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Understanding systematics in exoplanet observations

Pieter Deroo (1), Mark Swain (1) & Tom Greene (2)
1: NASA/Jet Propulsion Laboratory, California Institute of Technology; 2: NASA/Ames

Abstract:

The most successful exoplanet characterization method to date – combined light photometry – relies on extremely accurate spectrophotometric differential precision. The required dynamic range has pushed exoplanet observations into previously unexplored instrument systematics. Mitigating these small but very significant effects is core to exoplanet science and the methodology how to remove the instrument noise is frequently a source of controversy.

Here, we model the systematic noise floor induced by the most significant instrument systematic effects. We focus on near-IR spectroscopic characterization of exoplanet atmospheres using HgCdTe detectors. We establish the:

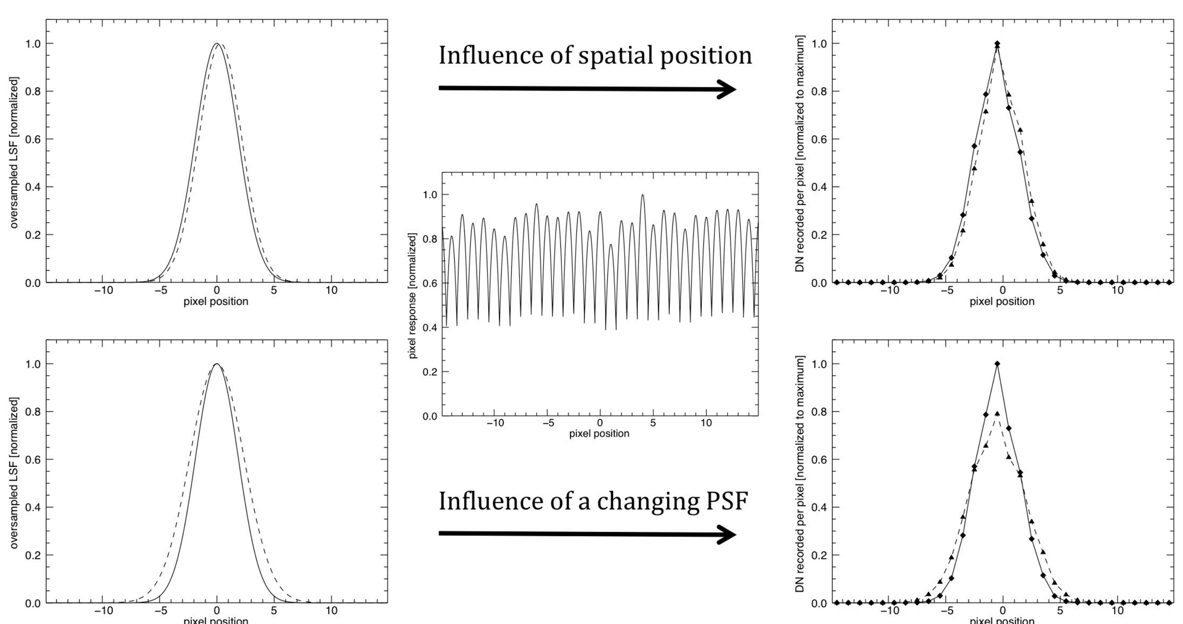
1. Raw systematics noise floor
2. Decorrelated/post-processed systematics noise floor

and this for a range in instrument parameters (right-hand side). Three specific instruments are considered as well (bottom): HST/NICMOS which allowed for the first spectroscopic comparative exoplanetology; JWST/NIRSpec &FINESSE, which are future instruments that will characterize exoplanet atmospheres from the optical to the near-IR (~ 0.5 – 5 µm). FINESSE is a 76 cm aperture Explorer mission with well-sampled spectra at R ~ 1000.

Methodology:

A Monte Carlo simulation in which common instrument errors (pointing & focus errors) are used as forcing functions for photometric variation induced by:

1. Position dependent gain variations and uncertainties in the focal plane array
2. Slit-losses



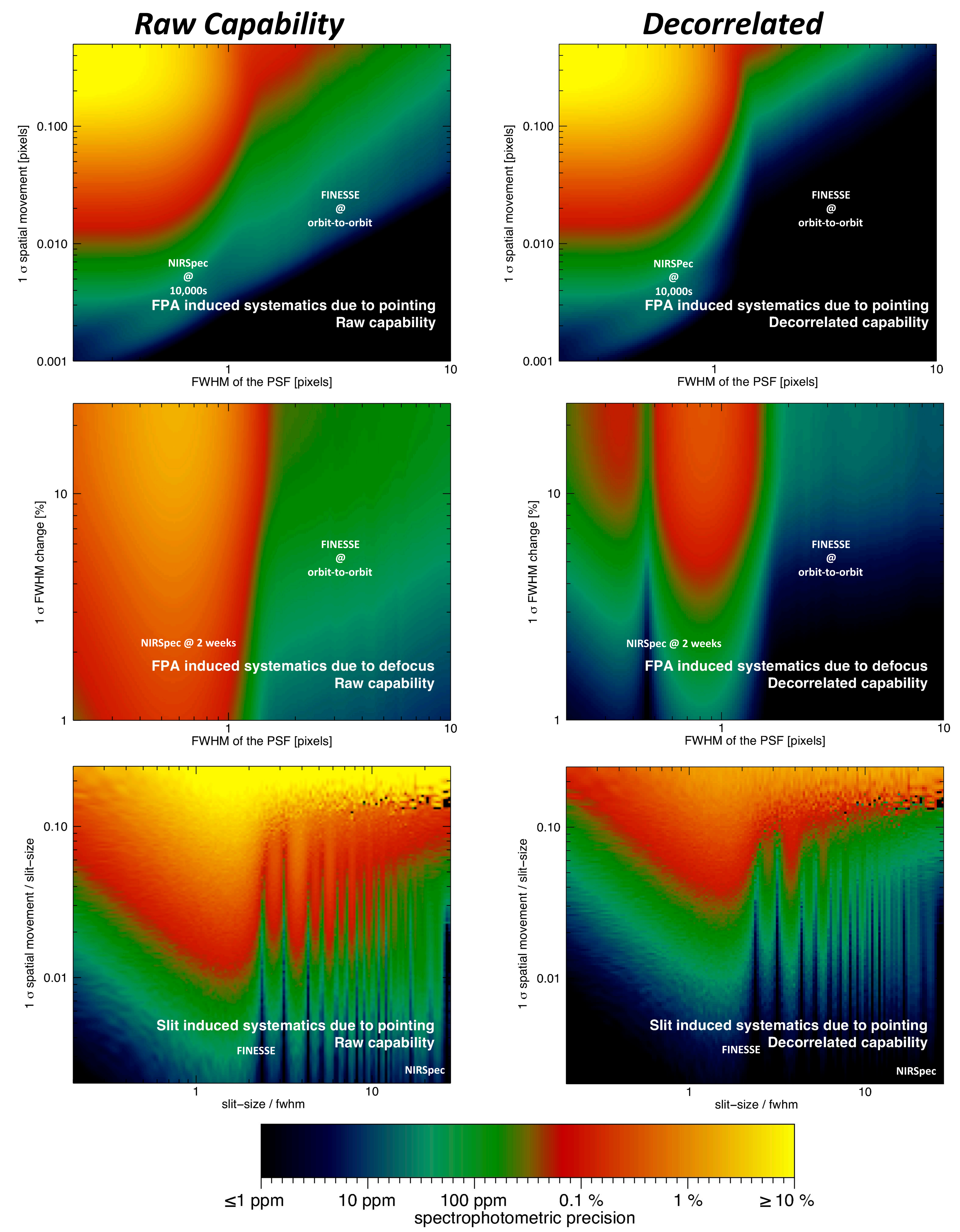
Various illumination patterns – PSFs with different width and position (left) – are propagated onto a detector with a specific inter and intra pixel gain variation (middle) and the oversampled PSF is read out at the different detector pixels (right). The FPA is Monte Carlo simulated; the ensemble of MC simulations together with a statistical distribution in pointings and PSF sizes (FWHM) is used to establish the systematic noise floor.

Conclusions:

Our simulations quantify the expected systematic noise floor for exoplanet spectroscopic observations and the improvements using the current-best decorrelation/post-processing [**right, bottom**]. Our simulations for HST/NICMOS are in agreement with the observed pre- and post-processed values, validating the simulations [**bottom**].

Simple trades in the instrument design can significantly optimize it for exoplanet spectroscopy [**right**]. As such, the well-sampled spectra of a modest aperture mission like FINESSE could have better limiting signal-to-noise than the poorly sampled JWST/NIRSpec at short wavelengths [**bottom**].

Instrument design vs spectrophotometric differential precision:



Assuming: state-of-the-art HgCdTe inter and intra pixel response; Gaussian instrument errors.
Overall systematics noise floor: combine the different partials appropriately
The approximate location for NIRSpec & FINESSE @ 2 µm is annotated. The error distribution for those instruments can significantly differ from the assumed Gaussian. Our instrument specific results are given below.

Instrument specific systematics

Overall systematics noise floor per eclipse [8 hr] @ 1.7 µm

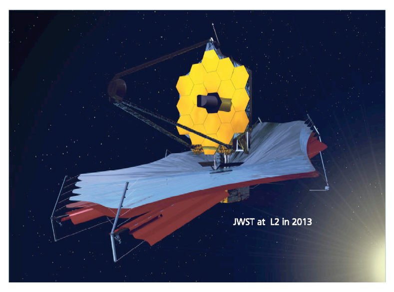
	HST/NICMOS	JWST/NIRSpec	FINESSE
RAW	1048 ppm/eclipse	1052 ppm/eclipse	67 ppm/eclipse
DECORRELATED	146 ppm/eclipse	217 ppm/eclipse	5 ppm/eclipse

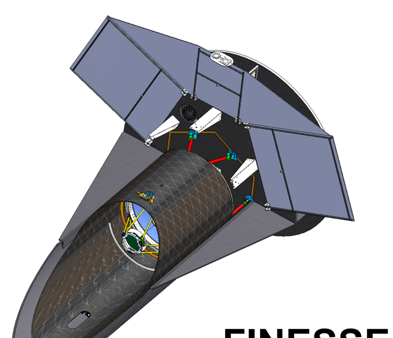
Raw instrument noise partials @ 1.7 µm

	HST/NICMOS	JWST/NIRSpec	FINESSE
Pointing induced gain changes	480 ppm/orbit	364 ppm/10,000s	17 ppm/orbit
Systematic PSF variations	932 ppm/orbit	3434 ppm/2wks	60 ppm/orbit
Pointing induced slit-loss	NA	1 ppm/10,000s	22 ppm/orbit

Decorrelated instrument noise partials @ 1.7 µm

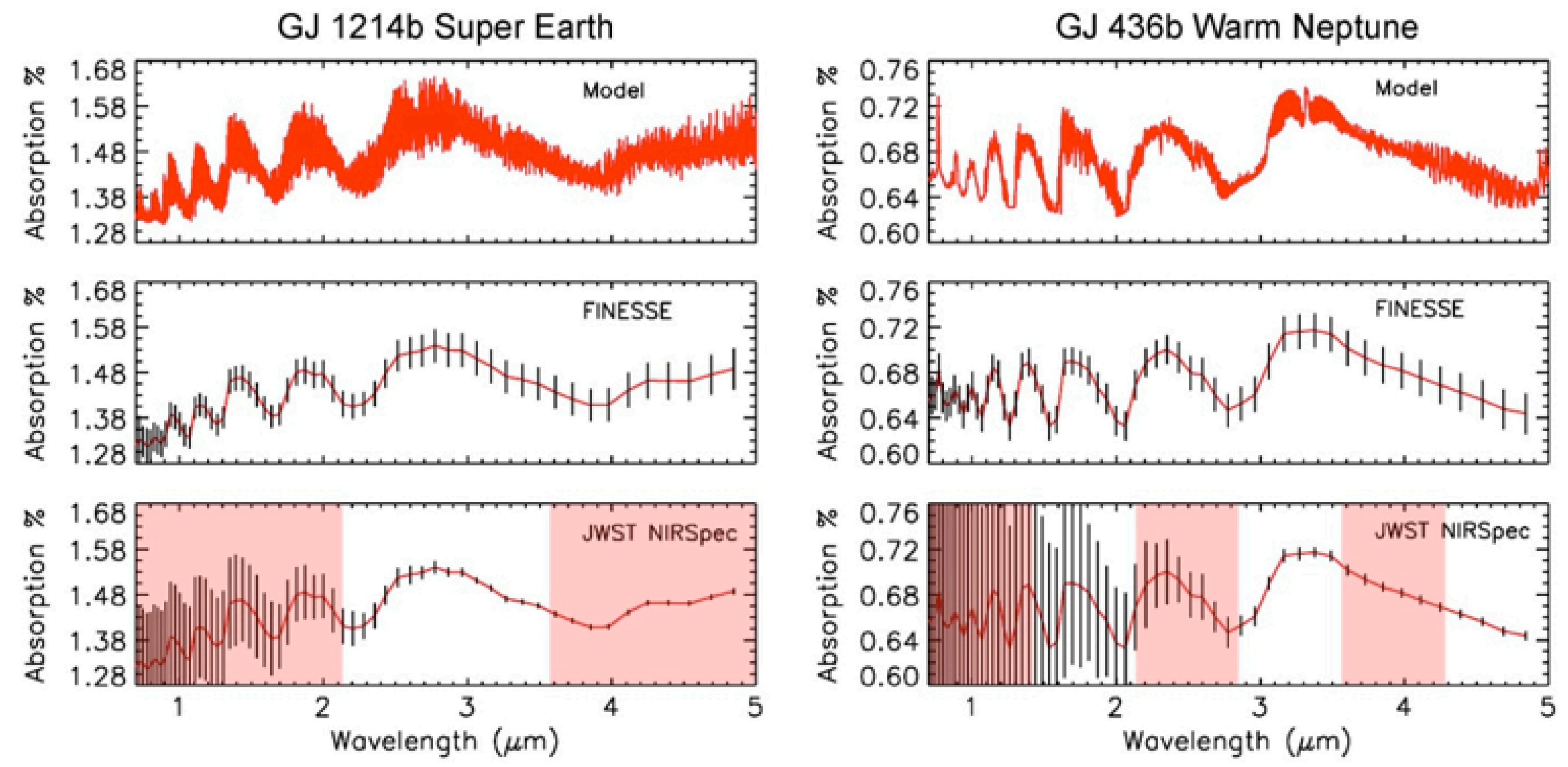
	HST/NICMOS	JWST/NIRSpec	FINESSE
Pointing induced gain changes	21ppm/orbit	75 ppm/10,000s	0.3 ppm/orbit
Systematic PSF variations	145ppm/orbit	49 ppm/2wks	4 ppm/orbit
Pointing induced slit-loss	NA	1 ppm/10,000s	2 ppm/orbit





FINESSE
Fast Infrared Exoplanet Spectroscopy Survey Explorer

Systematics and exoplanet spectroscopy:



Simulated spectra (top panel) for the Super-Earth GJ 1214b and the warm Neptune GJ 436b as observed with FINESSE (middle panel) and JWST/NIRSpec (bottom panel) taking into account all sources of noise, including systematic noise. The noise for FINESSE is dominated by photon noise; for NIRSpec, systematic noise dominates spectra at the short wavelength range. To illustrate the fact that NIRSpec requires multiple instrument settings to cover the entire wavelength range (and thus multiple eclipses), we have shaded the spectral region according to the minimum number of instrument settings required.

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