Spectroscopy of Exoplanet Atmospheres with the FINESSE Explorer

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ABSTRACT

FINESSE (Fast INfrared Exoplanet Spectroscopic Survey Explorer) will provide uniquely detailed information on the growing number of newly discovered planets by characterizing their atmospheric composition and temperature structure. This NASA Explorer mission, selected for a competitive Phase A study, is unique in its breath and scope thanks to broad instantaneous spectroscopy from the optical to the mid-IR (0.7 – 5 micron), with a survey of exoplanets measured in a consistent, uniform way. For 200 transiting exoplanets ranging from Terrestrial to Jovians, FINESSE will measure the chemical composition and temperature structure of their atmospheres and trace changes over time with exoplanet longitude. The mission will do so by measuring the spectroscopic time series for a primary and secondary eclipse over the exoplanet orbital phase curve. With spectrophotometric precision being a key enabling aspect for combined light exoplanet characterization, FINESSE is designed to produce spectrophotometric precision of better than 100 parts-per-million per spectral channel without the need for decorrelation. The exceptional stability of FINESSE will even allow the mission to characterize non-transiting planets, potentially as part of FINESSE's Participating Scientist Program. In this paper, we discuss the flow down from the target availability to observations and scheduling to the analysis and calibration of the data and how it enables FINESSE to be the mission that will truly expand the new field of comparative exoplanetology.

Keywords: exoplanet, atmosphere, chemical abundance, FINESSE, Explorer, atmospheric properties, survey, transit spectroscopy

1. INTRODUCTION

The FINESSE mission is a two-year, high-heritage, Earth-orbiting mission that dramatically expands the new field of comparative exoplanetology by probing the atmospheric composition and conditions of transiting exoplanets. FINESSE will systematically explore 200 newly discovered exoplanets worlds, ranging from Jovians to Terrestrials, by measuring their characteristics with molecular spectroscopy. FINESSE is the first mission dedicated to addressing two key exoplanet science goals: 1) measure the composition and temperature structure of exoplanet atmospheres and 2) trace the composition and temperature structure with longitude and time (Figure 1).

To measure exoplanet atmospheric composition and structure, FINESSE uses the proven, highly successful method of measuring the light curve produced by transiting exoplanet systems. This approach has revolutionized our knowledge on exoplanet atmospheres and is the leading method for characterizing exoplanet atmospheres and surfaces. Highlights in recent discoveries include the detection of molecular features, the observation of day-night contrasts, constraints on the vertical atmosphere structure, and a two-dimensional map of hot-Jovian dayside atmosphere [for a recent review see Seager & Deming 2010 and references therein; Majeau et al. 2012].

The field of exoplanets is ready scientifically and technologically to begin the next phase of detailed exploration of exoplanets as a class of objects: understanding the atmospheres of these new worlds. Surveys that find exoplanets can provide the planet mass and density together with an approximate temperature. Based on this limited information, we believe that these planets exhibit a huge variety, ranging from scorching gas giant worlds with a density similar to that of Styrofoam, to frozen, icy worlds, to worlds that probably have oceans of lava. Given Kepler's success and the continued ground-based effort to find even more planets, we have a large and growing target list; paradoxically, however, we know relatively little about these strange and varied cousins that form the extended family of planets to which our own Earth belongs.

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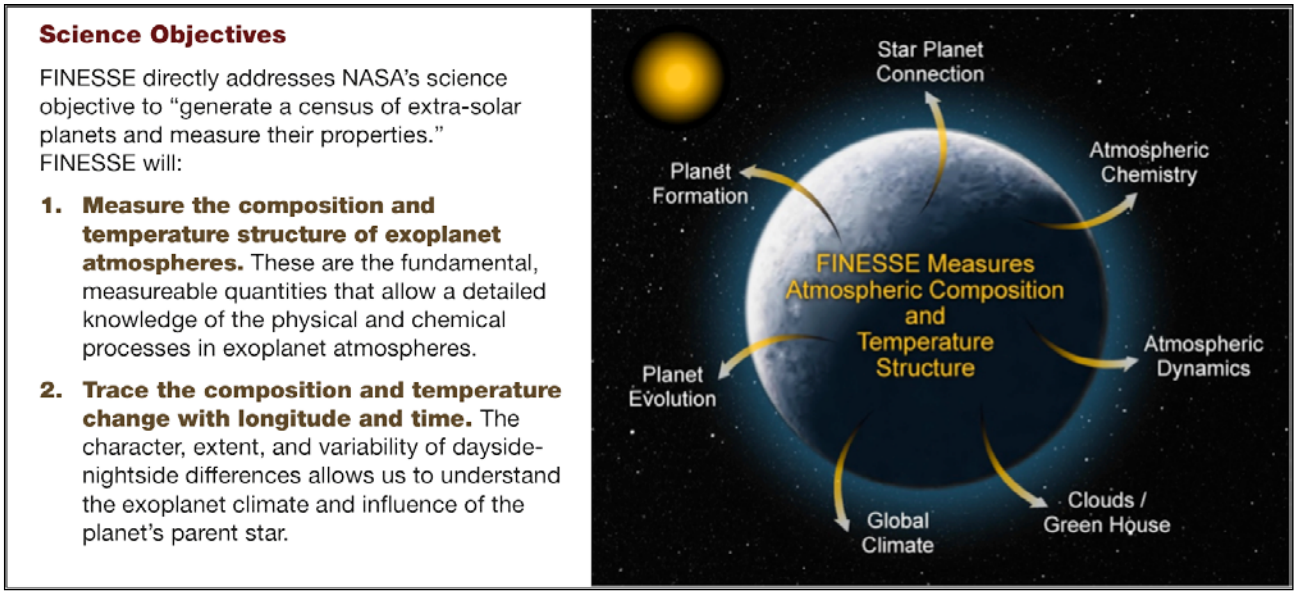

Figure 1. FINESSE probes atmospheric composition and temperature structure in a uniform, systematic way for 200 exoplanet atmospheres [left] and thus provides uniquely detailed information on many fundamental science questions [right].

1.1 Science

The FINESSE mission data set is unique in scope and breadth; this transformative set of measurements will give us a detailed picture of what other worlds are like. The temperature structure, atmospheric composition, chemical processes, planetary climate, planetary circulation, and weather are examples of the kinds of insights the FINESSE data set will provide. In some planets, FINESSE will be able to image atmospheric features such as large storms, analogs to the great red spot on Jupiter. The FINESSE data will revolutionize our understanding of exoplanets by bringing a level of detail that is akin to planetary science in the solar system. This will permit us to understand our solar system within the context of the extended family of planets. Part of the broad appeal of the FINESSE mission is that FINESSE takes the next step, scientifically, from discovery of exoplanets to exploring these alien worlds, within this decade.

1.2 Technology

FINESSE achieves high performance though optimized design, not new technology. The transit spectroscopy method has been demonstrated with Hubble and Spitzer instruments. The FINESSE mission implementation flows from the scientific objectives: to systematically characterize exoplanets as a class of objects by detection of molecular diagnostics. Significantly, FINESSE provides broad, simultaneous spectral coverage so that the data needed to characterize a transit event are all obtained in the same epoch; this removes any uncertainty due to astrophysical variability (either in the host star or the planet) that is intrinsic to combining data from multiple epochs. This also means that any differences seen in repeated FINESSE measurements can be confidently attributed to an astrophysical origin rather than to changes in the instrument. The optimization for stability affects every aspect of the mission; an example of this is the sun-synchronous terminator orbit which provides as stable thermal environment by minimizing the variations in Sunshine and Earthshine induced heating that can change instrument focus or other operational parameters. This level of detailed optimization for precision is required if measurements at different epochs or of different planets are to be meaningfully inter-compared. In the exoplanet area, there are numerous examples of lively scientific debate regarding the detailed methodology for correcting instrument systematic errors. The best way to resolve the situation is to design a build an instrument that is optimized for stable spectroscopic measurements; this may be the only way to generate the consensus needed for scientific progress. For example, experience with Hubble WFC3 shows that even changing the detector sub-array mode can affect the measurement of an exoplanet spectrum. For this reason, FINESSE uses a single, consistent detector readout mode for all measurements. New science possibilities such as imaging dayside atmospheric features place even greater demands on measurement stability – demands that are met by FINESSE. Ultimately, for understanding exoplanets as a class of objects, there is simply no substitute for a purpose-built, well-calibrated instrument that measures a large sample of exoplanets in a uniform way.

2. THE FINESSE SURVEY

2.1 FINESSE targets

FINESSE's main objective is to survey exoplanet atmospheric characteristics for each of three major planet categories of the "planetary family", including Jovians, Neptunians, and Terrestrials. FINESSE will cover a broad range of diversity including density, temperature, orbital eccentricity etc. enabling the first systematic census of exoplanet atmospheric properties.

FINESSE will operate in a sun-synchronous low Earth orbit. Much like the WISE Explorer mission, this was chosen for excellent thermal stability, and ease of mission observations, with one target viewed on each half orbit. The viewing angle of FINESSE during nominal operations keeps the telescope always pointed in the anti-sun direction and within a 40-degree cone from the telescope bore sight. This operational scenario allows access to more than 50% of the sky during its mission. To complete the FINESSE objectives, the FINESSE science team will choose confirmed exoplanet targets from the viewable sky spanning the known exoplanet parameter range. At the writing of this paper, there are 109 confirmed exoplanets available to FINESSE with targets in each planetary category; this satisfies the mission's threshold requirements and is an order of magnitude more than have been studied spectroscopically to date. In particular, existing ground-based transit discovery programs (such as Next Generation Transit Survey (NGTS), WASP, Super-WASP, HATNet, HATSouth and MEarth) have gained significant momentum in recent years and the trend is clearly developing for more sensitivity and more coverage, and hence more discoveries for the community. Given the fast rate of discovery [for the most recent confirmed planet count, see for instance www.exoplanet.eu], FINESSE will operate in a target rich environment well beyond the 200-target goal by its launch at the end of 2016.

2.2 Exoplanet spectroscopy

FINESSE measures the star-planet system light curve as a function of time; properties of the exoplanet are inferred by comparing portions of the light curve. This method has been employed extensively for photometry and spectroscopy with Hubble and Spitzer. The approach of exoplanet characterization based on comparing different portions of the system light curve was first demonstrated [6] with photometry in 2000, and it has even been extended to longitudinal light curves [2,7,8] and non-transiting planets [9,10]. Members of the FINESSE team developed methods for applying the technique to the problems of spectroscopic detection of molecules in exoplanet atmospheres with Hubble and Spitzer [1, 11-14].

Transiting planets with circular orbits have two "eclipse" events that modulate the system light curve: the "primary eclipse" (transit), when the planet passes in front of the parent star and the "secondary eclipse" (occultation), when the planet passes behind the parent star. A primary eclipse probes the planet's atmospheric transmission spectrum at the day-night terminator region. The secondary eclipse probes the planet's dayside emission spectrum (see Figure 2). For any target for transit spectroscopy, the planet must balance having a large enough atmospheric scale height to allow the light to pass through the atmosphere, while simultaneously having enough gravity to retain the atmosphere and not let it escape. Planets that are "hot rocks" and have lost their atmosphere are not amenable to characterization using primary eclipse measurements, but surface emission may be measured using secondary eclipse.

Once the stellar spectrum has been measured during secondary eclipse, it can be subtracted from any portion of the system light curve, enabling longitudinal changes in the planet's emission to be measured. In this way, FINESSE obtains the emission spectrum of the dayside, terminator, and nightside regions. In the terminator region, the atmosphere is probed in a unique way with nearly simultaneous transmission/emission measurements that, when combined, provide the strongest possible constraints for atmospheric characterization; the need for a combined analysis of primary/secondary eclipse spectra to find a self-consistent opacity source was recently demonstrated with Hubble/WFC3 observations of WASP-12b [5]. Atmospheric properties of the terminator region can then be used to provide additional constraints on the dayside and nightside emission spectra and, thus, improve our understanding of the planet as a whole. The ability of FINESSE to provide detailed knowledge about a planet's atmosphere from dayside to nightside is essential for understanding strongly irradiated planets, which have no analog in our own Solar System.

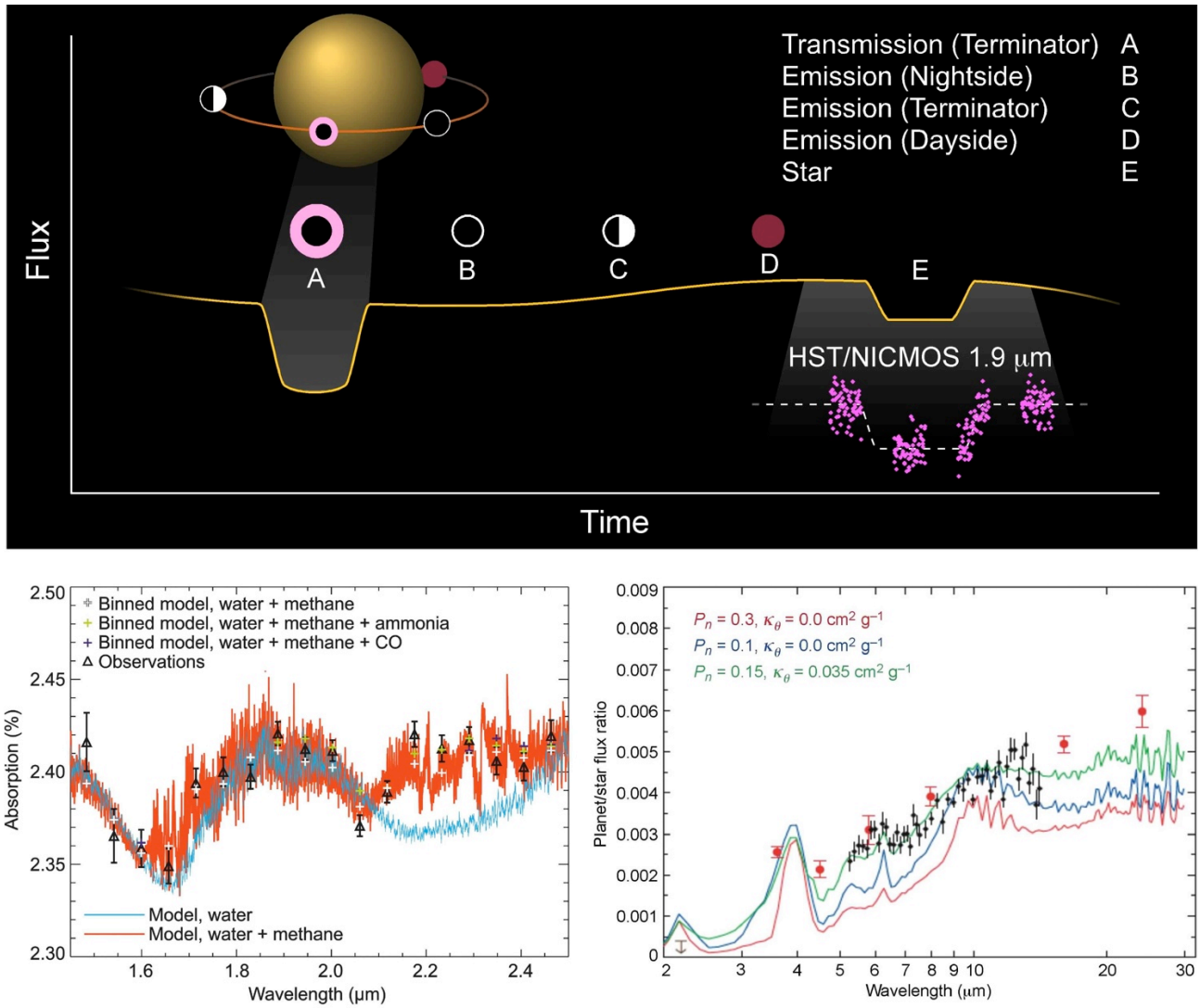

Figure 2. FINESSE will probe different regions of the exoplanet atmosphere based on measuring differences between portions of the system light curve. Discovery spectrum for methane [Swain et al. 2008] in an extrasolar atmosphere (transmission of terminator region) obtained by taking the difference between "in eclipse" and "out of eclipse" portions of the light curve when the planet passes in front of the parent star (lower left). The dayside emission spectrum of an exoplanet [Grillmair et al. 2008] obtained by measuring the change in the system light curve as the planet passes behind the parent star (lower right).

The FINESSE mission will probe the exoplanet composition and temperature structure from a single phase-curve measurement, or with multiple phase curve observations can characterize variations in atmospheric conditions. As such, FINESSE probes the atmosphere structure in great detail for various longitudinal regions and at different times for the same region giving FINESE the potential to detect an analog of the great red spot on Jupiter and to measure how the spot changes location and composition. The FINESSE measurement is optimized to provide:

1. Instantaneous broad wavelength coverage from 0.7 – 5 micron with an average spectral resolution > 30 covering multiple molecular absorptions that allows the determination of the instantaneous state of the atmosphere for the different longitudinal spectra.

2. A combination of nominal and calibrated stability for molecular exoplanet atmosphere spectroscopy with instrument stability better than 100 parts-per-million, allowing for a cross-calibrated comparison of the different spectra [over time or for different longitudinal regions] (Figure 3).

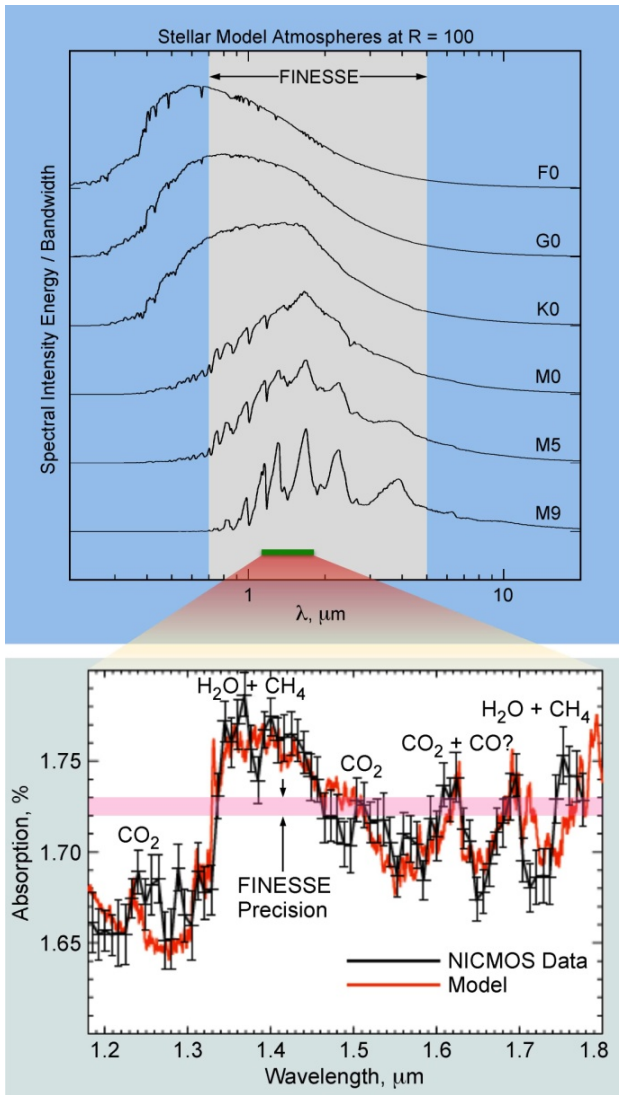

Figure 3. (Top) The spectral coverage of FINESSE is selected to maximize signal-to-noise (by including the peak of the stellar spectral energy distribution) and to maximize the number of molecular features. (Bottom) FINESSE 100 ppm precision (pink band) enables robust molecular detection. FINESSE expands spectral coverage compared to Hubble [14].

Compared to missions like Spitzer or the Hubble Space Telescope, FINESSE is targeting in a single-shot the broad spectral range needed, for the peak wavelengths of the stellar and planetary signal, with a purpose-built instrument with only a single science observing mode.

2.3 Diagnostic molecules

The FINESSE design is optimized to produce high sensitivity for detecting molecules. The FINESSE science team identifies four key molecules, which will be retrieved for each of the observed planets, namely H_2O, CH_4, CO_2 and CO together with the temperature structure. For the baseline science investigation, the spectral retrieval focusing on these key diagnostic molecules will be done in a uniform and consistent fashion by the science team. In addition to these key molecular species, the FINESSE pass band covers molecular signatures of various other molecules, which could be present in the various atmospheres depending on the conditions. While no retrieval is in the baseline for these additional molecules, those molecular species will be examined by the science team on a best effort basis and the spectra at full spectral resolution will be available to the community on a rapid pace for in-depth, individual target, investigations. In Table 1, we provide a summary table of the key diagnostic molecules and their absorption locations for FINESSE together with a list of potentially, depending on planet characteristics, important other molecules.

Table 1. Molecules and locations of their prominent bands targeted by FINESSE.

	Molecule	0.7–5.0 μm
Key Diagnostic Molecules	H_2O	0.82, 0.94, 1.13, 1.38, 1.9, 2.69
	CH_4	0.79, 0.86, 1.65, 2.2, 2.31, 2.37, 3.3
	CO_2	1.21, 1.57, 1.6, 2.03, 4.25
	CO	1.57, 2.35, 4.7
Additional Possible Molecules	C_2H_2	1.52, 3.0
	HCN	3.0
	O_3	4.7
	O_2	0.76, 1.27
	NH_3	0.93, 1.5, 2, 2.25, 2.9, 3.0
	C_2H_4	3.22, 3.34
	H_2S	2.5, 3.8
	SO_2	4
	N_2O	2.8, 3.9, 4.5
	TiO	0.7–3.5
	VO	0.7–2.5

During the phase A investigation, a spectral retrieval code was developed by one of the science team members (C. Griffith) based on an extension of the techniques used to analyze a combination of Hubble and Spitzer data for the emission spectrum of HD 209458b [13]. The approach is tailored to the retrieval of the four key diagnostic molecules and is based on picking specific wavelength windows that optimally couple to opacity bands for these molecules. If selected, the retrieval code will be optimized during the development of the mission to incorporate the latest innovations in exoplanet retrieval.

3. AN OPTIMIZED SURVEY INSTRUMENT

FINESSE incorporates the lessons learned from the exoplanet characterization heritage measurements such to become an optimized survey instrument. There are five key unique qualities:

1. **Sensitivity to molecules without the need for post-processing:** No "decorrelation" is required for molecular detection: FINESSE is designed to be void of systematic errors above the 100-ppm level so that molecular bands are detectable nominally.
2. **Broad continuous spectral coverage:** FINESSE provides broad, continuous spectral coverage with 100-ppm precision encompassing multiple molecular bands (see Table 1).
3. **Long-term stability**: Through the use of regularly scheduled calibrator targets, FINESSE has the ability to maintain photon-noise limited measurement precision for the duration of the mission.
4. **Large, uniformly measured sample:** The FINESSE survey of a large number of planetary atmospheres, measured in a uniform way, provides a sound basis for comparative planetology, which requires both a large sample and a consistent measurement method. Having a uniform and precise measurement method for the entire survey sample removes the question of systematic instrument effects from the interpretation of differences between planets in the sample.
5. **Bright target capability:** FINESSE has the capability to observe targets that would saturate other instruments. There are many bright current and future exoplanet targets; these enable ground-based follow-up (at wavelengths where the Earth's atmosphere is transparent) and high-resolution spectroscopy with future instruments.

The payload itself, though tailored for the FINESSE survey, significantly leverages flight-proven elements. In particular, the telescope is a near-copy of the Responder-1 telescope flown in 2009, and the spectrometer is a scaled version of the highly successful M3 spectrometer aboard Chandrayaan-1 flown in late 2008.

4. SYNERGY WITH JWST

FINESSE and JWST are mutually complementary missions, with FINESSE optimized for near-IR exoplanet spectroscopic survey of a large population of the exoplanet family, and JWST best suited for mid-IR pointed observations of a few high-priority targets. FINESSE complements JWST by providing scientific context only possible through a systematic survey. Additionally FINESSE complements JWST wavelength coverage and can provide calibration validation.

Target Selection: FINESSE will identify the most interesting candidates for an investment of time with detailed JWST observations. FINESSE prevents JWST from "shooting in the dark". Identifying good candidates for JWST is an important function for FINESSE; this will prevent JWST from expending valuable time on targets which seem exciting, based on mass and temperature only, but which are not good candidates for atmospheric characterization. Recently, there is an excellent example of this situation associated with the warm super Earth GJ 1214b. The discovery of 6.5 M_E GJ 1214b [15], by the ground-based MEarth survey [16], was a much noted, exciting discovery for exoplanet researchers worldwide. Theoretical models were rapidly constructed that showed a variety of possibilities for spectral features ranging from relatively easy to detect to completely undetectable, depending on the mean molecular mass of the planet's atmosphere. Numerous teams undertook follow-up observations with Hubble, Spitzer, and ground-based facilities. The somewhat disappointing result of this considerable effort was the determination that the Super Earth GJ 12314b has a flat, featureless spectrum [17]. FINESSE can identify the most promising candidates, with detectable spectral modulation, for follow up by JWST and other instruments.

Science Context: FINESSE will provide an understanding of atmospheric properties of exoplanets that spans this class of objects; JWST measurements of specific objects can then be placed in a larger scientific context. Providing this larger science context requires a purpose-built survey mission. FINESSE is optimized for high-precision, uniform (with a single instrument configuration) measurements of molecules, with sensitivity to variations in both longitude (dayside to nightside) and time (global climate change). The wavelength range covered by FINESSE (0.7–5.0 μm) contains multiple bands of the key diagnostic molecules (H_2O – 6 bands, CH_4 – 7 bands, CO – 3 bands, CO_2 – 5 bands) that probe both the C and O elemental abundances and the role of equilibrium and non-equilibrium chemistry. Coverage of multiple molecular bands improves temperature profiles and abundances derived from spectral retrieval. In addition, FINESSE's uniform measurements make the scientific interpretation of spectral changes as a function of target, longitude, and time highly robust. In short, FINESSE is optimized for comparative exoplanetology with a large sample of planets.

Wavelength coverage: FINESSE covers the near-IR while JWST offers the unique capability of exoplanet characterization in the mid-IR. This complementary nature of the two missions can be seen in Figure 3, which shows the excellent performance of the JWST/NIRSPEC spectrometer for wavelengths longer than 3 μm. The size of the JWST telescope does not have an advantage in the near-IR due to instrument systematics and bright-object saturation. The numerous possible observing modes and instrument configurations that JWST offers provide the capability to customize the observation to a particular planet, but may complicate the comparison with other measurements made with different instruments or modes. Although the mid-IR is not as rich in the number of molecular bands of key diagnostic molecules that are present in the 0.7–5.0 μm region, the mid-IR is a good wavelength region to characterize cooler planets. By working together to cover a large survey in the near-IR and pointed observations of specific high-value exoplanets in the mid-IR, the combination of FINESSE and JWST will offer the best available picture of exoplanet atmospheres.

Calibration Validation: Another important way that FINESSE complements JWST is in calibration and identification of possible instrument systematics. Experience with the Spitzer IRAC and IRS instruments and with the Hubble NICMOS and WFC instruments shows that pushing instruments outside the original design specifications, while possible, produces measurements that contain systematic errors. The overwhelming evidence is that general purpose instrumentation, with no tractable specification on measurement stability that is applicable to infrared exoplanet spectroscopy, will possess systematic errors.

Additionally, the evidence suggests that learning how to correct the systematic errors, or even identify the appropriate parameters, is a difficult process and achieving scientific consensus can be problematic. Over 200 Hubble orbits have been expended on NICMOS and WFC3 exoplanet spectroscopy and the community is still struggling to reach an understanding of how these general purpose instruments really operate for high dynamic range measurements. The most likely scenario for JWST instrumentation is that there will be similar experiences. Further, JWST instruments are very complex and different modes, including reading with different subarray sizes, of the same instrument may have different kinds systematics (as is the case for WFC3 and NICMOS). It is typical for measurements to be affected by multiple sources of systematic error, which simultaneously operate on a variety of time scales (e.g., the ramp effect, pointing errors, charge trapping, instrument optical state vectors, and so on). Past debate about Hubble and Spitzer measurements occurred because of the absence of "ground truth" measurements. FINESSE can play an important role for JWST by providing the "ground truth" measurements for selected shared targets. The calibration role that FINESSE can play for JWST is especially important for characterizing the most demanding targets – planets that are Earth analogs. The current schedule would have FINESSE and JWST operating during the same interval, providing excellent opportunities for joint simultaneous observation of targets, which is ideal for cross-calibration. By providing calibration measurements, FINESSE can save JWST and the community a great deal of time and significantly enhance the efficiency and science impact of what will be the world's premier astronomical facility.

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