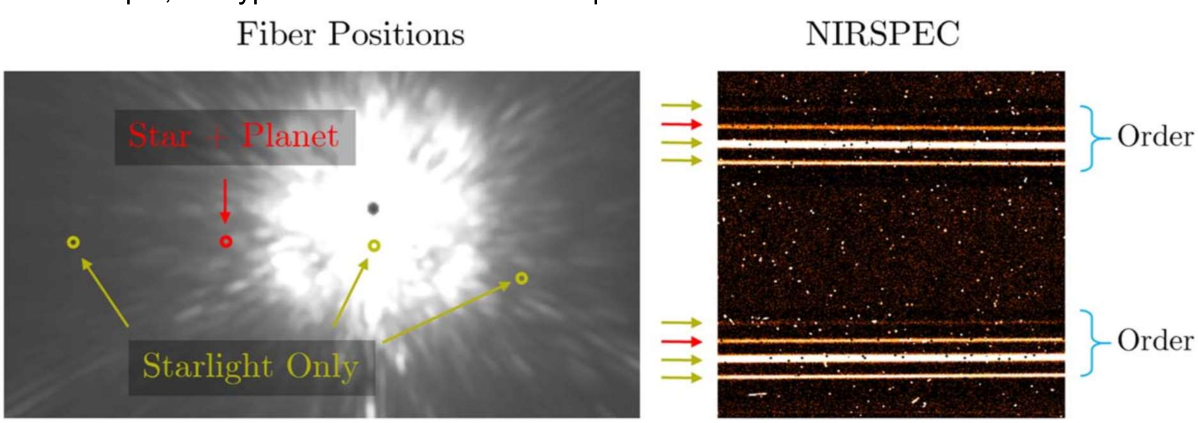
KPIC Overview

The Keck Planet Imager and Characterizer (KPIC) connects the Keck II AO system and the Keck/NIRSPEC high-resolution infrared spectrograph (https://www2.keck.hawaii.edu/inst/nirspec/) via a linear bundle of four single-mode fibers spaced by ~800 mas on the sky. Single-mode fibers provide a more stable quasi-Gaussian line spread function. Their small angular size, matched to the diffraction limit (FWHM~50 mas in K band), also provides excellent sky background rejection, as well as reduces the off-axis starlight injection into the single mode fibers. Currently, KPIC uses the Shack-Hartmann Wavefront Sensors for AO.

KPIC has a spectral resolution of R ~35,000 and utilizes the Kband-new filter of NIRSPEC, covering 1.952 to 2.501 microns. The NIRSPEC echelle grating and cross disperser angles are typically set up at 63.00 and 35.8 deg, respectively, so as to image orders 31-39 on the detector. There are four single-mode fibers, each with an angular size/FWHM at K ~50 mas and separated by ~800 mas between adjacent fibers in an almost straight line, for observers to place any of the fibers on the target. KPIC's four fiber outputs are projected onto the NIRSPEC spectrograph under the slit size mode of the 0.”0407 × 2.”26 slit. Note that the slit size is the NIRSPAO number, where the effective slit size for KPIC will be different as KPIC has a different focal length but it does not matter as the slit size is chosen to ensure all the fibers are feeding light through the slit and does not correspond to the on-sky footprint. Nine spectral orders (NIRSPEC orders 31-39) are recorded on the NIRSPEC 2048x2048 detector using this setup. The typical wavelength calibration precision, using early M giant star spectra and telluric lines (see the observing strategy and data reduction), is ~0.1-0.5 km/s, depending on the conditions.

As an example, the typical observation of a companion looks like



On the left panel, the four fibers can be used to obtain the spectra. In this case, the fiber labeled in red is on the planet, while the rest of the fibers are at different locations near the host star, each separated by 800 mas. On the right panel, a portion of two orders of 2D NIRSPEC spectra are shown, and the spectral traces are labeled corresponding to the left panel (HR 8799 system; from Figure 1 of Wang et al. 2021).

Target Requirements

KPIC uses a C-RED2 acquisition and tracking camera in the H band, which requires the host star H mag magnitudes to be between 0 to 10. KPIC is capable of observing the host star directly, including the planet host stars, telluric calibration stars, and any targets within this magnitude range.

For companions, KPIC can perform an offset to place the fiber on the companion to obtain high-resolution spectroscopy, using the host star as the guide star for acquisition and tracking (*H* = 0 to 10 mag). Observers are required to compute the offset from the host star in order to correctly place the fiber on the faint companion. The companion is required to have a separation between 0.1 and 4.0 arcsec. Prior to 2024A, KPIC was limited by instrumental systematics at small separations (<0.3") by fringing effects caused by the KPIC dichroics. At larger separations, KPIC is limited by the light leak from the NIRSPEC detector, unless the companion is very bright. After the KPIC service mission in 2024A, the dominant fringing signal was mitigated by wedging the transmissive dichroics and KPIC systematics are now within a factor of two of the stellar photon noise (Horstman et al. 2024, Wang et al. 2024). The KPIC Team has observed and detected delta K mag between 5 to 11 so far and the apparent *K* magnitude $\lesssim$ 17 mag. Since KPIC is at Keck II, the declinations of targets should have Dec > -40 deg (https://www2.keck.hawaii.edu/inst/common/TelLimits.html). For equal brightness binaries, the tracking algorithm may get confused on what is the guide star to track on. Observers should avoid equal brightness binaries, or observe with caution.

Generally, observers should avoid equal-brightness binaries to prevent tracking issues. Observers should also avoid targets where there is a second source within 5.5 pixels (~40 mas) of the tracking guidance star and bright enough to be seen on the guiding camera (within ~5 mag of the guiding star). However, the tracking *will* work for a binary of different brightness while the second component is visible on the tracking camera so long as that second component is beyond the 5.5 pixel tracking window. In the past, KPIC was able to track on an H~6.3 mag primary with a tertiary component at 300 mas and delta mag ~0.6.

Observing Overhead and Calibrations

For any star observed with KPIC, one should expect 10 minutes of acquisition overhead: 5 minutes of slewing to the target, ~2-3 min of AO acquisition overhead, and ~10 s of KPIC tracking loop acquisition overhead (which can be longer if the host star is faint H ~9-10 mag). Detector readouts overheads are the same as regular NIRSPEC, and can range from a few seconds to ~30 seconds per exposure.

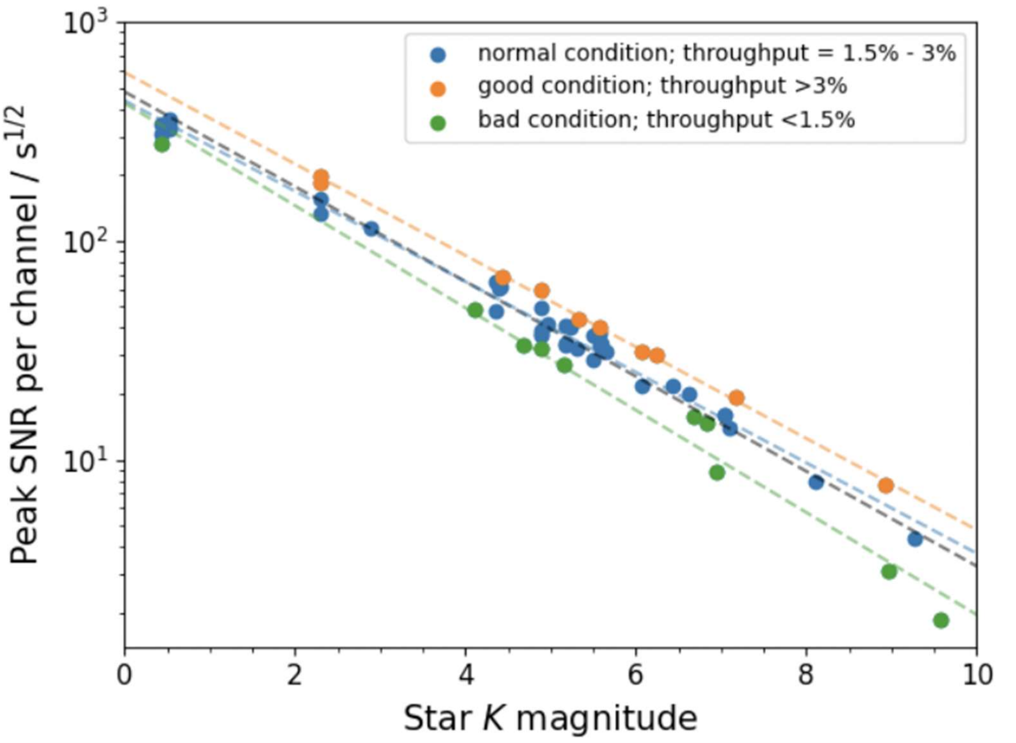
For each night, KPIC requires a few on-sky calibrations that require observing bright standard stars. KPIC observing requires an A0V for spectral trace finding and an early M giant star (M2III HIP 81497 or M0.5IIIb HIP 95771) for wavelength calibration for all science fibers. For Each calibration star, obtaining 3-5 exposures with the star placed on each fiber will suffice. Including the target acquisition overheads, observing each calibrator star takes about 10-15 min.

Typical KPIC observations place the science targets on two fiber positions in a sequence (“fiber bouncing”), which enable nod-subtraction to remove the residual sky and instrument backgrounds (similar to the pair subtraction in traditional slit-fed spectrometers). Using this technique, we generally do not need long thermal background observations taken separately. Note that the thermal background is dominated by the instrument background, as very little sky background couples into the limited angular extent of the fiber (SNR~3 on OH lines in 10 minutes). For the calibration stars, it is still useful to obtain separate observations of the instrumental thermal background. In the afternoon or end of the night, observers can take thermal backgrounds that correspond to the science exposure to subtract from the data. This only needs to be done for data that isn’t being reduced using nod subtraction. The KPIC typical background frames, taken under the same Kband-new filter and no lights are in the fibers, include 1.5, 5, 10, 15, 30, 60, 120, 180, 300, and 600s exposures, with each setting of five frames.

For faint science targets, KPIC has two observing strategies: one is to observe the target on a single fiber, and the data will be reduced by using the NIRSPEC background under the same integration time, the second method is to nod the target between two fibers (typical exposure times of 300s or 600s for a single frame). The exposures will be coadded in the data reduction to reach the required S/N. After 1 hour on any companion, it is recommended that observers move back to the host star and an A0V star to obtain a few spectra. Having spectra each hour can help in the data reduction to model the residual stellar light leaking into the science fiber and for telluric correction.

Signal-to-Noise Ratio

For host stars or bright targets, the empirical relation of peak SNR per spectral channel versus star K magnitude is shown below:



The peak SNR per channel is computed based on the 99th percentile SNR per channel of all orders for a given spectrum. A spectral channel is one element in the 1-D extracted spectra. The noise is computed from optimal extraction of the trace flux on the detector with the KPIC data reduction pipeline (DRP). The end-to-end throughputs can be computed during the observation to quantify the weather conditions. Good, normal, and bad weather conditions are >3%, 1.5–3%, and <1.5%, respectively. Strehl ratios (*H* band) of > 0.2 typically translate into throughputs > 3.5-4%, while Strehl ratios < 0.1 imply throughputs < 2%. The KPIC team has constructed an empirical [peak SNR / $s^{1/2}$] versus K magnitude based on real KPIC data over various conditions ($s^{1/2}$ stands for the square root per second to normalize different integration times for the observed targets). The equation 1 is defined as $log_{10}(\ [Peak\ SNR\ per\ channel]\ /\ s^{1/2})\ = a\ (Kmag)\ +\ b$. The parameters a and b depend on the conditions. Under all conditions, (a, b) = (-0.21676457, 2.68128545). Under good conditions (throughputs > 3%) ,(a, b) = (-0.2090274, 2.76946315). Under normal conditions (throughputs = 1.5-3%), (a, b) = (-0.20687957, 2.64094208). Under bad conditions (throughputs < 1.5%), (a, b) = (-0.2336775, 2.62866763). The SNR under a given integration time (tint) can be extrapolated by sqrt(tint), as the read noise is negligible in most cases.

The integration time [s] assuming a given SNR per pixel as a function of magnitude is shown in the table below, under typical conditions. There is also a Python script to compute integration time or SNR given a K magnitude and a condition (or a web tool TBD). Note that the minimum integration time for KPIC/NIRSPEC is 1.5s, and the overhead will be huge for short integration times.

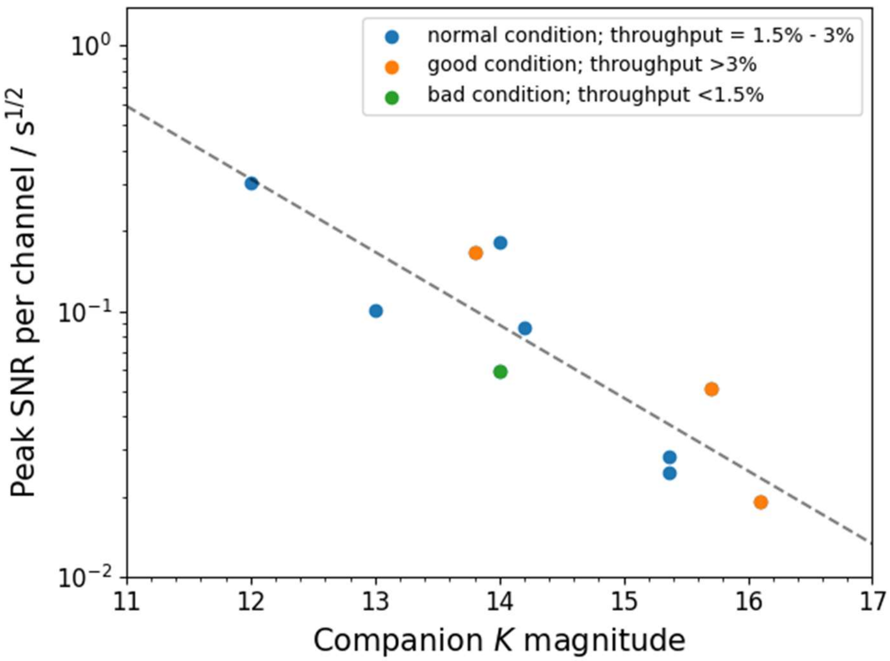
Table 1. Integration time (s) for a given S/N vs. Star K magnitude

Star K mag	S/N = 30	S/N = 100	S/N = 500
0	0.004	0.04	1.08
1	0.01	0.12	2.9
2	0.03	0.3	8
3	0.08	0.9	22
4	0.2	2.4	59
5	0.6	6.4	160
6	1.6	17	433
7	4.2	47	1175
8	11	128	3188
9	31	346	8652
10	85	939	23477

For faint companions, the integration time for a given SNR can be estimated using the following table, or using the Python script (or a web tool TBD).

There are different ways to define the SNR: SNR per spectral channel (or per spectral resolution element) and cross-correlation function (CCF) SNR. While the SNR per spectral channel represents the SNR at a single wavelength, the CCF SNR combines the spectral features (i.e., combines all the lines available) over the entire spectral band (e.g. K band). The CCF SNR is the metric relevant for a companion detection. It is the quantity that measures the total amount of information available for characterization, meaning that the CCF SNR directly correlates to the RV precision, abundance measurements, etc, unlike the SNR per channel. Generally, a peak SNR per spectral channel > 1.5 implies a CCF SNR > 5, which is typical for claiming detection. The CCF SNR depends on the molecular templates, deeper and more abundant molecular lines will increase the CCF SNR generally.

The peak SNRs per spectral channel of the companions are derived from the best-fit parameters that model the starlight and companion flux contributions (see Ruffio et al. 2019 and Wang et al. 2021 for details), and the noise again is originally computed from the KPIC DRP. Using all of the empirical measurements for the companions, the best-fit parameters using equation 1 are (a, b) = (-0.27486809, 2.79619483).



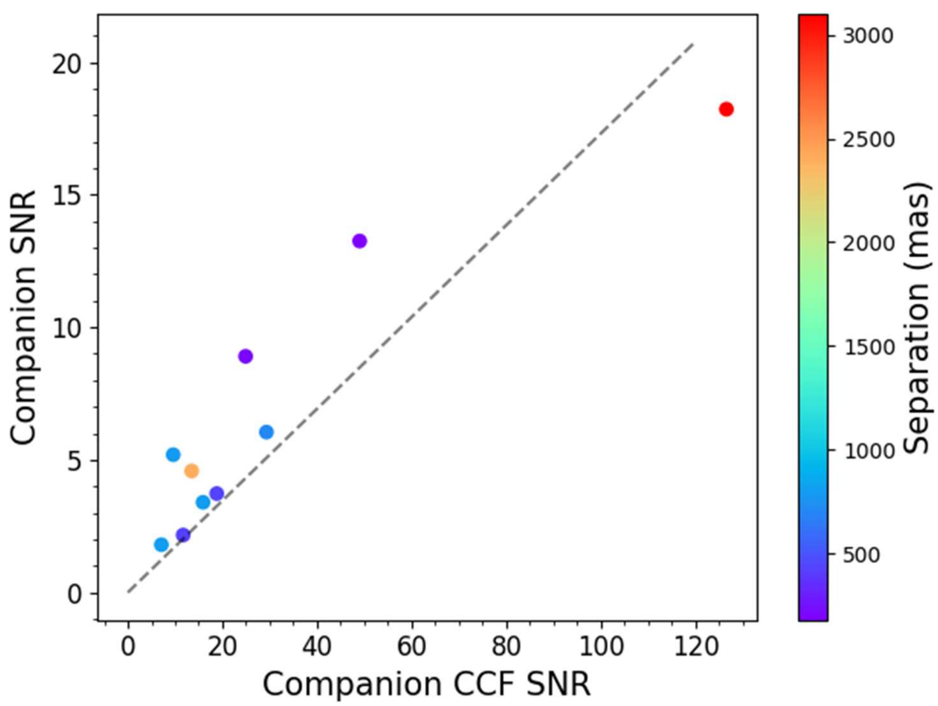


Table 2. Integration time (s or hr) for a given peak S/N per channel vs. Companion K magnitude. The peak S/N is defined as the 99th percentile flux over noise of the observed spectra.

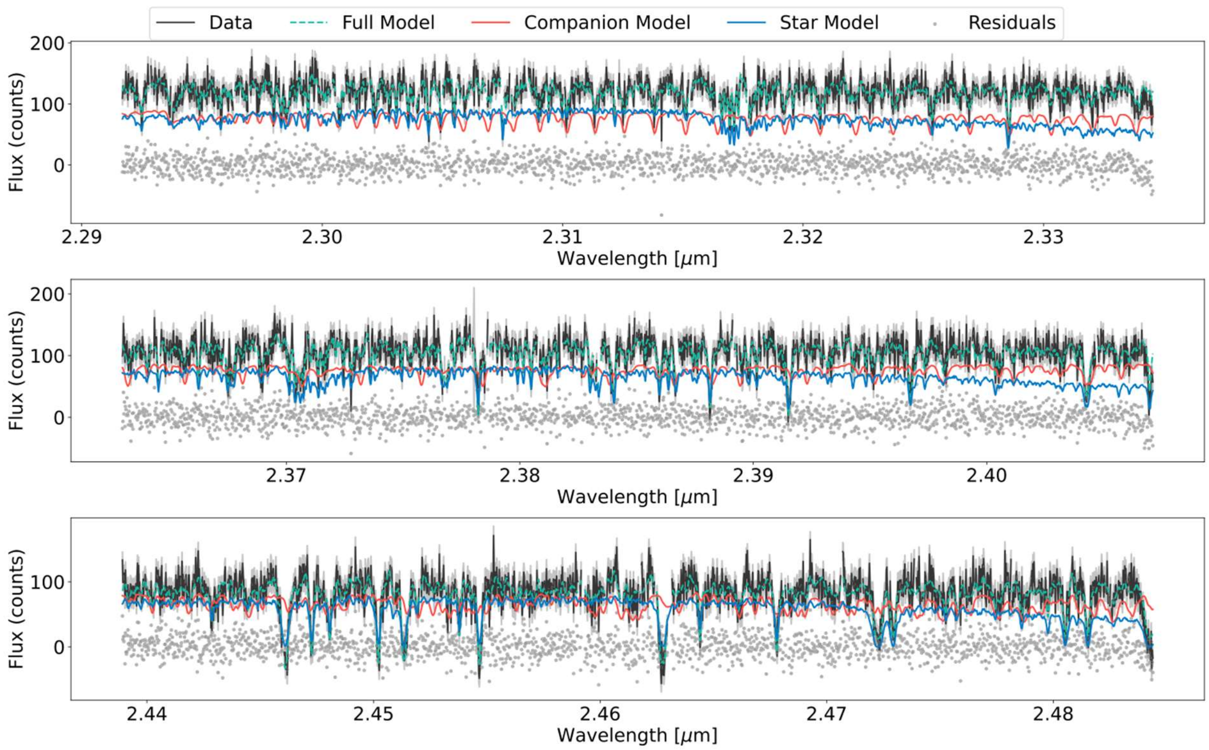
Companion K mag	Direct S/N = 5	Direct S/N = 10	Direct S/N = 100	CCF SNR = 5	CCF SNR = 10	CCF SNR = 100
11	71 s	285 s	7.9 hr	4 s	15 s	1533 s

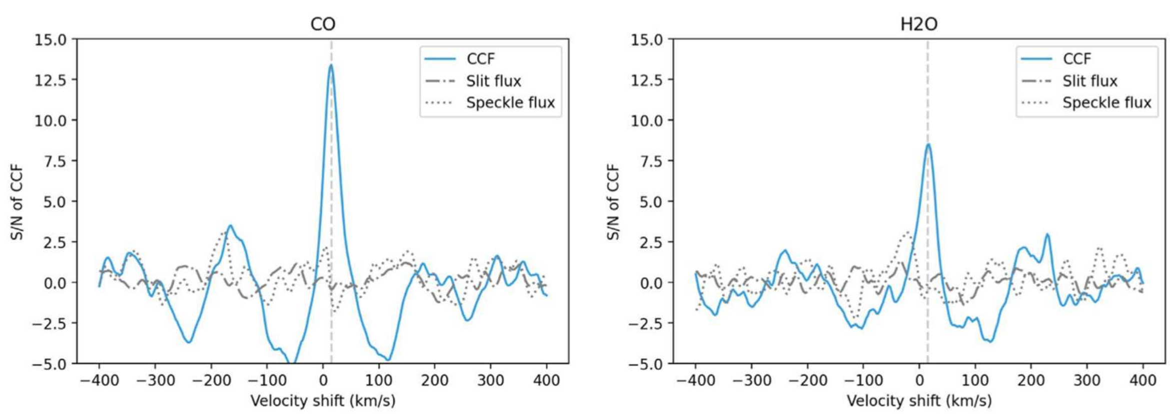
12	253 s	1010 s	28 hr	14 s	54 s	1.5 hr
13	896 s	3582 s	100 hr	48 s	193 s	5.3 hr
14	3176 s	3.5 hr	350 hr	171 s	684 s	19 hr
15	3.1 hr	12.5 hr	1250 hr	606 s	2424 s	67 hr
16	11 hr	44 hr	4450 hr	2149 s	2.4 hr	238 hr
17	39 hr	157 hr	15750 hr	2.1 hr	8.5 hr	850 hr

KPIC Data Reduction

KPIC has developed the reduction pipeline: https://github.com/kpicteam/kpic_pipeline, and the reduction examples are available (https://github.com/kpicteam/kpic_pipeline/tree/main/examples). Observers will need to run background (background_demo.py), trace (trace_demo.py), extraction (extraction_demo.py), and wavelength calibration (wavecal_demo.py) scripts.

Example extracted spectra of NIRSPEC order 31–33 (from 2.29 to 2.49 microns) and the corresponding CCF plots for CO and H_2O molecular species for HD 4747 B, a brown dwarf companion (67.2 M_{Jup}; *K*s = 14.4) at ~600 mas separation from the host star HD 4747 (Δ*K* ~ 9), are shown below (from Xuan et al. 2022). HD 4747 B was observed for 1 hr (600s x 6 exposures) under 1.8-2.0% throughputs. The host star HD 4747 was observed under 60s x 2 exposures.





Additional Considerations for Hot Jupiters with KPIC

Summary

Hot Jupiters successfully detected in emission with KPIC high-resolution cross-correlation spectroscopy (HRCCS) have primary Kmag < 8, period < 5 days, and in-band star/planet contrasts of a few x 10^-4. Due to the ~9 km/s velocity resolution of NIRSPEC, observations should aim to observe >30 km/s planetary RV shift, preferably >50 km/s. Details of these considerations are described below. Successful detections to-date range from 1200 K to 3700 K in planetary equilibrium temperature and from K to A in host star spectral type. Early analysis of

KPIC transmission spectroscopy observations suggests KPIC can also detect hot Jupiters in transmission.

Limiting primary magnitude

The apparent magnitude impacts both the quality of the atmospheric correction during post-processing as well as the AO performance while observing. In general, KPIC hot Jupiter programs have aimed for primary Kmag < 8, with a few targets in the 8 < Kmag < 9 range when the star/planet contrast is expected to be particularly favorable. The exact limits will depend on your goals, observing conditions, and the planetary contrast/composition. SNR > 100/extracted wavelength channel/time step is reliably achievable for Kmag<8 (see above table) and appears to be sufficient for retrievals.

Primary spectral type

To-date, KPIC high-resolution cross-correlation spectroscopy (HRCCS) has detected planets with K-A type primaries. For late G and later spectral types, cross-talk between stellar and planetary CO lines may impact interpretation of spectra, and should be assessed during the stellar/telluric removal process. Impacts of increased activity in late-type stars have not been assessed.

Limiting planetary temperature/contrast

KPIC has successfully detected a wide range of hot Jupiters, from ultra-hot Jupiters around A-type stars to a planet with equilibrium temperature (Teq)~1200 K around a K-type star. Planetary temperatures/bolometric luminosities appear to be less important for detectability compared to the strength of planetary molecular features relative to the stellar continuum, which is only indirectly dependent on temperature and can be significantly impacted by atmospheric composition, observed bandpass, and host star spectral type. In general, successful detections have had planetary molecular features with a strength of >10^-4 relative to the host star.

Minimum observed velocity shift

Successful HRCCS detection with KPIC requires the planetary radial velocity shift by >30 km/s over the observation, preferable >50 km/s. Detection in the 30-50 km/s range can be significantly improved by obtaining a high-SNR spectrum of the star during secondary eclipse to aid in detrending. For circular, edge-on orbits observed near eclipse, this corresponds to a maximum orbital period of about 5 days. Orbital eccentricity can facilitate detection of longer-period planets in some cases, while planets with significant orbital inclination may be non-detectable despite short orbital periods. Multi-epoch cross-correlation spectroscopy has not been demonstrated with KPIC data.

Doppler smearing and integration time

Planetary RV shifts > 4 km/s within a single frame can lead to noticeable broadening of the planetary CCF in a Kp-vsys diagram. This can be mitigated by replicating the smearing in the forward model, but is generally better to avoid by choosing a shorter exposure time. Exposure times should also be chosen to keep the maximum flux well under 20k counts to avoid non-linearity in NIRSPEC even as AO performance fluctuates. Note that the NIRSPEC readout time can lead to significant overheads at very short exposure times. Depending on the target and conditions, exposures of 60-300s are generally appropriate for HRCCS.

Nodding

Nodding is not recommended for HRCCS observations in K-band. Obtaining 10-20 background frames during the afternoon before and/or morning after observations has been sufficient to correct thermal background. KPIC has extremely low sky background (SNR~3 on OH lines in 10 minutes), and the detrending procedures used to filter out the stellar signal can generally handle sky emission as well. Nodding introduces tracking overheads and reduces average throughput compared with staring on the highest-throughput fiber. Additionally, each science fiber has a slightly different line-spread function (LSF), which can complicate combining data from multiple fibers. Observations in other bandpasses or observations which are particularly sensitive to sky emission may prefer nodding.

Transmission Spectroscopy

Transmission spectroscopy using KPIC has been tested for WASP-33b. Initial analysis appears to show the planet, but dedicated transmission analysis tools have not been developed. Transits which satisfy the velocity shift criteria and produce features ~few x 10^-4 relative to the host star out-of-transit spectrum are likely to be detectable.

KPIC Publications

The current KPIC publications are summarized in the following NASA ADS Library: https://ui.adsabs.harvard.edu/public-libraries/ISUJAGd3RjmGl6feOZey_g.