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Response to Request for Information:
THESIS – the Terrestrial and Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft

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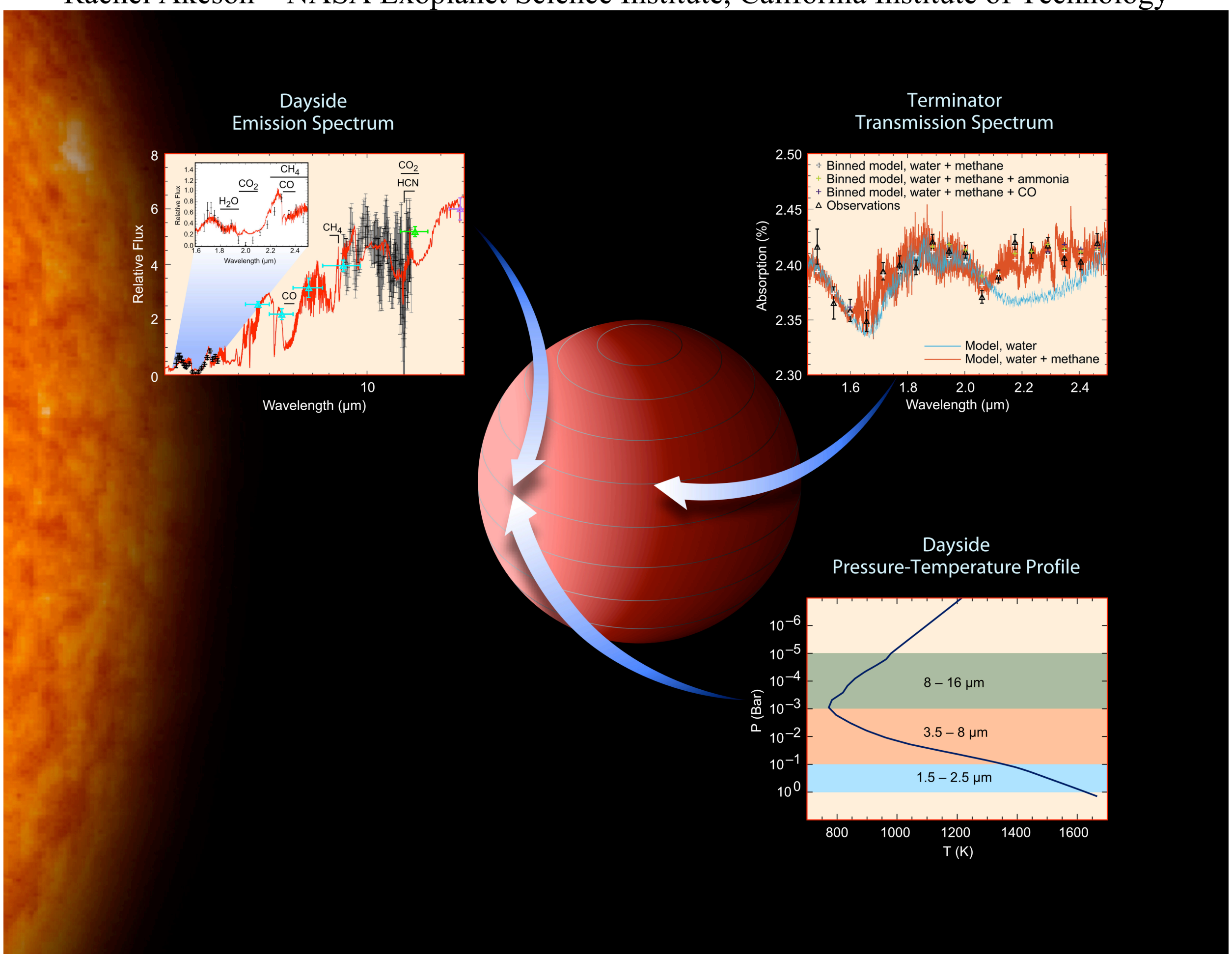


Understanding composition, chemistry and dynamics in exoplanet atmospheres.

Executive Summary

1. **Concept Name:** THESIS – the Terrestrial and Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft
2. **PI and Institution:** Mark R. Swain – Jet Propulsion Laboratory
3. **Description:** THESIS is a moderate-class space mission that will characterize exoplanet atmospheres via molecular spectroscopy.
4. **Key Science Questions:**
    a. What are the conditions, composition, and chemistry of exoplanet atmospheres?
    b. How do dynamics affect atmospheric composition and chemistry?
    c. Are biologically important molecules present in habitable-zone rocky or ocean worlds?
5. **Measurements to be made:**
    a. Primary and secondary eclipse events in transiting exoplanet systems at moderate resolution spectra (R~2000).
    b. Light curve measurements of transiting and non-transiting exoplanets with moderate spectral resolution.
    c. Repeated measurements to characterize short-term and long-term variability.
6. **Mission description:**
    a. 1.4 m telescope
    b. Wavelength range 2-to-14um (HgCdTe & Si:As BIB arrays)
    c. Falcon Launch
    d. L2 Orbit
    e. 3-yr lifetime
7. **Technology Drivers:**
    a. Fine Pointing Mirror
    b. Mechanical Cryocoolers
8. **Organization, Partnerships and Status:**
    a. Industrial partner is not selected.
    b. THESIS recommended by ESA EP-RAT for internal study by ESA.
9. **Status/Schedule:**
    a. Could be started immediately.
    b. THESIS requires no pre-mission technology development.
10. **Cost:**
    a. Total cost = $520 million (not including launch vehicle)

1. Introduction and Background

Detection of molecules in an exoplanet atmosphere has recently been demonstrated with the Hubble and Spitzer Space Telescopes for a transiting hot-Jupiter exoplanet. Because molecules serve as probes of an exoplanet atmosphere and allow us to answer fundamental questions about the temperature, composition, and chemistry, molecular spectroscopy is emerging as the most powerful tool available for characterizing exoplanet atmospheres. To date, water (H_2O), methane (CH_4), carbon dioxide (CO_2), and carbon monoxide (CO) have been detected via infrared spectroscopy (Fig. 1); H_2O, CH_4, and CO_2 have potential prebiotic or biological significance, and thus their detection in a hot-Jupiter atmosphere is an important step towards the eventual characterization of habitable-zone planets, including searching for biomarkers. The detection of molecules in both primary and secondary eclipses (which probe the terminator region and the dayside, respectively) has allowed some degree of longitudinal localization of knowledge about the atmospheric conditions, while the detection of CO_2 has raised the possibility that non-equilibrium chemistry may play a significant role in establishing the atmospheric radiation balance. By recovering the pressure-temperature profile and determining whether the atmospheres are in radiative equilibrium, we can estimate the radiative-forcing of the atmospheric dynamics and the redistribution of heat. The detection of spectroscopic variability presents both an opportunity and a challenge that has important ramifications for any future exoplanet characterization mission. *Perhaps the most surprising aspect of the recent results is the realization that today, with existing instruments, we can begin to answer the detailed questions about exoplanets that are only possible with molecular spectroscopy.* The recent results prove beyond doubt that (1) molecular spectroscopy is an essential tool for characterizing the composition, structure, and dynamics of exoplanets and (2) fully exploiting the potential of molecular spectroscopy of exoplanet atmospheres requires a dedicated mission optimized for this purpose.

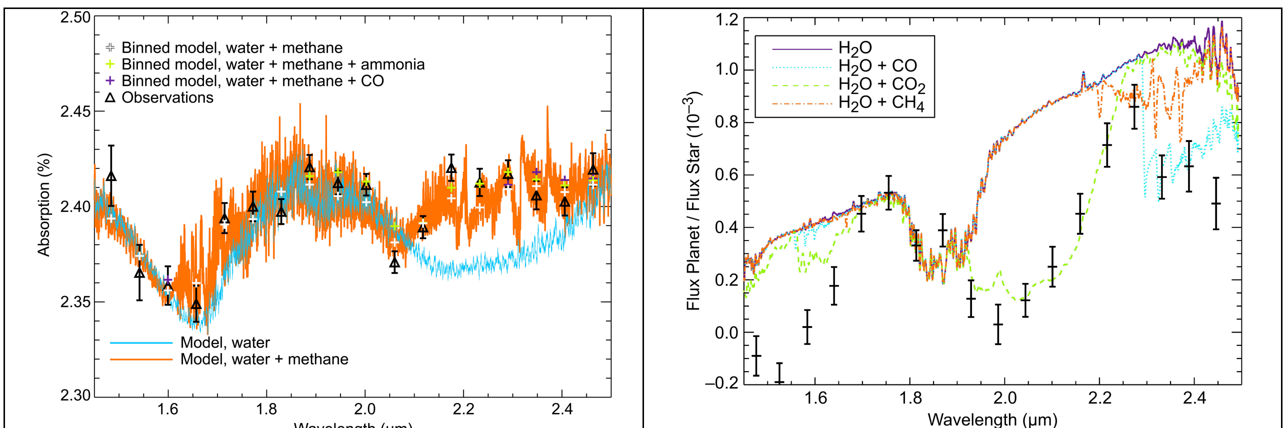


Fig. 1 **left:** A transmission spectrum (primary eclipse) of the terminator region of HD 189733b, showing the presence of water and methane (Swain et al. 2008). **right:** An emission spectrum (secondary eclipse) of the dayside region of HD 189733b, showing the presence of water, carbon dioxide, and carbon monoxide (Swain et al. 2009). Taken together, these spectra probe how the atmosphere changes from the hotter dayside to the cooler terminator regions. These results show the maturity of exoplanet molecular spectroscopy. The calibrated precision of these measurements is ~1 part in 10,000, while the largest effects of molecules at these wavelengths are ~ 1 part in 1000.

THESIS is a dramatically new and completely unique concept for an exoplanet characterization mission. Rather than spatially separating an exoplanet from its parent star, THESIS spectrally separates the two by compiling a spectral time series of the spatially unresolved extra-solar system. This approach requires that THESIS's optical system be extremely stable, but eliminates the exquisitely high contrast ratios required by missions that rely on spatial separation. Flying in an L2 orbit and built around two moderate-resolution infrared spectrometers fed by a 1.4-meter telescope, THESIS is a medium-class mission and would be implemented using simple, low-risk, flight-proven technology. THESIS can determine conditions on worlds where life might exist by identifying pre-biotic molecules on habitable-zone planets. By systematically characterizing many worlds around other suns, THESIS will deliver transformational science of profound interest to both professional astronomers and the general public.

2. Key Science Goals

2.1 Science Objectives

Molecules have recently been detected via infrared spectroscopy in an exoplanet atmosphere; this was accomplished using the "combined light" method in which temporal changes (e.g. during a primary or secondary eclipse) are used to infer properties of the exoplanet atmosphere. With the benefit of hindsight, we now understand that exoplanet molecular spectroscopy has been feasible with both Spitzer and Hubble for several years. However, the calibration requirements for a "molecular abundance grade" spectrum of an exoplanet are substantial, and it has taken the leading groups some time to develop adequate calibration methods. To give an approximate sense of the difficulty of the problem, for molecular spectroscopy in a hot-Jupiter type planet, one needs to obtain a dynamic range of ~1000 in the Spitzer bands and a dynamic range ~10,000 in the near-infrared bands over an observational time span of several hours. Given the bright host stars of many transiting planets, the desired dynamic range limits (set by photon, detector, and background noise considerations) are frequently higher, but the measurement dynamic range is limited by systematic errors (e.g. telescope pointing). Current calibration methods identify and remove instrument systematic errors; this has been highly successful, and these techniques now permit measurements that are very close to the photon-noise limit. Development of these calibration methods is an ongoing process, and it is likely that both a nightside spectrum and a spectrum of a non-transiting planet will be demonstrated in the near future.

Exoplanet molecular spectroscopy can answer fundamental questions concerning the nature of a planet's atmosphere and, by allowing the determination of elemental abundances, it can constrain the formation/evolution history. In the case of transiting planets, the primary eclipse sequence is used to obtain a transmission spectrum, while the secondary eclipse is used to obtain a dayside emission spectrum (Fig. 1); the light-curve can be used to obtain the emission spectra for disk-averaged views around the planet. The emission spectrum is sometimes termed an "emergent" spectrum because molecular signatures can appear either in absorption, emission, or both, depending on the shape of the pressure-temperature profile and the molecular vertical mixing ratio. This complexity, together with the potential for overlapping molecular bands, means that the spectra can be understood only through comparing them to detailed atmospheric models. These models depend on accurate molecular opacity data, and existing exoplanet spectra are reaching the limitations of our current knowledge of opacities. Spectral retrieval methods and forward models are used to infer the presence and abundance of specific molecules and, in the case of an emission spectrum, the pressure-temperature profile; this can lead to a natural ambiguity (in the case of an emission spectrum) between composition and temperature. Once the composition and temperature structure has been determined, knowledge of the atmospheric chemistry is inferred from the abundance estimates and vertical mixing ratios of individual molecules; for example, if the mixing ratio of CO_2 is higher than would be expected from purely equilibrium chemistry, a non-equilibrium chemistry mechanism (such as photochemistry) may be needed to explain the additional CO_2.

The data needed to answer the detailed questions of exoplanet characterization are relatively simple to obtain. We need:

1. **Broad, instantaneous spectral coverage** from approximately the visible to the mid-infrared where the data are obtained simultaneously. Broad wavelength coverage enables resolving the temperature/composition ambiguity in an emission spectrum; simultaneous measurement of wavelengths allows dynamical variability to be characterized and understood.
2. **Excellent intrinsic stability**. High-stability is needed for any exoplanet measurement. High-stability for periods of hours permits primary and secondary eclipse measurements. Achieving high-stability over periods of days, weeks, and months uniquely enables measurements of non-transiting planets and atmospheric variability.

The spectral resolution need not be high – a spectral resolution of a few hundred is adequate. The measurements should be photon noise limited (or background noise at the longest wavelengths); this implies stable, purpose-built instruments operating from space. A 1.4 m telescope enables dramatic scientific progress and is capable of probing super-Earth-type planets (both transiting and non-transiting) in the habitable zone around nearby M dwarfs. Regular calibrator measurements (as was done with the IRS instrument on Spitzer) make it possible to extend the photon-noise-limited calibration period beyond a single source; this is crucial for spectroscopy of non-transiting planets or for understanding long-term variability.

THESIS and JWST will provide highly complementary observations of exoplanets. For specific wavelength bands, JWST will provide the highest possible signal-to-noise (SNR) spectra possible for transiting planets. THESIS will provide the broad, simultaneous spectral coverage together with the stability needed for characterizing non-transiting planets and variability. This provides a natural synergy between the missions, with each mission making a unique and important contribution. With a 6 m primary mirror, JWST will have 4x more SNR than THESIS (all other things being equal) for measurements reaching the photon noise limit. However, THESIS acquires the 2–14 μm spectrum simultaneously at all wavelengths (something that cannot be done with JWST without rotating filter wheels). Because the THESIS spectrometer configuration does not change (no filter wheels in the spectrometer to change grisms), THESIS has the ability to achieve a photon noise-limited calibration that lasts the duration of the mission, making THESIS the ideal instrument for comparing spectra made days, weeks, or months apart. This ability to meaningfully compare spectra made at widely separated intervals is unique to THESIS and enables the characterization non-transiting planets and atmospheric variability.

2.2 Expected Significance

Exoplanet molecular spectroscopy has exceptional breadth and depth in terms of the questions that can be addressed. In the case of transiting planets, the spectra of different regions of the atmosphere can be obtained (via primary and secondary eclipse today – see Fig. 1); this allows the composition of the terminator region to be compared to the hotter dayside region. Where Hubble and Spitzer have both observed the same exoplanet, one can construct a composite spectrum with broad spectral coverage (see Fig 2.); this type of spectrum probes the atmosphere over a wide range of pressures, provides powerful constraints for models, and allows some molecules to be detected in multiple bands. Extending these kinds of measurement to non-transiting planets should be possible given stable, well-calibrated, space-based instruments; light-curve photometry of a non-transiting planet has already been demonstrated with Spitzer (Harrington et al. 2006). While extending these techniques to non-transiting planets provides a significant increase in the number of possible targets, transiting planets provide special opportunities for characterization. For example, the secondary eclipse ingress/egress portions of a transiting light curve can be used to search for spatial structure (e.g. detecting a spectral difference due to the presence of the hot-spot displaced by zonal winds). Temporal variability has been detected (see Fig. 2); whether this is due primarily to changes in temperature or changes in composition is unknown. However, the emergence of significant variability raises questions about the validity of the "composite spectrum". As we look forward to characterizing exoplanets via molecular spectroscopy in the 2010-2020 decade, we identify the following **key questions:**

- What is the atmospheric composition and temperature structure?
- Does non-equilibrium chemistry play a significant role in determining atmospheric composition?
- What significant dynamical processes are present, and do they influence atmospheric composition and chemistry through mechanisms such as quenching or vertical transport?
- What is the extent and origin of temporal and spatial variability?
- What are the elemental abundances, and how do they constrain the formation and evolution histories?
- What are the conditions on habitable-zone "super-Earths," and is there potential for generating and sustaining life?
- What do exoplanets reveal about the origin, evolution, and destiny of the planets in our solar system?

These key questions can be answered by THESIS using existing technology and proven methods. Answering the questions broadly for a large sample of exoplanets will require a dedicated mission. THESIS is completely unique in its ability to obtain photon-noise-limited spectra that can be compared in an absolute sense over a period of years. This capability permits emission spectroscopy of both transiting and non-transiting planets and will allow THESIS to characterize the nearest habitable extrasolar planet to Earth, which likely orbits an M dwarf in a non-transiting configuration.

2.3 Enabling Precursor Science

Measurements of bright exoplanet systems with Hubble and Spitzer are directly relevant to THESIS and have demonstrated:

- That exoplanet molecular spectroscopy is possible.
- Spectral-photometric calibration with both Hubble and Spitzer at very nearly the theoretical noise limit.
- Spectral retrieval of temperatures structure, composition, and molecular abundances.

- The need for broad spectral coverage (sampling a wide range of atmospheric pressures) to resolve the ambiguity between temperature and composition in interpreting emission spectra.
- The presence of significant variability in some planets.
- The possible role of non-equalibrium chemistry in determining the abundance of molecules that establish the atmospheric radiation balance.

In addition, exoplanet spectroscopy with both Hubble and Spitzer has resulted in an important realization about telescope size. Small telescopes (~ 1m) have a large discovery space for exoplanet spectroscopy using the combined-light technique because the observable scales as the square root of the number of photons in the photon-noise limit. Thus, everything else being constant, larger telescopes have a sensitivity advantage that scales as diameter, not area. To illustrate the potential for small telescopes, the Hubble detection CH_4 required a low duty cycle, which effectively reduced the Hubble telescope aperture to ~ 70 cm.

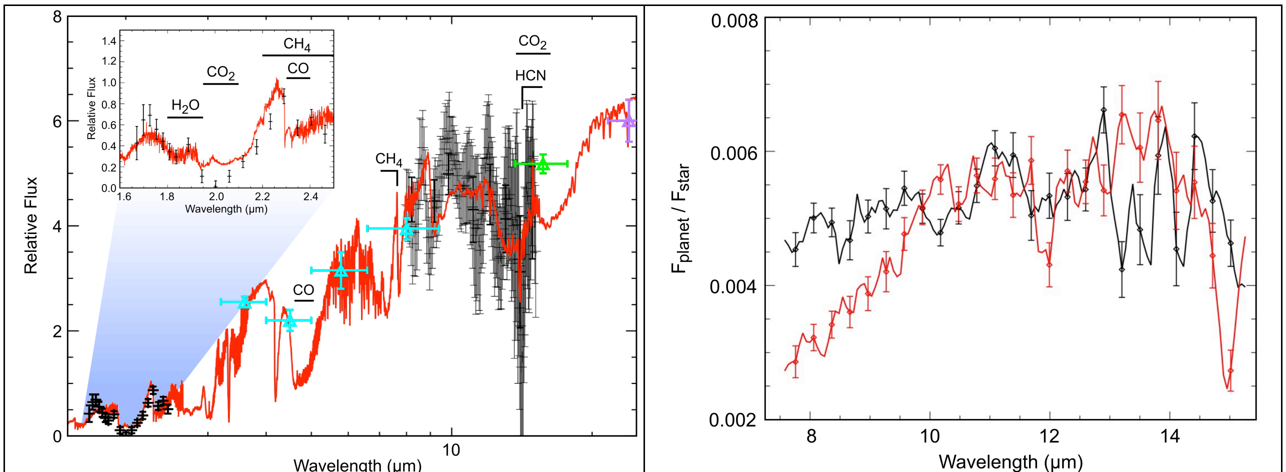


Fig. 2 **left:** A composite Hubble/Spitzer dayside spectrum for the hot-Jupiter HD 189733b, together with Spitzer photometry data and a model by Tinetti. The broad spectral coverage shown here probes the atmosphere from about 1 bar to about 10^{-6} bar and provides powerful constraints on the dayside pressure-temperature profile and atmospheric composition. The near-IR spectrum is from HST (Swain et al. 2009), the mid-infrared spectrum is based on data obtained by Grillmair et al. (2007); the light blue, green, and purple photometry points are from Charbonneau et al. (2008), and Deming et al. (2006), respectively. **right**: an analysis of data obtained by Grillmair et al. (2008) showing two spectra, taken 4.4 days apart, with significant differences around 8 μm; the implied variability emphasizes the need for simultaneous spectral coverage for the near-infrared to the mid-infrared.

3. Technical Overview

3.1 Mission Description

THESIS is a high-capability, low-risk approach to the study of exoplanets. Elegant in its simplicity, THESIS requires no new hardware technology or exotic optics with high-precision figures. THESIS measurements will be at or very near the photon noise limit. In this limit, the signal-to-noise ratio of the star+exoplanet system light curve scales as the square root of the number of photons. This has important consequences: in particular, for a given spectral bandwidth, sensitivity increases as telescope diameter, not as telescope area. Thus, with a 1.4-m primary mirror, THESIS can achieve a signal-to-noise ratio only a factor of four less than JWST. THESIS therefore emphasizes instrument stability and absolute calibration, not aperture size. The science instrument is straight forward and features no moving parts; it could be based on the ASPIRE mission moderate resolution (R=2000) spectrometer with a wavelength range of 2–14 μm. The spectrometer dispersion is determined so the focal plane array (FPA) is photon noise limited in every pixel for solar-type stars up to some distance (~100 pc). In this regime, the spectrum can be averaged to the desired spectral resolution to achieve greater SNR. No moving components are required to change spectral resolution, hence the instrument has only one observing mode (full spectral resolution). This increases instrument stability and simplifies the calibration process.

Calibration of THESIS will be accomplished by monitoring a calibrator network throughout the mission life. A fine-pointing mirror (FPM) in the science instrument allows precise, repeatable placement of the science and calibration targets. Otherwise unused visible light, imaged onto a CCD, provides the basis for fine-pointing mirror control At the shortest wavelengths and the lowest spectral resolutions, THESIS has the potential to achieve a measurement dynamic range of $\sim 10^5$. Figure 1-4 shows the photon-noise-limited dynamic range for low spectral resolution with THESIS. Photometry with a dynamic range of ~5000 at 2 μm is possible for a 12th magnitude G star, making the photometric study of exoplanets in the Kepler field an important part of the THESIS mission.

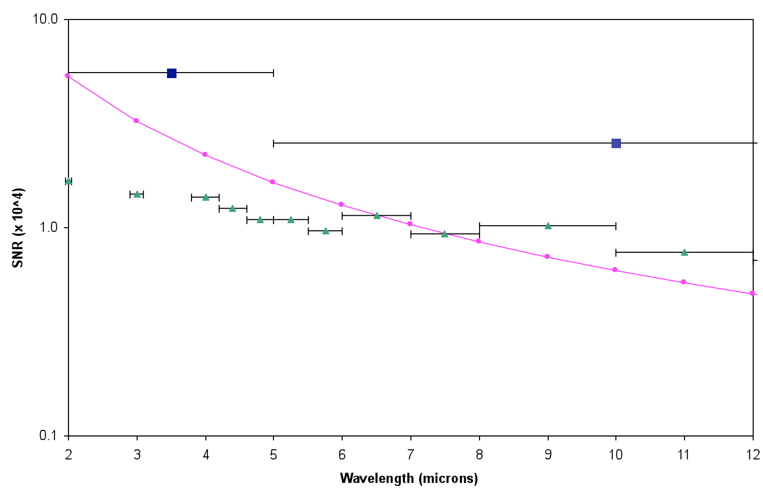


Figure 1-4. THESIS is extremely sensitive and capable of the high-dynamic-range spectroscopy necessary to detect pre-biotic molecules in habitable-zone exoplanets. Above is shown the dynamic range possible in 1 hr of integration with THESIS in the two spectroscopy modes for a solar-type star located at a distance of 100 pc. In blue are photometry SNRs. In green are SNRs for spectra binned to $\Delta\lambda/\lambda$ ~sized to optimally detect H_2O. In purple are SNRs for $\Delta\lambda$ = constant. The horizontal spans denote the bandwidth for binning.

Calibration: Calibration in THESIS accomplishes two objectives. First, it corrects any residual pointing error (see Figure 1-4; see Swain et al. 2007 for detailed methods description) and thus provides redundancy for the FPM performance. Second, calibration establishes the long-term calibrated stability through repeated observations of a calibrator network. Significantly, calibrated stabilities of 1000:1 over 3 years and >10,000:1 over 33 hours have already been demonstrated. Thus THESIS requirements represent only a factor of 10 improvement over demonstrated capabilities (see Table 1-3). While significant and essential to accomplishment of THESIS's science goals, we believe this improvement to be well within reach for an instrument and pointing system specifically built to achieve these levels.

Table 1-3. THESIS advances the state-of-the-art for infrared exoplanet observations.

SNR	Interval	Obs	λ μm	Telescope	Source	Reference
6,000	8 hr	Rel. photo	16	Spitzer	Transit	Deming et al. 2005
2,300	8 hr	Rel. spec	7.5-13	Spitzer	Transit	Richardson et al. 2007
1,000	3 yr	Abs. spec	7.5-14	Spitzer	Transit	Swain et al. 2008a
18,000	33 hr	Rel. photo	8	Spitzer	Transit	Knutson et al. 2007a
10,000	5 orbits	Rel. spec	1.4-2.5	HST	Transit	Swain et al. 2008b, 2009
4,300	4.46 days	Rel. photo	24	Spitzer	Non-transit	Harrington et al. 2006
3,500	4.2	Rel. photo	8	Spitzer	Non-transit	Cowan et al. 2007
10,000	6 hr	Rel. photo	8	Spitzer	Transit	Harrington et al. 2006
100,000	**3 yr**	**Abs. spec**	**2-3**	**THESIS**	**Tran/Non-Tran**	

The instrument transfer function for each wave band and observing mode (medium resolution spectroscopy, low resolution spectroscopy, and photometry) will be measured at regular intervals using calibrator stars. We expect the calibrators will be carefully selected photometric standard A-type stars observed every few days. This approach is a higher cadence version of the Spitzer IRS calibration methodology. In the case of THESIS, the FPM ensures precise placement of the calibrator (or science star) on the focal plane array. Because the calibration methodology is tied to specific pixels, the calibrator stars will be observed at four locations (twice the number needed) to establish a redundant focal plane calibration. The design of the calibrator observations will be such that the state of the array will be characterized at the photon limit. Use of multiple standard stars will protect against intrinsic fluctuations in the stellar luminosity. Repeated observation of the calibrator network will allow characterization of the common and non-common mode components of changes in the instrument transfer function. Calibration measurements will also characterize the charge trapping effect (Figer et al. 2004; Love et al. 2005) and be used to determine the amount of time (about 20 min., based on Spitzer) needed for array conditioning to mitigate the effect. Characterization of the charge trapping effect will allow us to model and remove it in post-processing.

3.2 Operations Concept

The best analog for THESIS operations is Spitzer. Like Spitzer, THESIS would be used for (pointed) science target observations intermixed with regular observations of a calibrator network. Like Spitzer, THESIS pointing constraints would be driven by the need to keep the spacecraft shaded (to passively cool the THESIS telescope), leading to a observing region +/- 30 degrees wide centered at 90 degrees with respect to the sun. THESIS targets would come from radial velocity and transit surveys; according to the Extrasolar Planets Encyclopaedia there are currently 344 exoplanets of which 58 are transiting. Since THESIS can characterize both transiting and non-transiting planets, there will be a large number of targets for observations and thus there are no implied constraints on the mission design. A typical "visit" might last approximately 5 to 6 hours for a transiting planet and approximately 1 to 2 hours for a non-transiting planet. Determining the difference between the dayside and nightside emission of a non-transiting planet would require ~ 4 visits.

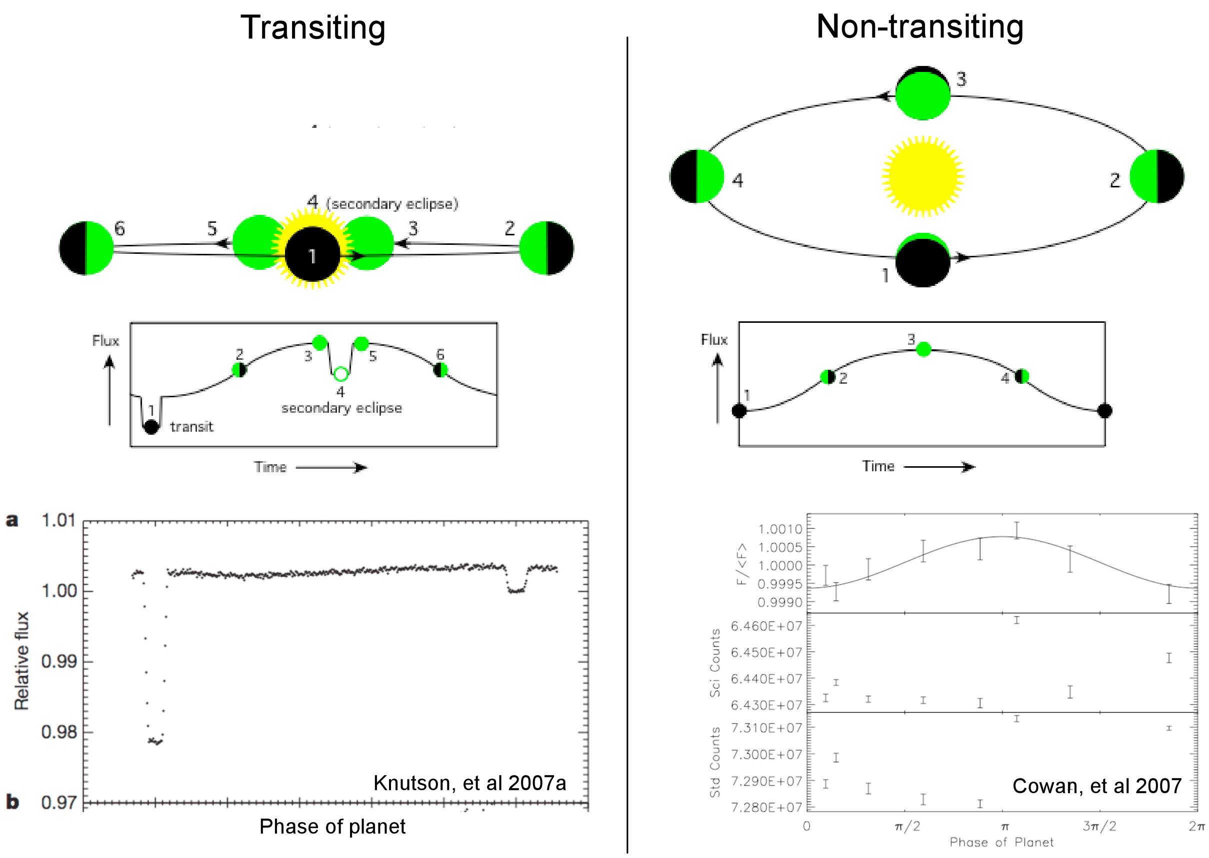


Figure 1-2. Observations of an exoplanet in transiting and non-transiting configuration. **Left** Transiting system and light curve obtained via Spitzer IRAC photometry. **Right:** Non-transiting system and light curve via Spitzer IRAC photometry. THESIS will compare spectra taken at different points in the orbit to characterize the exoplanet atmosphere. THESIS is capable of high-stability measurements over periods of years and thus has the potential to detect changes on terrestrial planets due to significant volcanism or bombardment.

3.3 Technical Feasibility

THESIS is based on simple, mature, proven, flight hardware and can be built today. The measurement method has been demonstrated with both Hubble and Spitzer.

3.4 System Description

Telescope and Instruments: A Falcon 9 will be used to deliver THESIS to L2; the injected mass for THESIS is 1249 kg (the KSC estimate of launch vehicle performance to L2 is 2040 kg giving a 790 kg mass margin) and has a power requirement of 890 Watts. In operation, THESIS is oriented within a range of ± 30° of the angle normal to the sun line. THESIS combines a 1.4 m diameter parabolic primary with a hyperbolic secondary to form an f/9 telescope with effective focal length of 12.6 m and good performance over a 2 arcmin field of view. The primary and secondary are passively cooled to 60 K, reducing the thermal noise contribution below the zodiacal background. The instruments are mounted to the back of the primary support structure. A second small parabolic mirror images the primary onto the FPM. The FPM removes the effects of spacecraft jitter and enables on-sky pointing stability of better than 20 milli-arcsec. The pupil is then reimaged onto a grism dispersing element. Visible and near-IR light (450-900 nm) is picked off immediately after the FPM and imaged onto the CCD used in the FPM control system. THESIS cost estimates were developed based on using the ASPIRE mission moderate resolution (R=2000) spectrometer covering the 2 – 14 μm region; this instrument design is well suited to the needs of THESIS.

Thermal architecture: THESIS will use a combination of passive and active cryocooling to achieve background-limited performance. The thermal architecture will follow the proven and well-understood passive cooling demonstrated on Spitzer to maintain the THESIS telescope well below the required 60 K. The Spitzer telescope is expected to remain below 45 K, with the outer shell remaining below 37 K, after depletion of the stored cryogens. Similar performance is expected for the Planck telescope which, like THESIS, will use mechanical cryocoolers for the instruments.

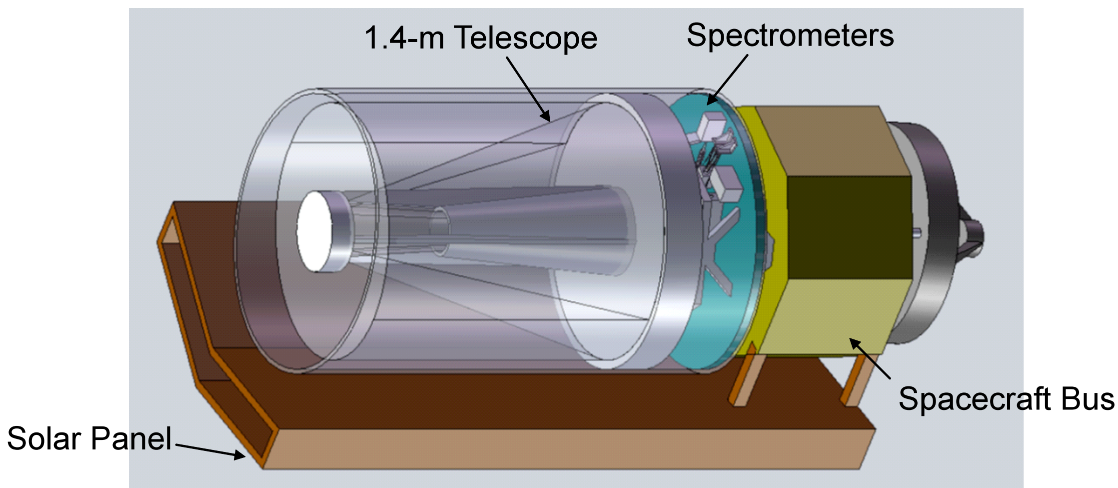


Figure 1-5. THESIS is an intuitively straightforward, low-risk design. A 1.4 m-diameter passively cooled telescope provides light collection for two actively cooled spectrometers, one covering 2-5 μm (SWIR) and the other 5-15 μm (MWIR). Readily available spacecraft cores possess the power, bus-level pointing and other capabilities required by THESIS. A Spitzer-like solar panel/Sun shield combination makes efficient use of mass and volume resources.

The THESIS MWIR focal plane will be cooled to 7 K. The SWIR spectrometer also requires cooling to ~30 K to reduce thermal photon background at the focal plane. A cryocooler of the ACDTP-type architecture can easily meet these requirements. One such cryocooler, with considerably greater capability than required for THESIS, is currently at TRL 6 and baselined for the MIRI instrument of JWST. We anticipate no difficulties in meeting all of the temperature and thermal stability requirements of the THESIS mission using existing or very-near-term flight-proven techniques and equipment.

Pointing control: The THESIS pointing requirement of 20 milliarcseconds (mas) rms can be met using a multi-layer pointing control approach based on the work of Brugarolas et al. 2006 with respect to the ECLIPSE mission. The first layer of the control system is comprised of two phases, both employing the spacecraft Attitude Control System (ACS) actuators to achieve 50 mas pointing stability. The normal phase uses the spacecraft star tracker as the primary control input and is characterized by multi-degree acquisition ranges and ten arcsec pointing uncertainties. The fine phase derives its control inputs from the CCD-based Fine Guidance Camera (FGC) within THESIS. The FGC has a tens of arcsec acquisition range and supports refinement of THESIS pointing control to the 50-mas level. Several NASA missions (e.g., the Spitzer Space Telescope; Bayard 2003), have achieved this level of performance using readily available ACS components. In fact, the Ball BCP2000 S/C advertised attitude control performance is 45 mas rms! The second layer of the pointing control system uses the FGC to provide control inputs to a FPM within the THESIS optical train to achieve the final pointing requirement of 20 mas. Compression of the optical beam, from a diameter of about 140 cm at the telescope primary to 3 cm at the FPM, results in a corresponding amplification of angular offsets. Thus, 5 mas on the sky becomes 0.25 arcsec at the FPM. Vacuum- and cryo-compatible, flexure-mounted, voice-coil- or piezo-actuated FPMs with better than 0.25 arcsec pointing resolution over a ± 1 degree range of motion are comfortably within the current state of the art, as is the corresponding centroiding capability required of the FGC. The effect of the FPM on spacecraft attitude is negligible (owing to relatively low moment of inertia), and no precautions, like momentum compensation, need to be taken. ***An important "engineering margin" aspect of the THESIS mission is post-processing compensation for suboptimal image stability***; currently, the plan is not to rely on post-processing although it could be invoked if necessary. By making an extremely precise flat field measurement and applying the appropriate correction, it is possible to largely correct the pointing error effects. This post-processing correction has been demonstrated with both Hubble and Spitzer and is the basis for the current exoplanet spectroscopy results.

FPA technology: We anticipate that no special advancements in detector technology are needed to accomplish precision spectrophotometry to the levels desired for THESIS. State-of-the-art infrared sensor chip assemblies baselined for the JWST/NIRspec and MIRI instruments (Rauscher & Ressler 2005) will be evaluated for suitability to our application (i.e., precision exoplanetary spectrophotometry). Two separate instrument focal planes will cover the entire science band. For the SWIR spectrograph, covering 2-5 μm, we will consider the mature HgCdxTe1-x based 1K2 Hawaii-1RG array (Rockwell-Teledyne; Figer et al. 2004) to provide the high sensitivity and radiometric stability necessary (Note: Two similar Hawaii-2RG 5-μm sensor chip assemblies will be flown in the JWST NIRspec instrument). Similarly, for the MWIR spectrograph, we will evaluate the performance of the 1K2 Si:As Impurity Band Conduction arrays (Love et al. 2005) developed by Raytheon Vision Systems for JWST-MIRI. The intrinsic detector noise in both types of detectors is low. We anticipate the SWIR focal plane will be cooled to a temperature similar to the optical bench (35-40 K). At these temperatures, the dark current is expected to be low (< 0.01 e/s/pixel). The MWIR focal plane arrays need to be operated at 7 K. The dark current at these temperatures is about 0.1 e/s. For both types of detectors, a read noise of about 10 e (16 Fowler samples) at 100 kilo-pixel/s read rates is achievable. Reference pixels, which mimic dark pixels, are available on all video outputs and can be used to monitor electronic drifts. Additional immunity against effects such as interpixel capacitive coupling (Finger et al. 2006) and intra and interpixel QE variations will be provided by optical spatial averaging.

3.5 Science Data Collection, Analysis, and Archive

THESIS data would be collected and archived by the NASA Exoplanet Science Institute (NExScI) at the Infrared Processing and Analysis Center (IPAC) based on NExSCI/IPAC experience from the Spitzer, WISE and Kepler missions.

4. Technology Drivers

All the components of THESIS are mature: 1.4 m telescope; moderate-resolution IR spectrometer; 2-14 um IR FPAs; FGS and FPM all *now* have TRL of 6 or higher. The required S/C pointing will be demonstrated by Kepler. The 2nd layer fine pointing will be demonstrated by JWST.

5. Activity Organization, Partnerships, and Current Status

5.1 Activity and Current Status

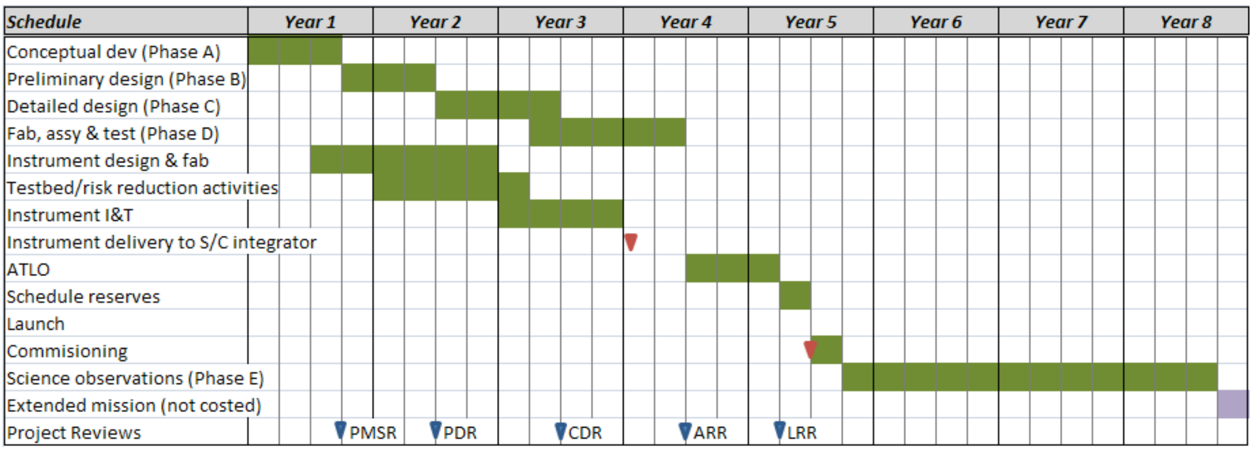
Currently the THESIS mission concept implementation is being developed at JPL. THESIS has been though a TeamX study for both the instrument and spacecraft at JPL (as reported in the costing section). Formation of the THESIS science team is ongoing and interested persons are encouraged to contact THESIS team members.

5.2 Partnership

For the purpose of exploring the THESIS mission concept, an informal science connection exists between the Jet Propulsion Laboratory and the Max-Planck Institute of Astronomy in Heidelberg. MPIA Director Dr. Thomas Henning has submitted a THESIS white paper (authored by Swain) to the ESA EPRAT (ExoPlanetary Roadmap Advisory Team). This team has recommended the THESIS mission concept for further study by ESA. There is an interest among the THESIS science team members (co-authors on this paper) of exploring the potential for international cooperation in the THESIS mission.

6. Activity Schedule

THESIS, due to low technical risk, can be executed relatively quickly and the mission could begin science operations in slightly less than five years from the beginning of phase A. The baseline mission is science operations for three years. However, there is adequate power from the solar array at the nominal end of mission life to operate an extended science mission.



7. Cost Estimates

Cost Estimate Interpretation Policy, Reserves, and Accuracy

Team X guidelines for this study were to provide independent design and costing analysis for each mission concept. Project-provided designs were used, but not project-provided cost estimates. The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were prepared without consideration of potential industry participation, and do not constitute an implementation-cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive. 30% reserves for development (Phases A-D) and 15% for operations (Phase E) are included in the estimate.

Project Cost is roughly $520 M '09 with appropriate contingencies, including 3- years of science operations. This cost does not include the launch vehicle.

This cost estimate results from a Team X session on March 18, 2009.

Cost Estimate

The THESIS project costs are itemized in Table 2. This cost reflects a PI-mode managed project with JPL as the implementing center. All costs in Table 2 were last estimated in March 2009.

Payload - The THESIS payload costs (telescope, instrument, instrument I&T) were estimated using the JPL Team X Large Telescope Cost Model, and the NASA Instrument Cost Model (NICM). The cost of the cryocooler is based upon the JWST MIRI cryocooler, but reflects recurring cost considerations and a simpler design.

Spacecraft Bus - The spacecraft bus is assumed to be a custom in-house build. Model-based estimates for the subsystems were additionally adjusted by analogy with equivalent implementations.

Launch Vehicle – A Falcon 9 launch vehicle would meet the needs of this mission, but costs for the Falcon 9 are not currently available. Project costs are calculated without the cost of the launch vehicle.

Table 2. THESIS life cycle costs are conservatively estimated at $520 M not including launch vehicle.

Item	Cost ($M 2009)*	Notes
Management, Systems Eng., Mission Assurance	35	
Payload System	155	1
-- Telescope	80	
-- Instrument	70	
-- Payload I&T	5	
Flight System	110	2
Mission Ops/Ground Data System	45	
Launch Vehicle		3
Assembly, Test, Launch Operations	15	
Science	40	4
Education and Public Outreach	5	
Mission Design	5	
Reserves	110	
Total Project Cost (not including launch vehicle)	520	

Notes
* Individual WBS elements have been rounded to 2 significant digits.
1. Payload system includes instrument.
2. Flight system includes all the equipment that leaves the launch vehicle, excluding the Payload System.
3. A Falcon 9 launch vehicle has been assumed in the mission design. However, pricing information for the Falcon 9 is not yet available.
4. Science budget includes the Science Team, support staff, funding of external investigators and processing of three years of science data.

Table 3. THESIS Phase Cost Table.

Phase A – Conceptual Design	5
Phase B – Preliminary Design & Planning	40
Phase C/D – Detailed Design, Fab. Integr., Test & Launch	410
Phase E/F – Operations thru Decommisioning	60
Total (not including launch vehicle)	520

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