NESSI: An optimized Near-Infrared (NIR) Multi-Object Spectrograph (MOS) for Exoplanet Studies

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ABSTRACT

NESSI: the **N**ew Mexico Tech **E**xtra(solar)planet **S**pectroscopic **S**urvey **I**nstrument is a ground-based multi-object spectrograph that operates in the near-infrared and is being deployed this fall at the Magdalena Ridge Observatory 2.4 m telescope. When completed later this year, it is expected to be used to characterize the atmospheres of transiting exoplanets with unprecedented ground-based accuracies down to about K = 9 magnitude. The superior capabilities of NEESI for this type of work lay, in part, in the design philosophy used for the instrument which is well-focused on the exoplanet case. We report here on this design philosophy, detail and status of the design and assembly, and preparation for first light in the fall of 2012.

Keywords: spectrometer; near-infrared; multi-object spectroscopy; exoplanet characterization

1. INTRODUCTION

Exoplanet spectroscopy and imaging are the closest proxies we have to “visiting” the newly found worlds that are now being announced daily using a variety of search techniques. However, such characterization is daunting for most exoplanet systems because the planets are typically very close to their parent stars (i.e. well within a typical telescope’s diffraction limit) and star-planet contrasts are very high, ranging from $1:10^{10}$ in the optical to $1:10^{4}$ in the mid-infrared. Undaunted by such challenges, today’s astronomical community continues to come up with increasingly clever ways to characterize these exoplanets, including active/adaptive optics coupled with coronography[1,2,3,4] and purpose-built space-based spectroscopic missions[5,6].

Exoplanet spectroscopy, as a natural extension of photometric characterization, started to become feasible a few years ago as observers using space-based platforms like Spitzer and HST realized the precision and techniques required to make the measurements[7]. However, even though ground-based wide-band photometry of exoplanets was relatively common, ground-based spectroscopy seemed to surprise many in the community when it was first announced in 2010 by Swain et al.[8] This is perhaps because astronomers frequently think of using the community’s substantial tools as direct measuring devices, rather than differential ones. In a differential reframing of the question of how to make the measurement, the astronomer strips away all the known contributions of the detector response to the incoming electromagnetic signal (often including features of the detector itself) and is left with what is presented by the object being assessed. A thorough knowledge of one’s instrument and of the controllable/assessable parameters affecting the measurement allows one to make a final determination of a measureable quantity, which can often be hidden by multiple larger, but predictable, signals also present in the data. Nowhere else is this example more prominent in the exoplanet detection game than in the use of high-resolution, high-precision spectrographs[9,10] where astronomers strive to control the spectrograph’s physical environment. They do this while obtaining more and more precise reference methodologies and stellar models in order to be able to detect the small Doppler shifts indicative of the presence of planets. This canonical model can easily be extended to all forms of exoplanet characterization.

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It is within this set of realizations that the NESSI team proposed a concept for a new purpose-built spectroscopic instrument capable of measuring the atmospheric spectral signal of an exoplanet transiting or eclipsing its parent star. While the techniques to reliably make these measurements are still under development, to date four papers have been published demonstrating the feasibility of doing so from the ground (see below). Undertaking exoplanet spectroscopy from a ground-based observatory has tremendous advantages including: 1) access to the spectrometer in real-time for upgrades and system characterization, 2) quick response time for new discoveries, and 3) over-subscription rates typically lower than space-based facilities.

2. MEASURING EXOPLANET SPECTRA

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Measurements of transiting exoplanet spectra from ground-based facilities currently rely on one of two methods for the data reduction process. These methods are called "Model Correlation Fit"[8] (c.f. Swain et al. 2010) and "Principal Component Analysis" [11](c.f. Thatte et al. 2010). (Ground-based exoplanet spectra can be examined in several papers[8,11,12,13].) The basic idea behind both of these methods is to: 1) determine a set of observables, 2) find a way to mathematically represent each of the observables, 3) remove the observables from the data (which one generally assumes are mostly uncorrelated with one another) leaving unbiased data products after each iteration, 4) produce a data set free of all instrument-/observing- induced observables not originating in the exoplanet data being measured. The resulting data set hopefully retains enough of the original signal, in the presence, for instance, of noise which cannot be controlled/removed, to provide a scientifically meaningful measurement. While these mathematical steps are elegant and often quite powerful, a better approach would be to begin with an instrument that affects the measurement process as little as is feasible. Often astronomers assume that the biggest impediments to making any measurement lie in the need for greater sensitivity (e.g. larger apertures, better detectors, no telluric affects). In fact, the fundamental impediments often lay in the compromises made when building instruments and a general lack of understanding of instrumental performance issues due to inadequate characterization of many ground-based instruments in use today.

In the case of exoplanet spectroscopic measurements, instrumental stability and repeatability on both short and long time-scales are required for meaningful measurements. The time-scales involved are governed on the "short" end by the time for the transit itself (typically only a few hours) including especially the crucial ingress and egress periods for the transits, which may only last a few tens of minutes. On the "long" end the time-scales are related to the cadences of multiple repeat visits looking for confirmation of either an earlier measurement or some presumed exoplanet events/features (e.g. weather, volcanology). Stability here refers to anything in the system that can affect the measurement itself on the relevant timescales, including but not limited to: telluric atmospheric events, telescope pointing/behavior, instrumental flexure, noise, detector-based changes, and potentially many more. The key to spectroscopic exoplanet observations is to gather data with enough signal-to-noise such that the data reduction process can reliably recover the exoplanet signal from data which is dominated by many other sources of photons. In our experience, signal-to-noise per timestep per individual spectral channel well into the thousands is required to successfully obtain an exoplanet spectrum from a generic astronomical spectrometer. This requires a new approach to gathering the data on all but the brightest sources.

Based on our experience working with several astronomical spectrometers in the community, the following issues affect an astronomer's ability to reliably extract the exoplanet spectroscopic signal from the observations:

- The ability to detect and remove the telluric effects during the observations which vary non-predictably on multiple timescales.
- The ability to control the telescope pointing and manage the coupling of the light onto the slit or aperture of the system.
- The system throughput at an appropriate wavelength regime which is high enough that very high signal-to-noise ratios can be attained, but on a small enough telescope that the very brightest sources (i.e. nearby bright stars with transiting planetary companions) do not saturate the detectors.
- The changing light path through the instrument (on all timescales) and how that differentially affects the measurements as the changes occur.

3. OVERVIEW OF NESSI

3.1. Implementation of the NESSI Design

The solutions to the issues listed above lie in purpose-built, rather than generic, spectrometers. These new instruments can address the multitude of issues in a variety of ways. For NESSI, our choices rely on deploying a rapidly deployed, lithe design, simplified in as many aspects as possible, but addressing all the major functionailities required[14,15]. The major design choices which most fundamentally drive the design of NESSI are the following: a) infrared operations, b) stable optomechanical system design, c) active guiding, and d) rethinking how calibration is preformed so that a "staring" mode can be used.

The infrared operability provides NESSI with several advantages. First is the detection of molecular signatures, which are preferentially seen in exoplanet atmospheres, but only in the very coolest stars. This choice allows us to use a state-of-the-art Teledyne Hawaii 2048X2048 RG (H2RG) array, which provides both high-sensitivity and deep detector wells in a high-speed readout format. Active guiding for the system can then be accomplished in the optical, without loss of scientific light. In the case of NESSI, the optical implementation for autoguiding is provided by a red-sensitive E2V EMCCD detector, and the optics are chosen to preferentially perform autoguiding up to 0.9 microns and science from 1.0-2.5 microns. This will eventually allow us to characterize exoplanets transiting M dwarfs.

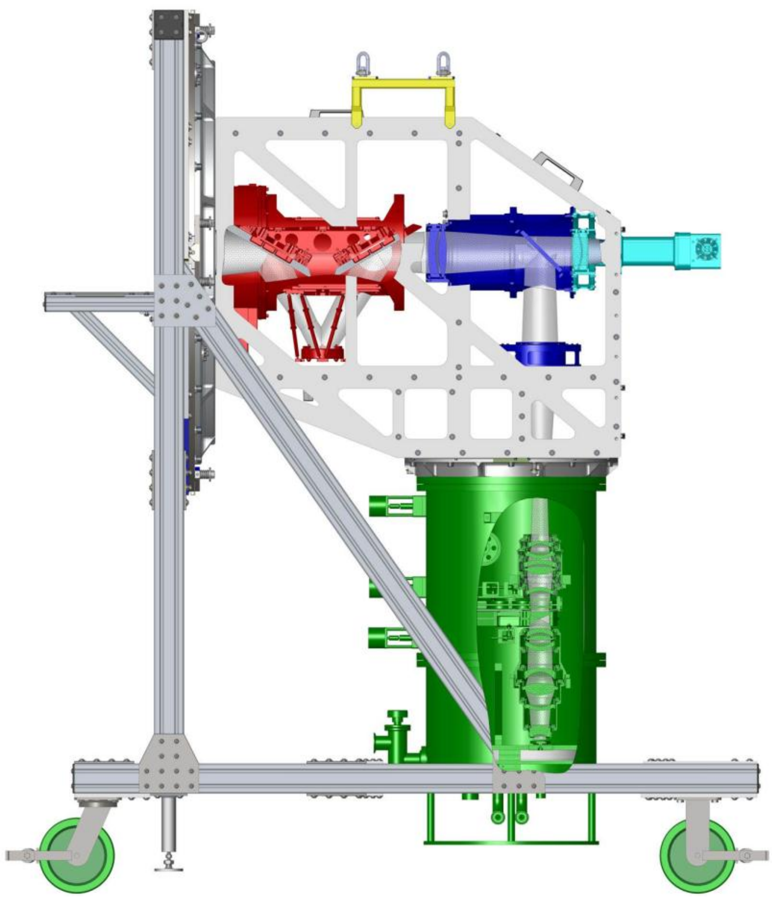

Figure 1: The NESSI instrument sitting on a servicing cart. Different functionalities of the system are color-coded (in the electronic version of this paper) as to function. In red (near the center left) is the derotator mechanism, in dark blue (near the center right) is the reimaging system, in turquoise (all the way to the right) is the optical guide camera, and in green (downward) is the cryostat with the cold multi-object spectrograph system. The darker grey/pale green wheels is the servicing cart, while the light grey and yellow are the support structure for the instrument while on the telescope.

To address stability issues, NESSI will be deployed on a Nasmyth port with a configuration that maintains the gravity vector in a fixed position with respect to the optics (Figure 1). In particular, the implementation supports a large field-of-view, which is advantageous for removal of telluric atmospheric features from the data while operating in a "staring" mode. For NESSI, we were able to design an optical system that will transmit a 12 arcminute field. This field allows from two to more than a dozen bright targets besides the exoplanet host star for the fifty-some brightest northern hemisphere transiting exoplanet fields we have examined. The field orientation is chosen to maximize the number of calibration targets, and maintained throughout the observations via a derotator system using a K-mirror.

While NESSI's autoguiding system is meant to maintain telescope system pointing and guiding throughout the observations, a reasonable question might well be posed: how does one maintain slit coupling to the incoming light simultaneously for all the stars in the field? In NESSI, a determination was made that apertures, rather than slits, would be used for the system. This has several advantages including: a) no differential coupling of the light as apertures are sized to accept over 98% of the light and not compromise spectroscopic performance, b) with the use of a derotator, the field pointing can be maintained throughout the observation, c) software offsets will be used for dispersion correction between the optical autoguider and the infrared spectrometer.

3.2. NESSI Specific Capabilities and Progress

We implement our solutions to the aforementioned challenges in the following specific ways in NESSI:

- Individual J, H, or K spectral coverage (by using grisms) at a resolving power of about 1100 for easy inter-comparison with space-based spectroscopy and to assess exoplanet atmospheric molecular constituents.
- Use of individualized cold multi-object masks over a field-of-view of 12 arcminutes so that from 2-3 to over a dozen calibrators can be characterized for each field, along with the exoplanet-star spectrum.
- Use of a red sensitive E2V CCD (out to 0.9 microns) with a 4 arcminute field-of-view and several-pixel point-spread-function for locating exoplanet host star and maintaining pointing.
- Simultaneous J-H-K spectral coverage at a resolving power of about 200 for comparison with space-based photometry and for "quick look" capabilities.
- Guiding at the 0.3 arcsecond precision for correcting telescope pointing during the transit observations. The red sensitive CCD will also allow NESSI to more easily acquire red targets like M dwarf host stars.
- Use of a derotator for the entire NESSI spectrometer field-of-view that allows us to select and maintain an angle on the sky most useful for an optimal selection and distribution of calibrators. The derotator specifications allow it to maintain the 0.3 arcsecond pointing stability for periods of several hours when used in concert with autoguiding.
- Spectrometer and mask design that allows for use of apertures, rather than slits, such that the throughput of a typical point-spread-function is >98% at all wavelengths and all field positions using a 3.0 arcsecond aperture. We will experiment with NESSI apertures in the size range of 4.0-6.0 arcseconds to determine optimal performance.
- Easily replaceable masks such that each field can utilize a precision cryogenic mask for observations. This decreases background and thus noise during the observations.
- Deployment on the telescope's Nasmyth port so that flexure issues and differential light coupling due to system motion can be minimized during a transit observation. For instance, wherever possible, concentric fittings are used to mount optical components. (See Santoro et al. 2012[15] for details.)
- Use of optimized coatings and a nearly 100% transmissive design so that a throughput of 25% or greater is achieved at all infrared wavelengths in the spectroscopic modes.
- Design of a cryostat by Universal Cryogenics that maintains vibrational and thermal stability (e.g. the liquid nitrogen tank runs the entire length of the up-looking vessel) throughout an observation.
- A design that is kinematic in the sense that it can be removed from the telescope and replaced in the same location via the use of registration pins and precision mounting plates.
- Use of a Teledyne H2RG array and ARC (Leach) electronics so that fast readouts of the entire array (or windowing in special circumstances) can be used for the observations.

To date, we have received nearly all the optics for the system, have built several of the optical mounts, have completed the testing cart, have begun assembling the autoguiding camera and derotator systems and the cryostat is ready for factory acceptance testing. Our last steps are the procurement of the electronics and detector, and assembly of the cryostat in the lab. Then all the components will be integrated and tested together in the laboratory before deployment at the telescope. Software development has been ongoing for the past 24 months, using a surrogate instrument (AMASING[16]) and components as they are available in the laboratory. In June 2012 we tested the autoguiding and derotator algorithms at the MRO 2.4m using AMASING and are confident of their capabilities under real-world use. First light for the system is scheduled for the late fall of 2012. Below several of the components that are presently available are shown in Figure 2.

Figure 2: A composite figure of NESSI components. Starting from the upper level/left and spiraling clockwise inward: a) the cold optics for the cryostat/spectrometer, b) the cryostat cold plate showing the aperture mask (top), filter wheels at center, and detector at bottom – the liquid nitrogen container runs the length of the back of the cold plate, c) mirror #2 in the K-mirror derotator – the back has been lightweighted, d) reimaging optics in their mount, e) a concave optic from the reimaging system before it is installed in its mount, f) the external shroud of the cryostat with several of the feedthrus showing, g) the first light optical-red image from the E2V EMCCD chip in a camera built by Finger Lakes Instruments.

3.3. NESSI Funding, Upgrade Paths and Access via Collaboration

NESSI funding has come from a combination of several sources. First, a NASA EPSCoR grant was secured in 2009 and has been used to support the team members. This grant has matching requirements for the university, and so a postdoc, two graduate students and a portion of the PI's summer salary were feasibly covered with the funds. Pledged money from the Magdalena Ridge Observatory's PI, who is the New Mexico Tech Research Vice-President, for the instrumentation hardware was secured in support of new instrumentation for the MRO 2.4m telescope. Additionally, work on the project was supplied by the MRO Interferometer professional staff toward design efforts. The total encompassed cost of the development and support of the NESSI instrument is in the $2.5-$3M range. Proposals for additional funding from NSF for some anticipated instrument upgrades and from NASA for scientific programs on exoplanets have been submitted and are pending.

We have anticipated a few upgrades to NESSI that will expand its science case beyond strictly exoplanet spectroscopy. In particular, NESSI has remarkable imaging capabilities (with 0.5 arcsecond per pixel resolution) across the entire 12 arcminute field of view. While backgrounds will be far too high to do wide-band imaging over this large of a field, it is possible to do slit spectroscopy (by creating a long slit and scanning across a distributed object) or pointed field observations with only the use of new aperture masks and some software planning. Another anticipated upgrade path, which was included in the NESSI cryostat design, is the use of narrow-band filters (10-50 nm widths) in the near-infrared. The NESSI cryostat has an additional 8-position filter wheel which can be used just for this purpose. Finally, there was not enough funding available to afford a science grade H2RG detector, and so there are hopes of purchasing one in the future as well. An NSF proposal was submitted to support narrow-band filters and the focal plane array; however the proposal was not successful.

Access for the use of NESSI for exoplanet or other work will be done on a collaborative basis with the NESSI PI and New Mexico Tech. NMT operates the MRO 2.4m as a cost center at the university, charging direct costs per night of observing time. Current nightly costs plus overheads for the MRO 2.4m are fairly reasonable and on the order of one week per month is available for faculty access at NMT. It is our hope in the future that NESSI will become a fully-supported observatory instrument at MRO, available publically for anyone using the MRO 2.4m facility.

4. CONCLUSIONS

NESSI will be one of many new exoplanet characterization instruments likely being built in the coming decade. We believe the key elements of NESSI's design philosophy will prove to be a fundamental driver for future instruments doing this type of work. At our current assembly, integration and testing pace, a late 2012 deployment at the 2.4m is being anticipated for initial commissioning work with NESSI. Thereafter, we hope to use this new NIR MOS as an exoplanet characterization instrument on the order of 30-40 nights per year. Initial observations with NESSI will help establish whether the above detailed design philosophy and the specific implementations of it in the NESSI instrument are robust enough to continue exoplanet characterization from the ground in future decades.

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REFERENCES

[1] Hugot, E., Ferrari, M., El Hadi, K. and 5 coauthors, "Active optics methods for exoplanet direct imaging. Stress polishing of supersmooth aspherics for VLT-SPHERE planet finder", Astronomy and Astrophysics, 538, 139 (2012).
[2] Galicher, R., Marois, C., Macintosh, B., Barman, T. and Koopacky, Q., "M-band Imaging of the HR 8799 Planetary System Using Innovative LOCI-based Background Subtraction Technique", Astrophysical Journal Letters, 739, 2, 41 (2011).

[3] Thomas, S. J., Poyneer, L., de Rosa, R and 8 coauthors, "Integration and test of the Gemini Planet Imager", Proc. of SPIE, 8149, 2 (2011).
[4] Mawet, D., Serbyn, E., Moody, D. and 7 coauthors, "Recent results of the second generation of vector vortex coronagraphs on the high-contrast imaging testbed at JPL", Proc. of SPIE, 8151, 45 (2011).
[5]Vasisht, G., Swain, M., Green, R. and Jeganathan, M., "The FINESSE Instrument: enabling 0.7-5.0 micron spectroscopy of extrasolar planets via precision spectrophotometry", Proc. of SPIE, 8442, these proceedings (2012).
[6]van Boekel, R., Betremieus, Y., Bouwman, J, et al., "The Exoplanet Characterization Observatory (EChO)", Proc. of SPIE, 8442, these proceedings (2012).
[7]Seager, S. and Deming, D.,"Exoplanet Atmospheres", Annual Reviews of Astronomy and Astrophysics, 48, 631 (2010).
[8] Swain, M., Deroo, P. and 10 coauthors, "A ground-based near-infrared emission spectrum of exoplanet HD189733b", Nature, 463, 637 (2010)
[9] Perruchot, S., Kohler, D., Bouchy, F. and 23 coauthors, "The SOPHIE spectrograph: design and technical key-points for high throughput and high stability" Proc. of SPIE, 7014, 17 (2008).
[10] Vogt, S., Marcy, G., Butler, P., and Apps, K., "Six New Planets from the Keck Precision Velocity Survey", Astrophysical Journal, 536, 2, 902 (2000).
[11] Thatte, A., Deroo, P. and Swain, M., "Selective principal-component extraction and reconstruction: a novel method for ground based exoplanet spectroscopy", Astronomy and Astrophysics, 523, 35 (2010)
[12] Snellen, I., de Kok, R., de Mooij, E. and Albrecht, S., "The orbital motion, absolute mass and high-altitude winds of exoplanet HD209458b", Nature, 465, 1049 (2010).
[13] Bean, J., Miller-Ricci Kempton, E. and Homeier, D. "A ground-based transmission spectrum of the super-Earth exoplanet GJ 1214b", Nature, 468, 669 (2010).
[14] Jurgenson, C., Santoro, F., Creech-Eakman, M. and 10 coauthors,"NESSI: the New Mexico Tech Extrasolar Spectroscopic Survey Instrument", Proc. of SPIE, 7735, 43 (2010).
[15] Santoro, F. and 14 coauthors., "Mechanical Design of NESSI: New Mexico Tech extrasolar spectroscopic survey instrument", Proc. of SPIE, 8446, these proceedings (2012).
[16] Schmidt, L. M., PhD Thesis, "AMASING: Aperture Masking and Speckle ImagiNG instrument", New Mexico Institute of Mining and Technology, Department of Physics (2012)