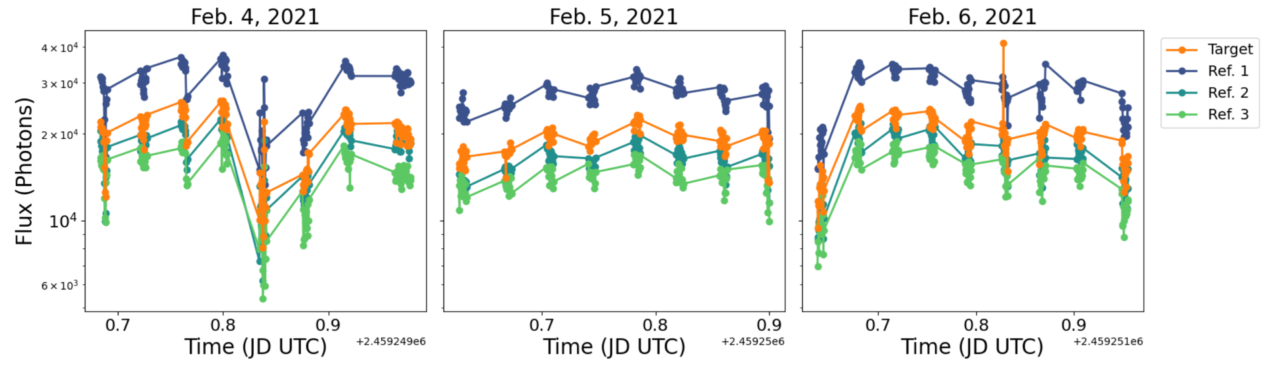
The PINES Analysis Toolkit is a custom photometric pipeline designed to automatically reduce and analyze PINES data (paper in prep.). The code is open-source and available to the public on Github. The following plots visualize the major steps in the pipeline. **Bad pixels have been corrected in these images, and the plots focus on a cutout of the detector for ease of visualization.** The region around the target is shown in the inset.



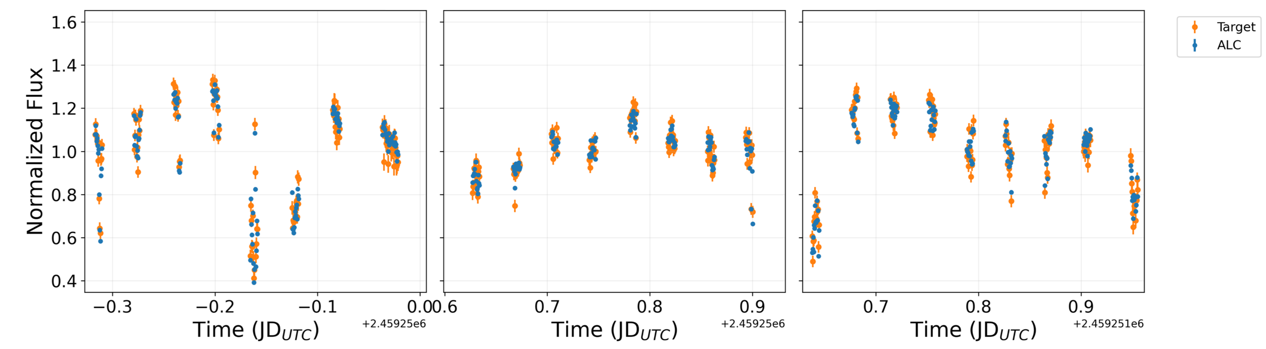
1) Raw image is read in. 2) Image is reduced.



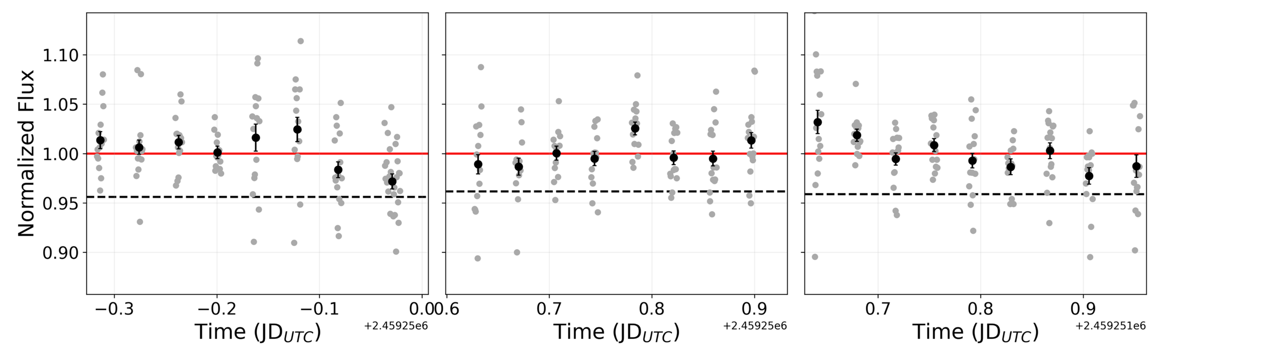
3) Target/references are centroided. 4) Aperture photometry is performed.



5) Raw flux is measured for each source across all nights of observation.



6) A weighted mean of reference star fluxes is used to create an artificial lightcurve (ALC), which is used to correct the target's normalized flux. The ALC is created following a procedure similar to the one used by the SPECULOOS transit survey (Murray et al. 2020), which de-weights variable reference stars.



7) The target's final corrected lightcurve is created using the ALC. **This lightcurve can then be searched for potential transit or variability signals.**

Future Work

- Determining an astrometric solution for Mimir data
- Examining the impact of precipitable water vapor on target lightcurves
- Follow-up on transit candidates and new variable objects
- Making the PTO remote capable
- Assessing our photometric performance and its affect on predicted satellite yield

tamburop@bu.edu | @PatrickTamburo | pines.bu.edu

PINES is funded by NASA XRP grant #80NSSC20K0256.

BOSTON UNIVERSITY · NASA · American Museum of Natural History · UC San Diego · UNIVERSITY of WASHINGTON