Ground-Based Observations of Exoplanet Atmospheres:
IRTF/SpeX and MRO/NESSI

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ABSTRACT

Of the more than 500 known exoplanets, the detailed chemical composition of only a handful of exoplanet atmospheres is known. We endeavor to remedy this imbalance by using ground-based spectroscopy, which has been demonstrated to reliably reproduce space-based results while obtaining new and unexpected information. [12] Our IRTF/SpeX SXD (0.8-2.4 μm cross-dispersed) observations of a secondary eclipse of the exoplanet WASP-1b, obtained September 2010, will be used to accomplish two main goals: first, to extend the application of exoplanet ground-based spectroscopy to a wider range of targets than are presently characterized; and second, to probe the temperature structure and begin to characterize the composition of the dayside of the atmosphere. We will show our data reduction steps and initial results based on the reduction method introduced by JPL's ExoSpec team. [12]

WASP-1b is a 1.44±0.04 R_J, 0.89±0.11 M_J exoplanet in a 2.52 day orbit around its parent star. [1][2] It has a very low density, which puts it in a group of highly irradiated hot-Jupiters with overly inflated radii known as pM class exoplanets. Theory predicts that we should expect to find a thermal inversion, as well as evidence of H_2O and CO. [3] However, the reason for the inflated radii of these exoplanets is still a matter of great debate; determining the structure and composition of the atmospheres of this class of exoplanets may help us sort among competing theories as to the structure and source of the inflated radius. [8][10][7][5]

INTRODUCTION

Infrared spectroscopy is the most effective tool we have to gain an understanding about the composition and temperature structure of exoplanet atmospheres. Thus far, our observational focus has been on determining the fundamental properties of hot-Jupiters. Spitzer and HST have been used to detect molecules of CO, CO_2, CH_4, and H_2O in exoplanet atmospheres. [3][11] Furthermore, IRTF/SpeX has been used to reproduce space-based results and yield new information about the atmosphere of HD 189733b; this presents us with the opportunity to observe exoplanet atmospheres from the ground. [12] Our groups current observational efforts are to extend this method to other exoplanet atmospheres. Here we present the results of the calibration of our observations of WASP-1b.

Table 1: Summary of the properties of the WASP-1 system

Stellar Parameters	Spectral Type	F7V
	K_{mag}	10.276
	Stellar Mass	1.24 M_{Solar}
	Stellar Radius	1.382 R_{Solar}
Planet Parameters	Planetary Mass	0.89 $M_{Jupiter}$
	Planetary Radius	1.358 $R_{Jupiter}$
	Equivalent Temperature	1816 K
	Semi-Major Axis	0.0382 AU
	Incident Flux	~2.5×10^9 $ergs^{-1}$ cm^{-2}
Orbital Parameters	Period	2.52 days
	Transit Depth	0.0105 mmag
	Transit Duration	3.77 hours

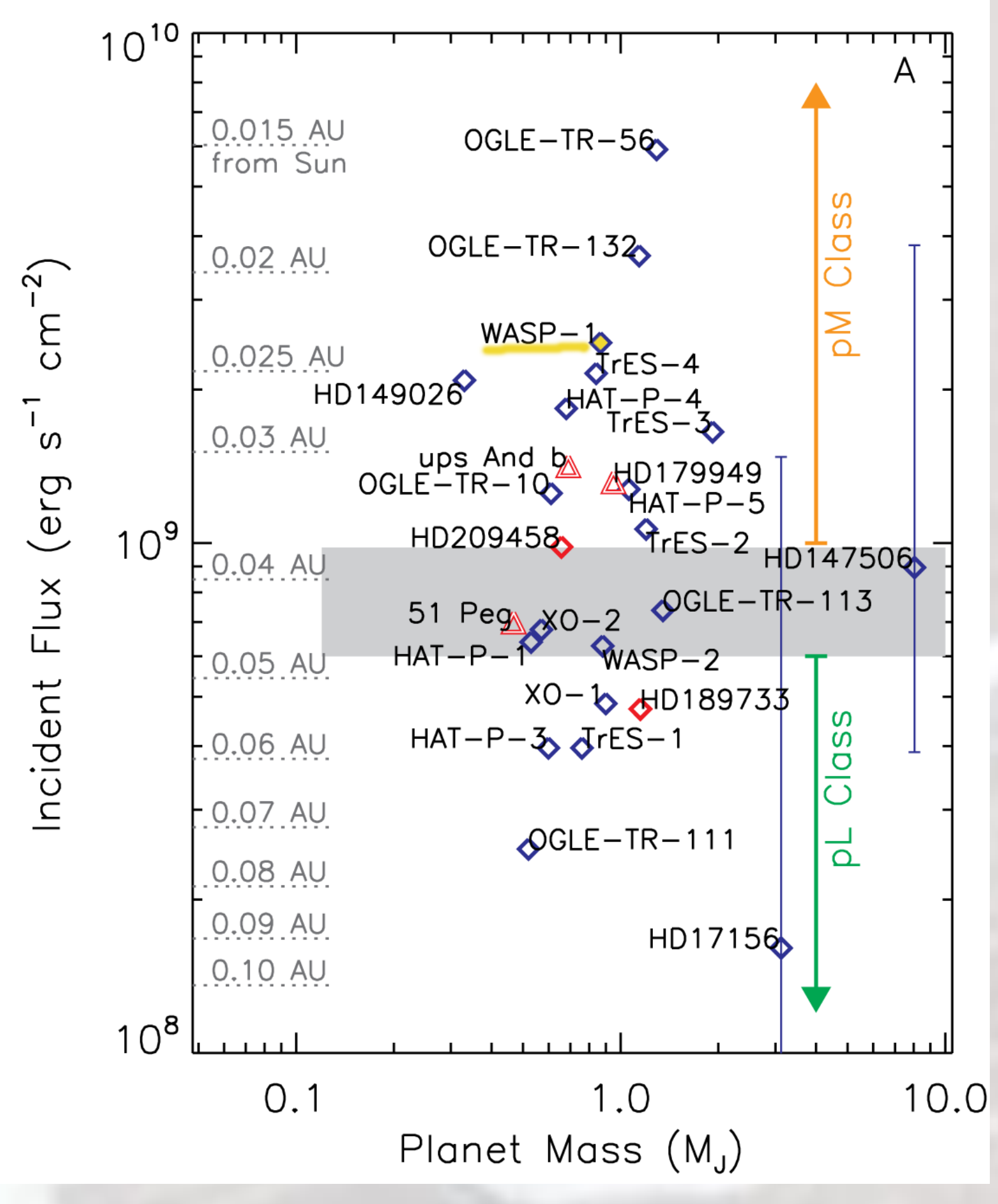

Figure 1 **Plot of Incident Flux vs. Planet Mass:** WASP-1b is one of the most highly irradiated exoplanets studied to date. Current theory classifies WASP-1b as a pM class exoplanet. This means that we expect prominent absorption due to CO and H_2O, large day/night contrasts, hot stratospheres (with brightness temperatures greater than their equilibrium temperatures), and therefore a pressure-temperature inversion. [4][13]

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ABOUT THE OBSERVATIONS

The initial results presented here are based on data obtained on September 10, 2010, using the SpeX instrument on the NASA Infrared Telescope Facility (IRTF). The observations of the WASP-1 system were timed to observe the secondary eclipse light curve; we began approximately 1.5 hours before and ended approximately 1.5 hours after the eclipse.

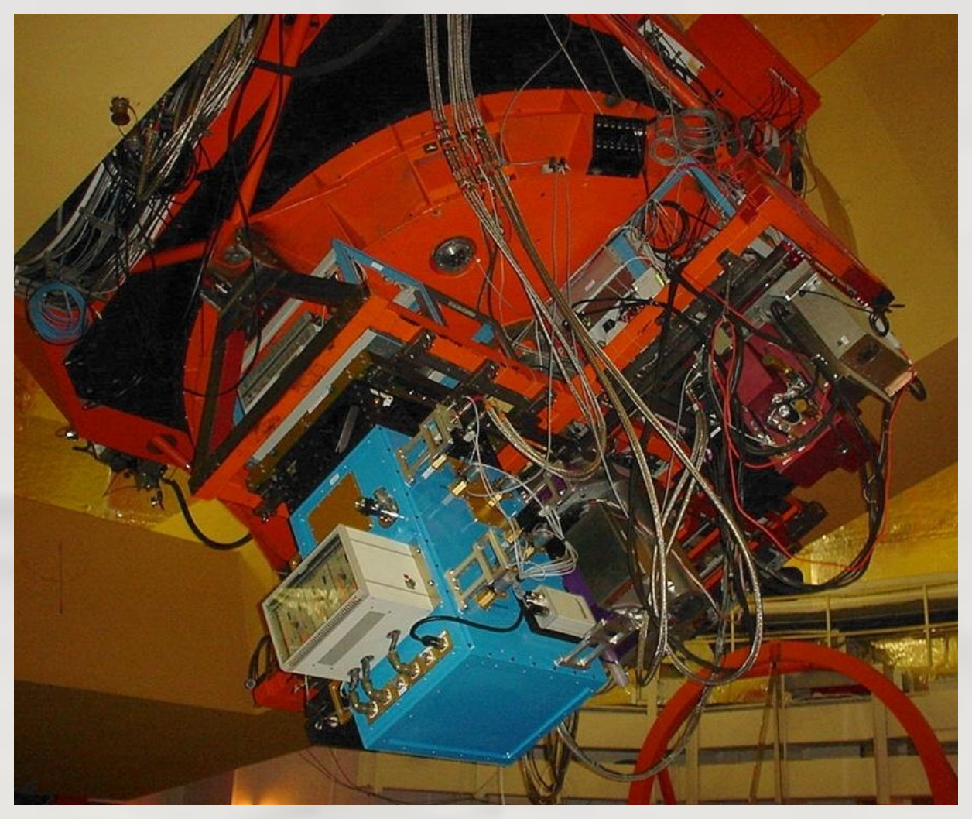


Figure 2 **Photo of NASA-IRTF/SpeX:** The SpeX instrument was configured to observe between 0.8 – 2.46 μm, with a 1.6 arcsecond slit width and slit length of 15 arcseconds. [9]

DATA REDUCTION METHOD

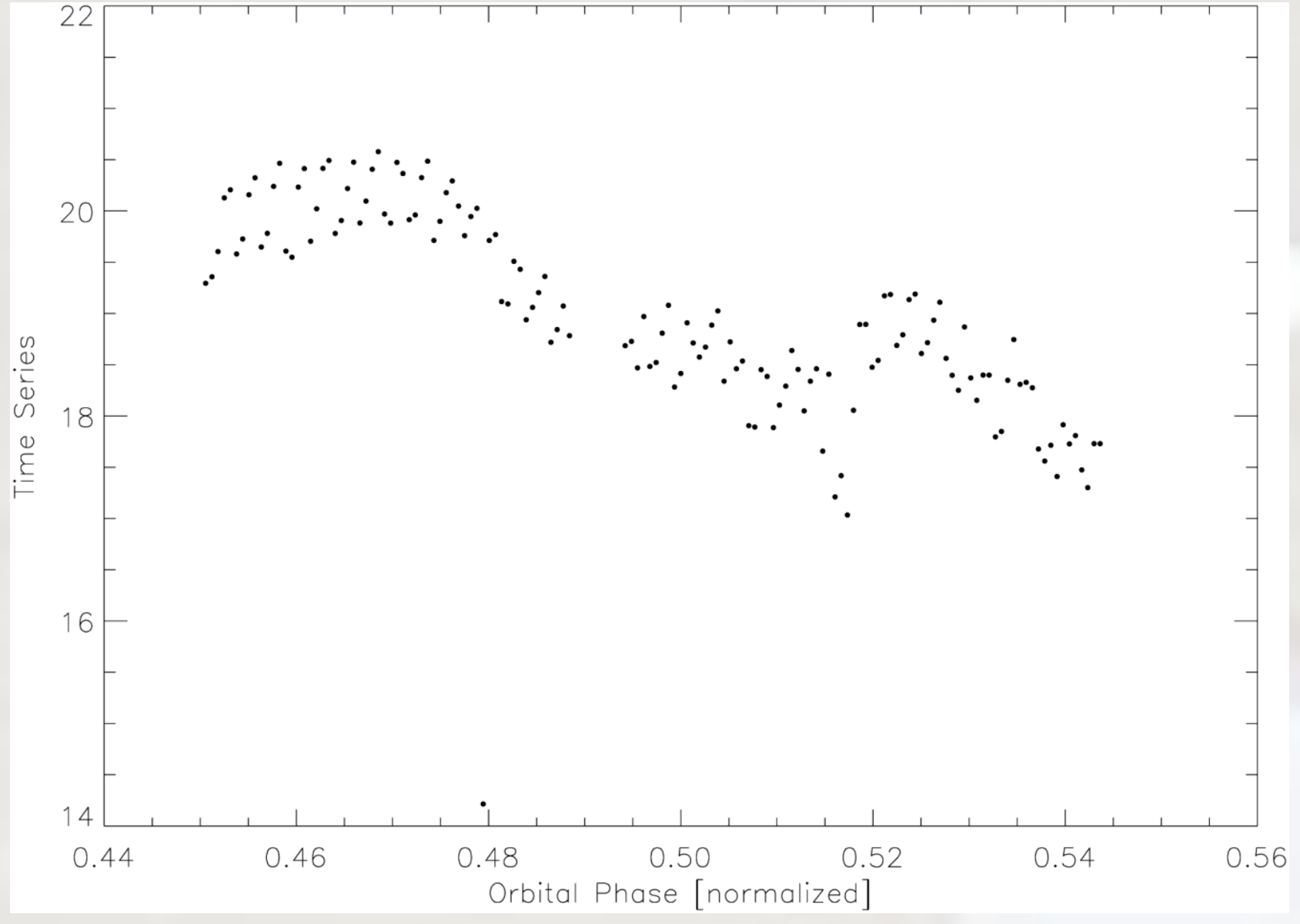


Figure 3 **Plot of Original Data:** The uncalibrated data for wavelengths 1.17 – 1.33 μm plotted as a function of orbital phase (i.e., time). The calibration method to remove the systematic error is based on an iterative approach, while the secondary eclipse is extracted by computing the self-coherent spectrum of groups of channels. [12]

This process has 2 main steps:

1. Perform an iterative fit to remove the error due to airmass in each wavelength channel, and renormalize the resulting flux values. Normalization allows us to remove error that is a function of wavelength (common-mode errors). The iterative fit removes error that is a function of time (non-common-mode errors).
2. Extract the signal correlated in time using a Fourier transform/inverse Fourier transform. This allows us to extract the signal that is correlated in time.

Once this is complete the data is calibrated. All that remains is to remove the residual curvature and extract the eclipse. This is accomplished by performing a joint minimization to a polynomial and the eclipse depth.

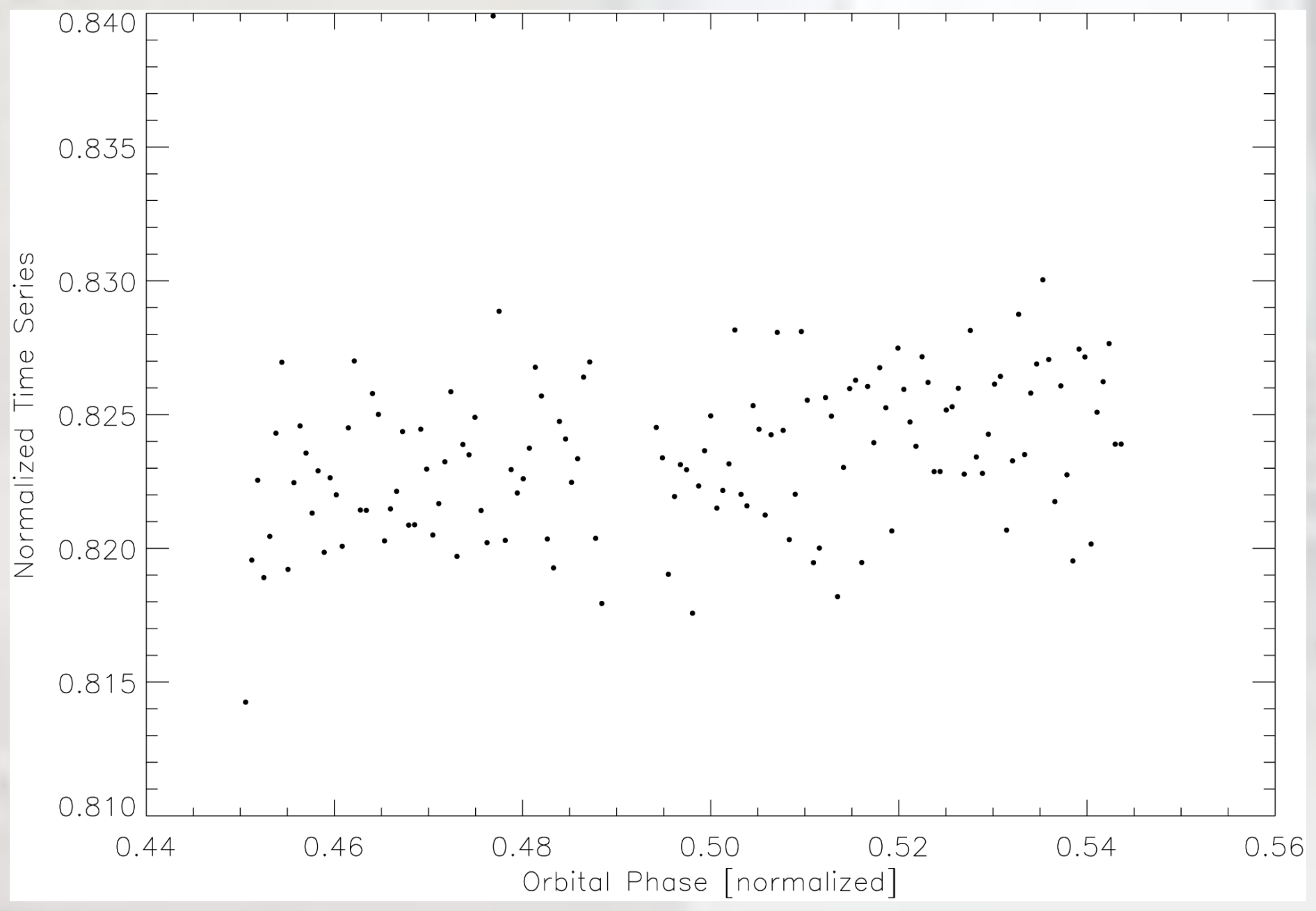
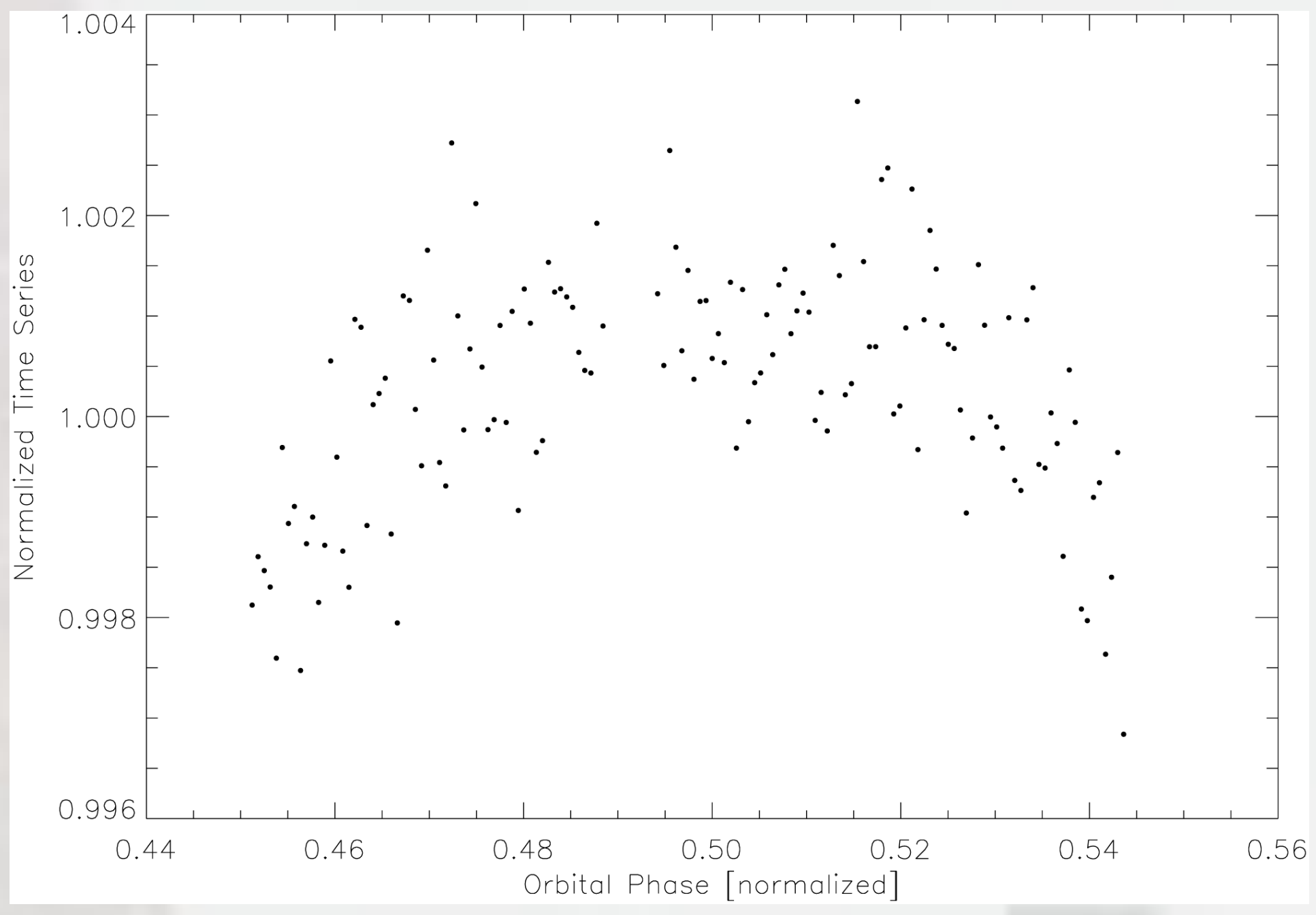


Figure 4 **Plot of Data After Step 1**: The iterative airmass correction and subsequent normalization converges quickly at most wavelengths. Convergence is defined as the renormalized flux density changing by less than 1 part in 10,000 at all wavelengths. At this point the systematic error has been removed.

Figure 5 **Plot of Data After Step 2**: Now our data is properly calibrated and shows the eclipse event with the correct timing and roughly the correct shape. This is significant since no assumptions about the shape of the eclipse have been made. Also note that we have removed enough of the systematic error that the deviation of the data is ~0.062%.



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NESSI

The New Mexico Tech Extrasolar Spectroscopic Survey Instrument (NESSI) is a purpose-built multi-object spectrograph being designed to operate in the J, H, and K bands with a resolution of R = 1000 in each and lower resolution mode (R = 250) that spans the entire J/H/K region. [6] The design emphasizes optomechanical alignment to be highly repeatable and stable over short (tracking) and long (repeat visit) timescales. Stability is achieved by:

1. Deploying at MRO's Nasmyth position with a K-mirror derotator, therefore NESSI will experience a constant gravity,
2. Minimizing moving parts, and
3. High-fidelity characterization of the focal plane array

In-situ atmospheric characterization is achieved by:

1. A large field of view (12 arcminutes), which allows simultaneous observations of another star in the field during transit observations (multi-object capabilities) and,
2. Never chopping or nodding during the transit observation.

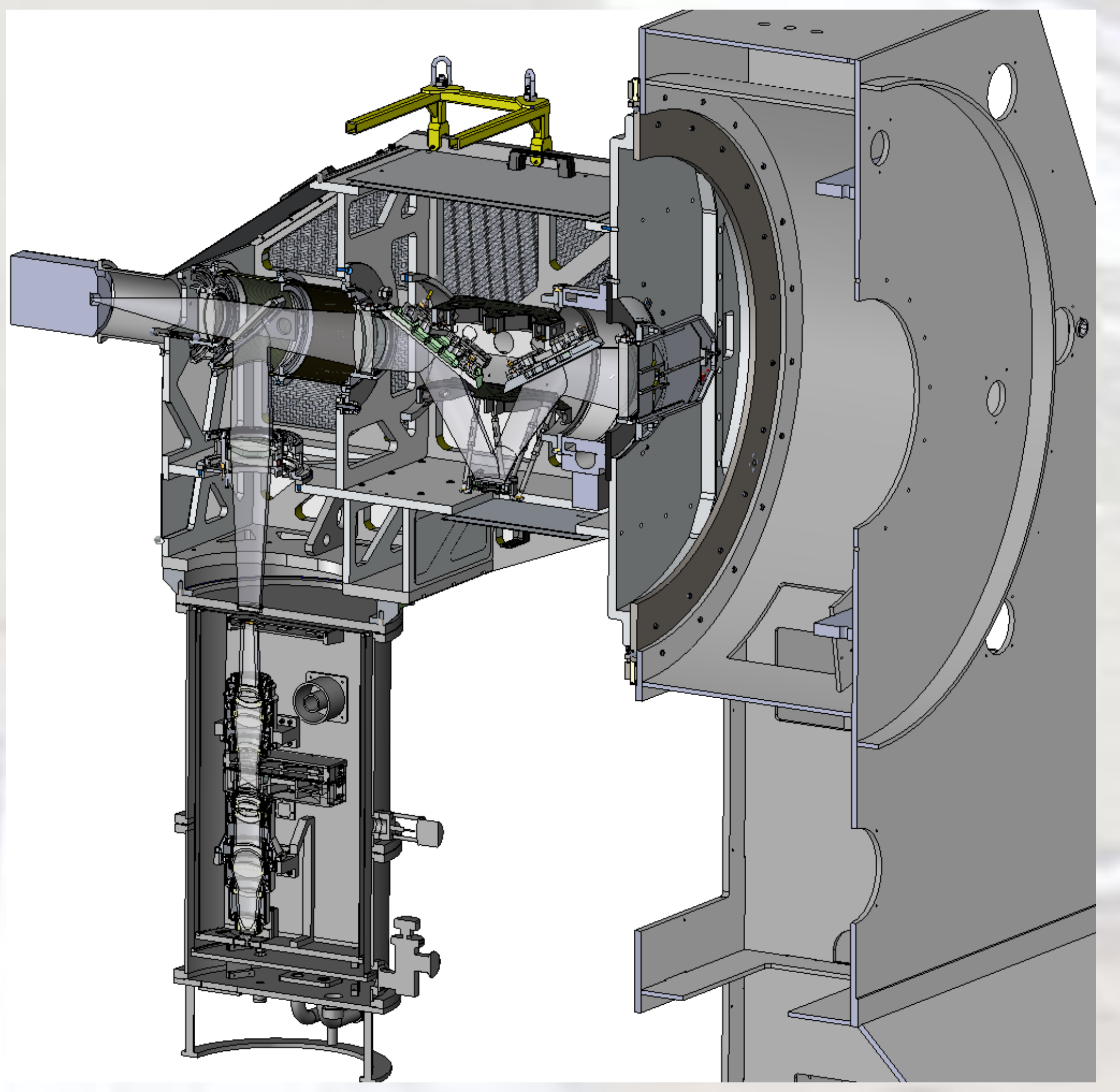
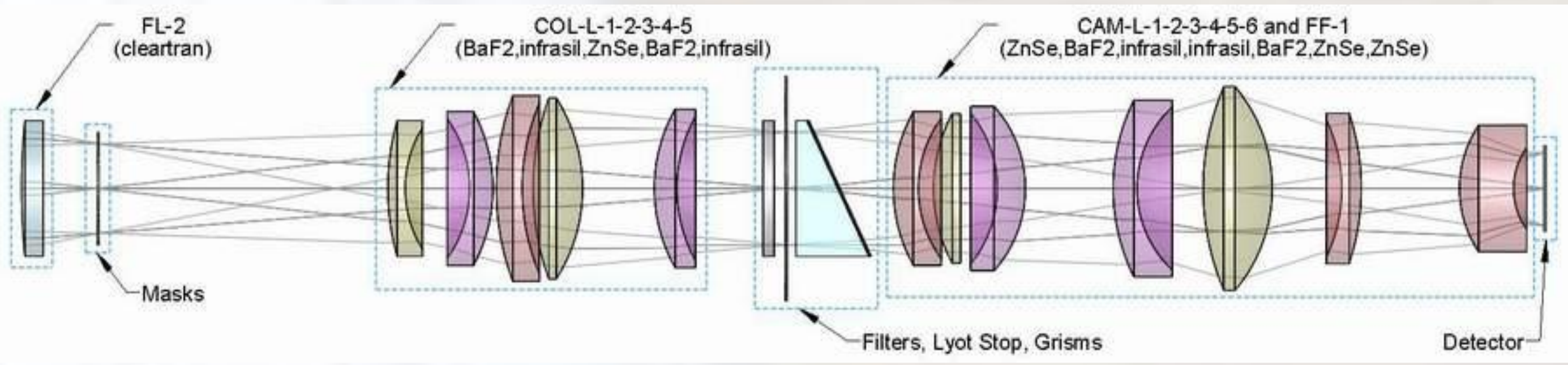


Figure 6 (left) **Cross-Section of the NESSI Assembly:** Starting at the right-hand-side of the image is the Nasmyth port of the telescope, moving left is the K-mirror, collimator optics and dichroic. Here the light is split: visible goes left to auto-guider, IR downward into the cryogenic spectrograph.

Figure 7 (bottom) **Spectrograph Optics:** The optical train of the spectrograph, with collimator and camera groups.



CONCLUSION

The deviation of the first 30 minutes of uncalibrated data was roughly 37.754%. Performing the channel-by-channel airmass correction removes the majority of the systematic error present in the data, giving us a deviation of ~0.3131%. The result of extracting the signal correlated in time has a deviation of ~0.0629%. We therefore conclude that this method has allowed us to remove a significant portion of the error present in the data and see the secondary eclipse event (Figure 5) without making any prior assumptions about the eclipse. Furthermore, the eclipse has the correct timing and approximate correct shape. The next step is to remove the residual curvature and extract the eclipse by performing a joint minimization to a polynomial and the eclipse depth. The self-coherence method used here was originally developed on HD 189733b data. Our ability to replicate this method for a system with a planet with a shallow transit depth (WASP-1b has a transit depth of 0.0105 mmag, compared to HD 189733b's transit depth of 0.0241 mmag), demonstrates the possibility of observing many more transiting exoplanets with ground-based instrumentation. We also believe that it will be possible to apply this calibration method to other instruments, and that further improvements could be realized with purpose built instrumentation.

One such instrument is NESSI, which will use lessons learned from IRTF/SpeX and other facilities to enable ground-based exoplanet spectroscopy a routine endeavor. The optomechanical design of NESSI is nearing completion, long-lead items have been ordered, and our final design review is scheduled for July 2011. We anticipate deploying NESSI on the MRO 2.4m telescope in 2012 and at that time will greatly increase the number of exoplanet spectra obtained from ground-based facilities.

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