TECHNOLOGY DEVELOPMENT FOR EXOPLANET MISSONS

Technology Milestone White Paper
A Novel Optical Etalon for Precision Radial Velocity Measurements

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Table of Contents

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1 Objective

In support of NASA's Exoplanet Exploration Program and the NASA Strategic Astrophysics Technology (SAT) Program, this whitepaper defines the planned milestones for the project entitled ***A Novel Optical Etalon for Precision Radial Velocity Measurements*, **explains their purpose, and establishes the success criteria against which the milestones will be evaluated. The overall program goal is to design, build, and demonstrate a miniature monolithic optical etalon referenced to an optical frequency comb as a wavelength calibration source for Precision Radial Velocity (PRV) instruments in the visible portion of the spectrum from 400 nm to 800 nm and suitable for single measurement RV precision below 10 cm/s. The etalon is an ultra-stable standalone composite Whispering Gallery Mode (WGM) resonator. The WGM resonator etalon design envisioned in this development program has several features that distinguish it from existing, state-of-the-art PRV calibration sources. WGM etalons have no mirror coatings on the resonator and are millimeter-scale devices that lend themselves well to robust, high thermal stability packaging. The fundamental frequency reference for the WGM etalon will be a laser frequency comb (LFC) with the same level of stability traceable to the Système international (SI*)* definition of the second provided by Menlo Astrocombs, but will be generated in the NIR so as circumvent lifetime issues associated with comb generation at wavelengths blue of 500 nm. Furthermore, the reference LFC will not require mode filtering, further simplifying the design concept. Ultimately, our objective is to demonstrate that WGM resonator etalons can provide a compact, robust, reliable, and cost-effective reference wavelength solution for visible band PRV spectrographs.

2 Definitions

To make clear the motivation and strategy described in this Milestone White Paper, we offer definitions of selected terms used in the text in subsequent sections.

Allan Deviation, denoted $\sigma_y(\tau)$, is a statistical tool that is a measure of frequency stability in clocks and oscillators. It is the square root of the Allan Variance, and is an estimate of instability due to noise processes. Allan Variance is defined as one half of the time average of the squares of the differences between successive readings of the frequency deviation of an oscillator sampled over the sampling period. The Allan Variance depends on the time period used between samples, commonly denoted as τ, and is displayed as a graph rather than a single number. A low Allan variance is a characteristic of a clock with good stability over the measured period. An Allan deviation of 1×10^{-9} at observation time 1 s (i.e. τ = 1 s) should be interpreted as there being an instability in frequency between two observations a second apart with a relative root mean square

(RMS) value of 1×10^{-9}. For a 10 MHz clock, this would be equivalent to 10 mHz RMS movement [1].

Etalons are optical devices in which light goes through multiple reflections and the interference of the light causes a modulation in the transmitted and reflected beams. In Fabry Perot Interferometer (FPI) etalons, the devices consist of parallel plates coated with reflective material and separated by a small fixed distance. When light is incident on one of the surfaces, a portion of it is transmitted out, and the remaining part is reflected back. If the additional optical path length of the reflected beam (due to multiple reflections) is an integral multiple of the wavelength, then the reflected beams will interfere constructively. Thus, the transmission varies periodically with the optical frequency. In the case of Whispering Gallery Mode (WGM) etalons, the device is a dielectric cavity with curved surfaces and the reflection results from the boundary interface. Constructive interference occurs when the round-trip path length along the curved surface in the cavity is an integral of the wavelength.

Finesse is defined as the ratio of the free spectral range (the spacing between resonant frequencies) to the Full Width at Half Maximum (FWHM) linewidth of the resonances. While the free spectral range is a measure of the distance between resonance peaks, the finesse of a resonator is an expression of the distance between the resonance peaks in terms of the number of FWHM linewidths that go in between two consecutive resonant peaks. Finesse thus conveys the effective resolution of a resonator as an interferometer (roughly, the number of different frequencies that it can distinguish). Finesse is proportional to the quality factor, scaled by the fraction of the spectrum (up to the resonant frequency) covered by one free spectral range of the resonator [2].

Quality (Q) factor is the ability of an optical resonator to confine the electromagnetic field. Q is approximately the duration of time a light wave will circulate divided by the optical period of the wave [3], or similarly in the high Q regime, the Q factor is the ratio of the resonance frequency ν_0 to the FWHM bandwidth $\delta\nu$ of the resonance [4].

Pound-Drever-Hall (PDH) locking is a technique for actively stabilizing the frequency of a laser by tuning it through a feedback loop to a stable reference cavity. The technique entails creating side bands on the light source to be locked through phase modulation. The light is then directed onto a high finesse Fabry Perot cavity. Light reflected off the cavity is measured using a photodetector. The photodetector signal is processed to provide a measure of how far the laser frequency is off resonance with the cavity and may be used as feedback for active stabilization. The feedback is typically carried out using a proportional–integral–derivative (PID) controller that takes the PDH error signal readout and converts it into a voltage that can be fed back to the laser to keep it locked on resonance with the cavity [5].

Thermorefractivity is the temperature dependent refractive index of an optical material.

3 Motivation

3.1 The Need for the Precision Radial Velocity Method

Precise measurement of the Doppler shifts of starlight resulting from the radial velocity of planet-hosting stars is one of the first and most powerful methods of exoplanet detection, and the only ground-based method for reliable determination of exoplanet mass. Extreme Precision Radial Velocity (EPRV) measurements are therefore a critical component of NASA's technology program leading up to exoplanet imaging missions such as HabEx or LUVOIR. EPRV will enable prioritization of potential targets for study and will provide the planet masses critical to the interpretation of the spectra returned by a future flagship mission. The recent National Academy of Sciences report on a Strategy for Exoplanet Science (EXSS) study identified Precision Radial Velocity (PRV) measurements as a critical step toward the detection and characterization of potentially habitable Earth-analogs. The NAS report [6] issued these findings:

1. "The radial velocity method will continue to provide essential mass, orbit, and census information to support both transiting and directly imaged exoplanet science for the foreseeable future …"
2. Radial velocity measurements are ***currently limited by*** variations in the stellar photosphere, ***instrumental stability and calibration***, and spectral contamination from telluric lines. Progress will require new instruments installed on large telescopes, substantial allocations of observing time, advanced statistical methods for data analysis informed by theoretical modeling, and collaboration between observers, instrument builders, stellar astrophysicists, heliophysicists, and statisticians."

Thus, creating more powerful tools for calibrating PRV spectrographs is central to obtaining the required Doppler measurements.

3.2 PRV Calibration Sources

Classically, RV spectrograph calibration has relied on atomic hollow cathode lamps (HCL) or molecular absorption cells (e.g. I_2) for precise wavelength determination. However, these methods have a variety of shortcomings when pushing towards the highest precisions.

HCLs, such as thorium and uranium lamps, have transitions throughout the optical/near-infrared (NIR), but present a sparse, irregular grid of usable lines, significant line blending, and highly uneven line intensities. The fill gases used in these lamps, e.g. argon or neon, also contaminate portions of the underlying stellar spectrum with bright emission features that reduce the spectral information available for RV measurements. Instruments such as HARPS have demonstrated ~1 m/s precision using standard thorium lamps on-sky [7], but have yet to push beyond this level.

Gas absorption cells have been used with great success at the ~1-2 m/s precision level on-sky (e.g. I_2 cells have been used on the Keck HIRES [8], CHIRON [9], and numerous other spectrographs, but are inherently limited in bandwidth (~100 nm), and reduce the overall instrument throughput significantly as they are absorbing stellar photons, both leading to significantly reduced efficiency. Imprinting the complex absorption cell spectrum on top of the stellar spectrum also presents a significant computational challenge – one that has not been demonstrated below the ~1 m/s level.

More recently, broadband optical laser frequency combs (LFCs) have been developed for the highest precision RV applications. LFCs intrinsically produce a uniformly spaced, dense grid of laser lines, each at frequencies known to better than 10^{-12} accuracy. LFCs represent the pinnacle of RV calibration systems, providing wide bandwidth calibration at levels of precision far better than those set by other instrument systematics. Menlo Systems, a German company, has developed broadband 'astrocombs' specifically for optical RV applications that have been implemented on the NEID and EXPRES spectrographs. The design employs mode filtering of low repetition rate (~100-200 MHz) combs through a series of 3 Fabry-Perot filter cavities, thus eliminating ~99% of the comb lines to achieve the sparse line spacing (10-30 GHz) needed to match high resolution (R>100,000) PRV spectrographs. Astrocombs are inherently highly complex devices that require significant engineering efforts to make 'turn-key' and suffer from several drawbacks. These devices are relatively expensive (>$800K), and have yet to demonstrate both long-term operability at the observatory and reasonable performance at wavelengths blueward of 500 nm. Furthermore, these systems require periodic maintenance to replace consumable components, such as the photonic crystal fiber (PCF) that enables spectral broadening of the combs, and fiber amplifier, compounding the high costs.

Other methods of achieving reliable visible band, 10-30 GHz repetition rate LFCs for PRV applications are being investigated by multiple groups; most of these approaches involve nonlinear spectral broadening and second harmonic generation of Near-Infrared (NIR) frequency combs generated through either electro-optic modulation of a CW laser, or in high-Q disk or ring microresonators through nonlinear optical processes (so-called Kerr microcombs [10,11]), or a combination of both, i.e. pulse-pumped microcombs. NIR astrocombs have been implemented with great success as exemplified by the 800 nm to 1300 nm electro-optic modulation frequency comb on the Habitable Planet Finder instrument at the Hobby Eberly Telescope [12] that, at the time of this writing, has been operating nearly continuously for almost 2 years. However, broadening NIR combs into the visible range with 10-30 GHz line spacing is challenging because at these high pulse repetition rates, it is difficult to achieve the threshold pulse energies needed to realize the non-linear optical effects without substantial pulse amplification.

3.3 Etalons for PRV

The challenges associated with the above PRV spectrograph calibration sources provide the motivation for our efforts to develop broadband etalon systems. Etalons are being used as the spectrograph calibration source for concurrent, on-sky observations in multiple state-of-the art PRV planet-hunting and characterization facilities.

The ideal etalon leverages fully single-mode operation, has broad wavelength coverage that extends into the blue (<500 nm), is contained in a compact design that is easily thermally stabilized, provides high line brightness and good uniformity, and is referenced to a proven frequency standard. Previous PRV etalon calibration sources, such as those developed for the NEID, HPF, ESPRESSO, HARPS, and MAROON-X instruments, have satisfied some subset of these requirements. The line positions of these etalons are set by physical parameters, like etalon spacer thickness, and they inherently rely on an external reference for absolute accuracy. Most of them are passively stabilized through precise environmental control (temperature, vacuum) to produce a stable output spectrum, and require comparison to an absolute calibration standard like a Thorium lamp or a LFC, to verify their long-term stability. The etalon for MAROON-X is continuously monitored for drifts by referencing it internally to an atomic standard, in this case a hyperfine transition of rubidium at 780 nm, using a laser to probe both the etalon lines and the rubidium transition simultaneously. However, it is only referenced to one wavelength, leaving the stability of etalons lines far from this point in question due to material dispersion; this is a particular concern at bluer wavelengths. Further, frequency drifts can occur for many reasons in passively stabilized FP etalons, including aging of materials like the Zerodur spacers in vacuum-gap etalons [13], long-term degradation of the dielectric mirror coatings that form the resonator, changing environmental conditions (temperature and pressure), as well as changes in the illumination (i.e., thermo-mechanical stability of the light injection). Some of these changes can result in a wavelength dependent drift of the calibration spectrum [14]. Monitoring and, if desired, active control of a FP etalon tailored for astronomical research at sub-m/s accuracy thus requires precise metrology [15].

Unlike traditional Fabry Perot etalons that use a vacuum gap between parallel plates of ULE glass or Zerodur, the devices we will develop in this program are based on crystalline CaF_2 and MgF_2 whispering gallery mode (WGM) resonators that can overcome many of these challenges. Through their intrinsically high quality (Q) factor and small size, they can provide an extremely broadband calibration spectrum and lend themselves to robust environmental control. Further, no optical coatings are required in a WGM resonator; light is trapped by total internal reflection from the dielectric boundary along which it travels. WGM resonators operate at any wavelength as long as the dielectric is transparent and the resonator surface is well-polished to reduce surface scattering losses.

4 WGM Resonator Etalon PRV Calibration Sources

The stabilized WGM resonator etalons that are the subject of this effort may provide a viable nearer-term solution for PRV spectrograph calibration while work continues on developing robust, long-lived blue-visible light LFCs. Indeed, these etalons may serve as an adequate long-term solution to the calibration challenges.

A WGM resonator etalon consists of a high-quality (Q) factor, axially-symmetric, dielectric resonator structure that supports discrete optical modes. The name “whispering gallery mode” is derived from the whispering gallery of Saint Paul’s Cathedral in London [16-18] where whispers are audible all around the chamber due to sound waves traveling around the concave surfaces. In optical resonators, these modes allow light to circulate around the perimeter of the structure, close to the surface. As with almost all monolithic etalons, WGM resonators have four major sources of loss. The intrinsic loss mechanisms include radiative loss, loss due to surface scattering, and loss due to material absorption. These losses can be made extremely low so that achieving optical Q factors exceeding 10^{11} are feasible. The fourth loss mechanism is associated with the resonator coupling with the external input/output light beams. The intrinsically high-Q factor of the etalon is important to the successful implementation of this project because it allows for the resonator to be strongly overloaded (a regime where the coupling loss dominates all the intrinsic loss mechanisms) and still have sufficiently narrow linewidth. By overloading the etalon using an evanescent field coupler, one is able to create an etalon structure with low optical attenuation and that produces a quasi-uniform comb of stable optical modes. Such performance (finesse) is very difficult to achieve in FP etalons with mirror coatings.

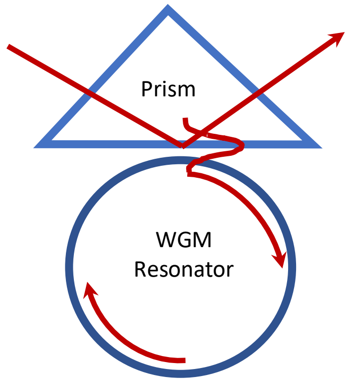
The WGM etalons we will develop in this work are fabricated from optical crystals that, unlike ULE glass or Zerodur, have significant thermal expansion that must be compensated to achieve a frequency stability suitable for PRV measurements. The task of frequency stabilization of the WGM etalons includes two major parts: 1) suppression of fundamental thermo-optic fluctuations and 2) removal of the environmental fluctuations. The first task can be accomplished by engineering a composite WGM etalon that balances thermal expansion and thermo-refractive behavior. The arithmetic signs of the thermal expansion coefficient and thermo-optic coefficient are opposite in some optical crystals. By sandwiching a resonator in between layers of lower thermal expansion material and thereby constraining its thermal expansion, it is possible to reduce the influence of thermal fluctuations on the resonator spectrum, rendering it "thermally insensitive" over a particular temperature range. We refer to such a layered design as a "compensated resonator". Environmental factors such as changes in temperature and atmospheric pressure, and acceleration can be controlled by mounting the resonator in an appropriately engineered evacuated package.

In spite of the small (sub-mm) dimensions of WGM resonators, the resonators required for this program are large enough that, for realistic values of the mode volume, the fundamental thermo-refractive fluctuations only limit the relative optical frequency stability to $5x10^{-15}$ at a second, a value more than adequate for PRV studies. However, an external reference atomic transition is ultimately necessary to stabilize the etalon over *long* periods of time – months to years – in order to achieve the stability required for PRV detection of Earth-like planets orbiting solar analogs. The etalon modes must be compared with such a reference and a feedback mechanism employed to "lock" the etalon to the reference.

WGM etalons offer great flexibility because, similar to waveguides, their modal properties can be engineered. Usually, the optical frequency spectra in conventional crystalline WGM resonators are dense with multiple optical modes of similar contrast across a free spectral range. This high modal density of the spectrum is detrimental to PRV applications as it can result in frequency related power fluctuations. However, the spectral density can be reduced by properly shaping the resonator.

A demonstrated etalon shape for this purpose is a planar waveguide ring at the surface of a cylindrical preform that plays the role of waveguide cladding [19]. The structure has been dubbed a 'photonic belt' resonator. The high quality factor of these etalons has resulted in the total optical loss in the waveguide being much smaller than the attenuation in existing planar waveguide structures.

Even with a drastically reduced mode density, the single mode etalon still has two mode families analogous to TE- and TM-modes of a standard waveguide. It is possible to select one input polarization to eliminate coupling of the undesired polarization mode.



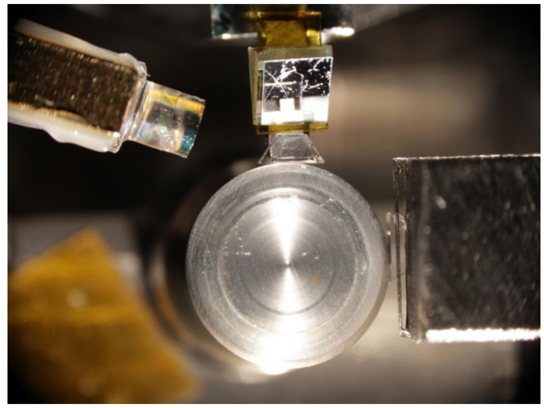


Figure 1- Left: Illustration of light coupling into WGM resonators using prism coupler [20] and b) a WGM resonator with prism couplers in the laboratory at OEwaves

Prism couplers with frustrated total internal reflection are among the oldest methods of coupling light into WGM resonators (see Figure 1). The simple yet efficient prism technique is based on three main principles. First, the input beam is focused inside a high-index coupling prism at the angle that provides phase matching between the evanescent wave of the total internal reflection spot and the WGM, respectively. Second, the beam shape is tailored to maximize the modal overlap in the near field. And third, the gap between the etalon and prism is optimized to achieve critical coupling. Prism-waveguide coupling efficiency of more than 90% has been demonstrated [21].

4.1 Optical crystal material choice

The materials of interest for PRV etalons are crystalline CaF_2 and MgF_2. CaF_2 is an easily machinable crystal that allows fabrication of high-quality optical etalons. The material has a negative thermo-optic coefficient that partially compensates positive thermal expansion, making thermal stabilization of the resonators relatively straightforward. A CaF_2 etalon with a thermal turning point at 33 degrees C has been demonstrated previously [22] with a relative frequency stability of better than 10^{-12} at 1s integration time.

Another material of interest is crystalline MgF_2 which features excellent mechanical stability, hardness, and optical transparency, making it suitable for production of very high-Q WGM optical etalons. The small thermo-refractive constant of this material enables efficient stabilization of the resonators and increases the threshold of low-frequency thermo-optical instabilities.

Both CaF_2 and MgF_2 crystals are broadly available and relatively inexpensive. They are used as material for optical windows with high transmissivity from the UV through the mid-infrared (~140 nm to ~ 8.0 um for CaF_2 and ~110 nm to ~ 6.0 um for MgF_2). Etalons made with these crystals are robust and the main challenge is related to maintaining the cleanliness of their surfaces.

Comparatively, CaF_2 has higher transparency than MgF_2 and has a cubic lattice structure that makes its spectrum more robust with respect to temperature changes as the TE and TM mode families have nearly equal temperature tuning coefficients. Magnesium fluoride, in contrast, is a uniaxial crystal which supports ordinary and extraordinary polarized light with different indices of refraction. Consequently, the WGM spectrum changes when the temperature changes (modes of different polarizations change their frequencies in different ways).

5 Requirements

Here we define the key requirements that any PRV calibration source must meet in order to provide the necessary reference for exoplanet science, and that drive the design of the WGM resonator etalon in this effort.

1. ***Single mode***: Calibration sources must be single mode, or at least have higher order mode suppression at a level such that the free spectral range (FSR) does not contain any other modes with an extinction ratio of less than 40 dB power contrast. Otherwise, variations in intensity between the mode families can shift the centroid of the unresolved lines on the spectrograph. Such a shift masquerades as a RV shift. For example, for two etalon modes separated by 250 MHz, the 'center of mass' of the two modes lies between them, yet would be entirely unresolved by a PRV spectrograph with ~6 GHz primary mode spacing. If the power of one of the modes changes by 1%, the 'center of mass' will shift by approximately 30 cm/s (roughly proportionally to the intensity fluctuation). Therefore, the relative stability of the two modes at $\sim 3 \times 10^{-4}$ is needed to maintain <1 cm/s centroid stability of the 'center of mass'.
2. ***Mode density (or free spectral range):*** The source must provide a density of calibration lines that strikes a balance between providing an adequate number of reference lines to compare with stellar spectral features while still being resolvable on the spectrograph in use. It is this need for sparser line density that imposes the requirement for multi-stage mode filtering of fiber laser combs in the commercial systems currently in use. Figure 2 from Murphy et al [23] shows simulated expected relative velocity precision as a function of repetition rate. The optimal repetition rate, providing a velocity uncertainty of 0.45 cm/s (a minor contribution the instrument error budget compared to other error sources) is around 10 GHz for a spectrograph with resolution (R) of 150,000. Acceptable performance extends out to beyond 20 GHz. For comparison, the NEID spectrograph's etalon mode spacing is 25 GHz.

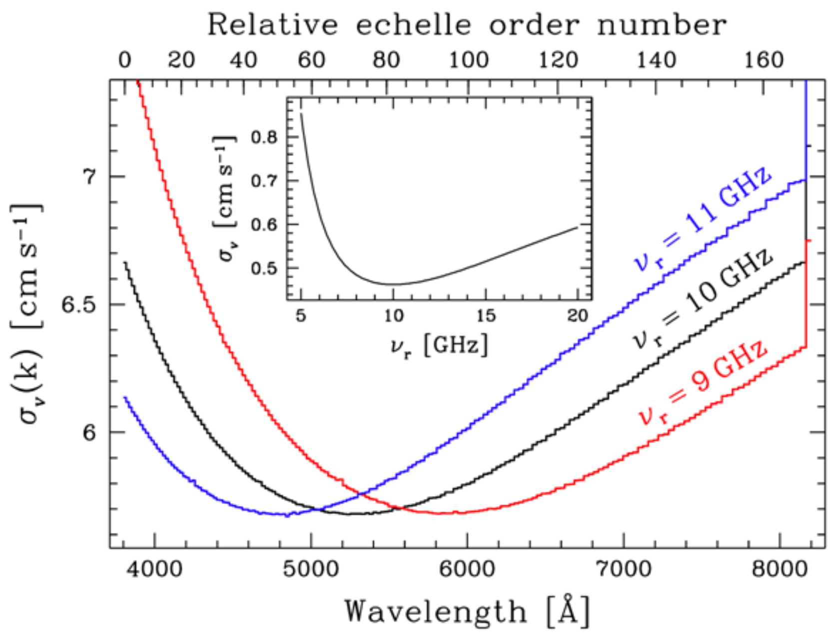


Figure 2 - Results from comb simulations with R=150,000, (S/N)max = 500 and Bd,max = 0.01. The spectrograph's resolution (FWHM) is sampled with 3 pixels and each echelle order is assumed to be 2048 pixels long. The main panel shows the expected velocity precision available from each echelle order (sv(k), for three different line spacings while the inset shows the total velocity precision sv, integrated over the full wavelength range of the simulated spectrum, 380 nm. – 820 nm [23].

3. ***Mode spacing uniformity:*** Ideally, a calibration source has perfectly repeatable mode spacing to provide a wavelength solution for the spectrograph, but etalon modes are only quasi-uniform due to material dispersion. Etalons are typically referenced/locked to one spectral feature for stabilization (e.g. Rubidium D2 Doppler-free transition), but this does not control drift far from the reference wavelength. The crystalline MgF_2 and CaF_2 WGM resonators will also provide this quasi-period comb of lines, but the intention is to use frequency comb-referenced laser lines to provide better control and stability, monitor multiple line positions that span the full bandpass, then characterize each line position to create a spectrograph wavelength solution.
4. ***Line width***: PRV spectrographs, even high-resolution ones, cannot resolve calibration sources line widths of ~GHz or narrower. For example, the ESPRESSO etalon line width ranges from 2.7 GHz at the red end (780 nm) to 5 GHz at the blue end (380 nm) and has a corresponding line spacing of 2-7 times the line width [24]. So long as the centroid of the calibration line does not shift, line width is not a driving requirement for PRV observations. However, line width does become important when characterization measurements and stabilization come into play; line width should be narrow enough to characterize the line-spread-function of the PRV spectrograph, and heterodyning etalon lines with a reference laser to obtain adequate SNR (~20) of the beat note for stabilization drives towards narrower line width (<100 MHz). On the other hand, broader line width transmits a larger photon flux from the white light source while reducing total required input power so as to reduce thermal drift induced in the etalon.
5. ***Frequency Stability:*** for sub cm/s calibration source stability, Allan Deviation of better than 3×10^{-11} is necessary from 1 s to 10^8 s for PRV detection of Earth analogs orbital in the habitable zone of /solar-type stars.

6. ***Spectral coverage:*** Stellar information content of Sun-analogs is rich in the 400-700 nm range. Coverage further into the red provides a means for analyzing and correcting for stellar activity which shows a wavelength dependence while RV shift is achromatic. Maintaining red wavelength coverage also enables precision RV calibration for spectral regions most heavily favoring M-dwarfs. Importantly, LFCs currently cannot presently cover the spectral region blue of 500 nm reliably.
7. ***Intensity (power per mode):*** This value is best matched against the intensity of the stellar target under observation. On the NEID spectrograph, typical counts per pixel are ~2000 counts/s for the brightest standard stars. Etalon line intensity is a function of the white light source used to illuminate the etalon, the line width, and the wavelength-dependent coupling efficiency. In this project, we will use an Energetiq Laser Driven Light Source (LDLS) model EQ 99-FC (see Figure 3 for a plot of the spectral power as a function of wavelength) [25]. The emission varies from 40μW/nm to 50μW/nm between 380 nm and 780 nm. Although this would seem to supply ample margin (for 100 MHz line width at 400 nm there would be ~10^9 counts/second), systems that employ integrating spheres would see 10^6 reduction in intensity without accounting for other losses.
8. ***Intensity uniformity (power per mode uniformity)***: Variation of mode intensity across the full spectral bandpass of approximately 10dBm may be expected due to the wavelength-dependence of coupling efficiency, white light source intensity and beam quality, and linewidth.
9. ***Intensity stability:*** Intensity nonuniformity across the bandpass must be static. Flux changes per comb mode must integrate to nearly constant counts over the integration time of each individual observation. Comb line intensity variations over the course of an observation can result in the manifestation of detector pixel effects such as "brighter-fatter" [26] that cause erroneous RV shifts. We will target a maximum of 10% flux variation per comb line over 100 s and longer.

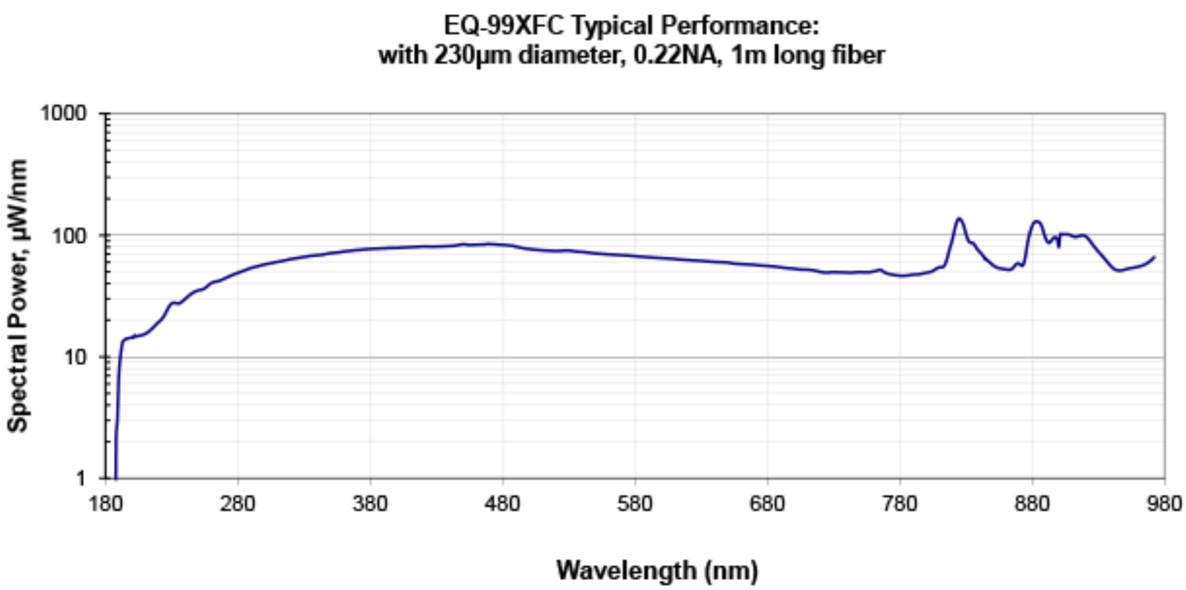


Figure 3 - Energetiq EQ-99XFC laser driven light source that will be used with the WGM etalon. This is the same model white light source used in the qualification of the EXPRESSO etalon[25].

6 Method

6.1 Design and fabrication

6.1.1 Modeling and design

An ultra-stable, high intrinsic Q-factor composite WGM etalon with a thermal compensation factor of 1000 will be designed using software packages such as COMSOL and SolidWorks. The compensation factor means that the etalon will be 1,000 times less sensitive to ambient temperature variations when compared with a standard, uncompensated WGM resonator. Thermal and acceleration sensitivity of the bare resonator can be evaluated numerically. We will evaluate the degree of compensation of the external temperature as well as mechanical fluctuations needed to achieve the required frequency stability of the entire resonator spectrum. We will demonstrate via numerical simulations that the WGM resonator can be stabilized to better than 10^{-11} per 1 second to 1-year integration time. The resonator shape will be engineered to provide the desired spectral density of optical modes. The analysis will take thermal, mechanical and optical properties into account, including influence of material stress on refractive index. Both magnesium fluoride and calcium fluoride are resonator material candidates, and the impact of the material properties on the long-term drift will be analyzed to advise a down-selection.

6.1.2 WGM etalon fabrication

The etalons will be fabricated using mechanical polishing with a 3-micron tolerance. First, the components of the composite etalon structure will be manufactured and verified against the specifications. Next, the components will be bonded together. It is important to keep tight tolerances on layer thicknesses, and thus they will be closely monitored during the assembly procedure using optical profilometry as well as microscopy. After the layered structure is assembled and cured, it will be installed on a metal pin and processed on a lathe using mechanical grinding with diamond slurry tools. The shape of the final structure will be controlled using optical profilometry. The quality of the surface will be verified with dark field microscopy. Wideband, evanescent prism couplers can then be integrated with the composite etalon on a breadboard for initial testing. Our calculations show that we can achieve coupling covering 400 nm - 800 nm with 4dB coupling strength variation. The coupling strength modifies the line width of the etalon modes, but not the mode contrast.

6.2 Packaging and Stabilization

The compensated resonator package is one of the most critical components of this project. To achieve relative frequency stability (Allan Deviation) to 10^{-11} (equivalent to 0.3 cm/s radial velocity precision), both the high compensation factor of the etalon frequency drift achieved through lamination of the etalon with optimized ceramics and the environmental noise rejection by the packaging design are needed. Both research directions are challenging and have high impact on the success of the development program.

10uK temperature stabilization is readily achieved in OEwaves devices made with standard (bare) resonators when averaged over 1s and over the resonator mode volume. This value is achieved using a standard thermoelectric cooler (TEC) and electronic feedback loop. The long-term drift of the system can be suppressed by the composite structure by three to four orders of magnitude, and is further controlled by a high-quality thermal control system (resistive heaters).

Thermal sensitivity of a bare resonator is approximately 10 ppm. Because the composite structure to be employed here will suppress that by 10^3 to 10^4 times, the WGM etalons will have 10^{-8}/K to 10^{-9}/K thermal sensitivity. Thus, to achieve 10^{-11} stability, the thermal control system must provide 10 uK stability at 1 s and 1 mK stability at 10^6 s. This is achievable as 50uK RMS stability is accomplished presently in the etalon chambers of our collaborator (C. Schwab) at Macquarie University, and the NEID and HPF systems are only a factor of a few worse.

The etalon package will be built up in layers to provide the necessary degree of thermal and vibrational isolation. Thus, it is necessary to free-space couple the white light source, which is external to the entire assembly, to the compensated etalon through multiple windows of the nested assembly with a collimated beam. Atmospheric pressure variations are detrimental to the bare compensated resonator, so the package will be evacuated. The package will consist of an innermost assembly containing the etalon and coupling prisms mounted on a thermal control stage. This assembly will be mounted inside an enclosure to protect against contamination, and thermal and pressure changes. The second layer encloses the first with a hermetic seal, providing further isolation. Both input and exit windows are required, and we will also design a viewing port to observe the etalon inside of the housing once mounted.

The small size of the etalon facilitates a relatively simple thermal design while the monolithic structure minimizes the effect of mechanical vibrations. To increase the thermal capacity of the etalon, it will be placed on a substrate. Integrated microprisms will be used to couple light in to and out of the etalon. The coupling alignment will be optimized on the substrate as an integrated unit. The integrated compensated etalon assembly will be thermally isolated by tethers to the inner wall of a thermal shield inside a hermetically sealed vacuum enclosure. These tethers, which can be adjusted for mechanical stiffness and located in the nodal points, provide both vibration control and thermal isolation. Resistive heaters will be used to raise the temperature inside the vacuum enclosure to the required temperature turning point. The overall design will account for all temperature coefficients and optimize the compensation strategy to achieve an inflection point over the widest temperature range.

Design of the proper etalon mount is important since the mount propagates the environmental temperature variations and associated thermal and mechanical stress to the etalon. SolidWorks will be utilized to design the mounting structure for the selected etalon design. The mechanical package should provide maximum isolation of the resonator while constraining the package volume. The team will perform extensive numerical simulations of the frequency noise of a packaged WGM resonator, including all sources of fundamental and technical noise, with the goal of identifying the needed parameters and validate the feasibility of the packaged resonator with the targeted performance. The simulations will be used to determine the best package material as well as configuration for the implementation of the ultra-stable resonator. The acceleration and thermal sensitivity of the packaged resonator will be simulated numerically. The package will be evacuated to the degree needed to reduce the impact of the atmospheric pressure on the frequency of the resonator. Epoxies, their lifetimes, and outgassing will be taken into account.

Factors that may limit the achieved performance of the etalon package are:

1. The degree of thermal stabilization and isolation achievable with the packaging,
2. Performance (uniformity, longevity) of the white light source,
3. Achievable Q of the WGM resonator while still maintaining single-mode performance, and
4. Overall coupling efficiency.

6.3 Measurement and Diagnostics

Characterizing the etalon in the laboratory with an absolute, independent calibration source is crucial for demonstrating the long-term utility of the system prior to delivery to the observatory. We will implement a multi-pronged test approach to quantify the long-term performance of the packaged etalon system. We will: 1) probe the absolute stability of a single etalon resonance, 2) measure the chromatic stability of the resonator by the monitoring the frequencies of multiple modes, and 3) precisely measure the overall spectral energy distribution and mode-to-mode intensity stability of the etalon output using a compact echelle spectrometer. For 1) and 2), we will leverage multiple scanning lasers to simultaneously probe the etalon transmission profile and compare against a known frequency standard, such as a laboratory frequency comb or atomic standard vapor cell [27], thereby transferring the accuracy of the absolute reference to the scanning lasers. Recording the precise positions of multiple etalon modes over many months will verify that stability requirements are being met across the spectrum.

Two underlying frequency references will be used for this work. The first is a rubidium stabilized diode laser at 780 nm. The second will come from an optical frequency comb locked to a GPS disciplined oscillator (GPSDO) which will provide a frequency uncertainty of less than 10^{-11} at times greater than 1000 seconds. The comb spans ~1000 nm to ~2000 nm, and will be used to lock a 1560 nm Orion RIO laser. The stabilized RIO laser light will then be sent through a periodically poled, magnesium doped lithium niobate ridge waveguide chip for 1560 nm triple harmonic generation and pigtailed with PM480 fiber (single mode at 520nm and 780nm).

We will explore locking laboratory lasers to individual etalon modes, via Pound-Drever-Hall (PDH) or similar techniques, and heterodyning the etalon-locked lasers against known modes from a broadband (unfiltered) laboratory LFC. This technique also probes the stability of the etalon lines with a potentially simpler laboratory setup.

A 10^6 second stability test requires monitoring the frequency stability (Allan Deviation) of one or more WGM etalon lines for ~2 weeks, which can be readily accomplished in a laboratory given the resources and timeline for development under this program. Longer test periods, e.g. 10^7 seconds, require continuous data logging for 4 months, and may be possible in Year 3 of the program. Measurements on longer time scales is clearly well beyond the scope of this program. However, the Allan Deviation curves will reveal a great deal about the nature of the drifts in the etalon; true white noise should average down quickly. For drifts resulting from intrinsic design, material properties or operating procedures, then the standard deviation will be a measure of that bias, not the white noise. The stability measurement we are able to perform during this program will indicate the time scales over which these drifts act and advise future investment, if so needed.

By way of comparison, NEID's etalon experiences a daily drift at the ~10^{-10}/day level. This is not consistent with the cavity ULE aging, but may be dominated by the optical contacting stresses settling over time. In the case of the compensated WGM etalon, changes in material stresses will serve to change the thermal turning point, which we should be able to adjust for by tuning the temperature. The thermo-refractive fluctuations in the etalon only impose a limit to the optical frequency stability of ~5×10^{-15} at a second, but the stability floor may be imposed by the clock reference for the fiber laser comb, at the level of 10^{-12} over longer time scales.

We will use a benchtop single-mode-fiber-fed cross-dispersed echelle spectrometer to monitor the full spectral output of the etalon system. The instrument is an existing design that will be provided to JPL for a period of several months during the etalon testing phase. The spectrometer is thermally stabilized and fits onto a small breadboard; it allows for two spectra to be recorded simultaneously through two single mode fiber inputs. This will enable us to demonstrate the broadband behavior of a WGM resonator source against a reference spectrum. The spectrometer is moderately high resolution (R~65,000, sufficient to resolve separate etalon modes at >11.5 GHz spacing for wavelengths redward of 450 nm), and will record repeated broadband (400 nm – 800 nm) spectra of the etalon output. We will analyze these data to ensure mode-to-mode and broadband intensity fluctuations are within the 10 dBm specification. Further, we will have access to the high-resolution Fourier-transform ultraviolet spectrometer (FTUVS) at the Jet Propulsion Laboratory's Table Mountain Facility [28] to ensure that the etalon mode shapes remain stable at the resolving power of the spectrograph. The FTUVS instrument is designed with an unapodized resolving power near 500,000 at 300 nm, or 1.8 GHz. The spectral coverage is <300 nm to 1000 nm. Ultimately, we will target a demonstration at a RV spectrograph with an existing calibration source such as NEID or Keck Planet Finder depending upon availability of engineering hours.

The etalon output will be fiber coupled using a collimator, and thus can be coupled to one of the optical fiber array inputs on either of the NEID of KPF instruments. We will have to meet maximum optical power per mode requirements specific to each of those systems to match the flux of the target star under observation by providing the appropriate attenuation of the etalon light. In the case of NEID, the calibration light is sent through an integrating sphere, and is attenuated by 60 dB. In the case of KPF, no integrating sphere is used, and ~10% throughput of the calibration light is expected. Given the broadband nature of the etalon output, photonic crystal fiber (PCF) - 'endlessly single mode fiber' by, e.g. NKT photonics - is likely to be used. Once coupled to the multimode fiber used in the instruments, the calibration light will be subject to the same mode scrambling as the science light. It will be important to log etalon parameters along with other instrument telemetry with same facility time stamp for a demonstration; modification of facility software will be required for permanent data logging. The reference comb will require power, as will the white light source, the lifetime of which will also be a factor for long-term operation. Access to the facility GPS signals will be required. In summary, we foresee no major risks to implementation, but careful programmatic coordination will be required so as not to interfere with the prime science program and schedule.

We will have access to a traditional PRV FP etalon for comparative performance evaluation against a commonly used system. The etalon system we will use is an improved version of the system used at MAROON-X, and is baselined as the calibration source for the iLocater instrument at the Large Binocular Telescope and the Keck Planet Finder spectrometer. It is housed in a vacuum chamber with nested layers of thermal control with a performance of <50uK, and is fed by 'endlessly single-mode fiber' manufactured by NKT Photonics. It covers the wavelength range of 380 nm to 950 nm. Fabry Perot etalons with spacers that provide either 37 GHz or 15 GHz free spectral range will be available, with a finesse of >40 (linewidth < 375 MHz). The system is integrated with a Doppler-free saturation spectroscopy setup to reference the nearest etalon line the hyperfine transitions of the Rb D2 line at 780 nm. Additionally, we have a second laser and gas cell to monitor the stability of another line by using Cesium at 852 nm in the same manner. Using this finely tuned etalon system as a benchmark, and recording both simultaneously in the benchtop echelle spectrometer, will provide a way to demonstrate the performance of the new WGM resonator etalon architecture in the lab.

An erbium fiber frequency comb based on a compact and highly reliable design [29] will be referenced to a GPSDO by phase locking both degrees of freedom of the frequency comb (the offset frequency and the repetition rate) to the 10 MHz GPSDO output. Performance of the GPSDO oscillator will be verified against a Hydrogen MASER. The complete frequency chain including GPSDO, digital locking controls, and RF signal conditioning will be tested on a NIST frequency comb with a design identical to the JPL comb. The optical stability of this locked system will be fully characterized at 1550 nm by comparison to a NIST cavity stabilized laser and a hydrogen MASER to both verify $<10^{-11}$ uncertainty at times greater than 1000 seconds and to determine how much the averaging time can be shortened while supporting the $<10^{-11}$ level.

Accurate temperature measurements will be critical; the best commercially available temperature sensing device was found to be a standard platinum resistance thermometer (SPRT). The SPRT datasheet shows that the triple point resistance is stable to +/- 0.0001Ω (+/- 0.001°C) per year. The team is planning to use the SPRT as our sensor for the external thermal electric coolers. The thermal suppression factor from the package will be utilized to improve the short-term stability, and an active feedback from the reference laser will maintain the long-term stability. The team will place the SPRT in the outer layers where the they will sense the larger temperature variations from the outside elements (greater than +/- 0.001°C). After the active feedback from the thermal electric cooler, the residual temperature fluctuation will be passively damped and effectively rejected by the package, and only a small fraction will reach the resonator.

6.3.1 Fiber laser comb sum frequency generation

The reference laser that will serve as a bridge between the comb and the etalon will also be locked to the comb to verify long-term stable operation and will be tested with a periodically-poled lithium niobite (PPLN) waveguide (magnesium oxide-doped) and erbium doped amplifier to ensure that >100 μW of light is generated at the tripled wavelength (520 nm), and > 1 mW is generated the doubled wavelength (780 nm). We will also test the reference laser against the etalon. If we are reliably able to tune the reference laser and the etalon such that both the 520 nm and 780 nm reference laser frequencies fall within 500 MHz of an etalon mode, then we can greatly reduce the required optical power by using a silicon avalanche photodiode instead of a high-speed silicon detector.

If additional wavelengths are needed to query the stabilized resonator, harmonic generation of 390 nm light should also be possible, but the ultimate power levels are speculative.

6.3.2 Use of Commercial-off-the-Shelf (COTS) instruments

With the exceptions of the compact fiber laser comb, which was built under direction by NIST from commercial fiber components, the hydrogen MASER that is a facility instrument at NIST, and the spectrograph and FP etalon for comparative measurements to be loaned by Macquarie University, the instruments used in diagnostics and operation of the WGM etalon are all commercial items. The following table provides a list of the vendors and major instruments planned for use in this program. Smaller components are readily available from vendors such as ISOTECH, Thorlabs, Newport, and Minicircuits.

Table 1 - Commercial instruments to be used in the WGM etalon development program.

Vendor	Instrument
Orion	RIO laser (1560 nm)
Vescent	Rubidium locked laser (780 nm)
ADRV	SFG/SHG pigtailed PPLN waveguide
SRS	GPS Disciplined Oscillator – e.g. model FS725
Thorlabs	OSA 201C (350 nm -1100 nm)
NKT Photonics	Photonics crystal fiber (LMA-PM fiber)
Tektronix	Spectrum Analyzer

It should also be noted that prior to obtaining access to the Macquarie University spectrograph, we will be using an optical spectrum analyzer to examine the etalon spectrum. The resolution of the OSA at the blue end of the target bandpass is not better that 3 pm at 350 nm, while a 25 GHz mode spacing at 400 nm corresponds to 1.3 pm. We will therefore only be able to resolve the envelope of the spectrum initially. This does not affect stability measurements, which are all conducted through heterodyne measurements.

7 Milestones

The following technology milestones address PRV spectrograph WGM etalon-based calibration source development, with the final objectives being the validation of the stability of the calibration lines and uniformity of the line intensity across the desired bandpass, and ultimately a demonstration of the technology at a telescope on a PRV spectrograph. Successfully achieving these milestones is an indication of the readiness of this technology to be deployed at a telescope with a visible band PRV instrument.

1. **To validate performance in the case of a compensated WGM resonator etalon, we plan the following milestones:**

Milestone 1a: Complete the design of a compensated WGM resonator etalon

Using software design tools, complete the design specifications for a compensated WGM resonator etalon that predicts a high intrinsic Q factor, mode spacing of 10-25 GHz, and single mode-like performance in the 400 nm - 800 nm spectral range. Demonstrate via numerical simulations that the resonator can be stabilized to better than 10^{-11} per 1 second to 1-year integration time at an achievable thermal turning point.

Risk/Difficulty: Low - similar efforts conducted previously for CaF_2 proof-of-concept demonstration.

Milestone 1b: Demonstrate an effectively single mode spectrum of a composite WGM resonator etalon using single wavelength measurements.

Using a composite etalon with integrated prism couplers and housed in packaging to control contamination, humidity, and temperature, demonstrate single mode-like performance with one input polarization at two wavelengths between 400 nm and 800 nm separated by at least 200 nm with >40 dB contrast with any higher order modes.

Risk/Difficulty: Low to Medium – team has experience with coupling light through prisms and achieving single-mode like performance over an octave in the telecom band. Risk area is demonstrating this over an octave *in the visible*.

Milestone 1c: Demonstrate efficient white light coupling with a composite WGM resonator etalon with uniform intensity across a 400 nm to 800 nm bandpass.

Using a composite etalon with integrated prism couplers and housed in packaging to control contamination, humidity, and temperature, and a white light source with bandpass filters, demonstrate coupled intensity uniformity of <10 dB coupling variation with respect to the input light source across the 400 nm to 800 nm bandpass. Characterized the device for its optical insertion loss across the operation band by comparing the spectral luminosity profile of the input white light source to that at the output.

Risk/Difficulty: Low to Medium – intensity uniformity across the octave bandwidth in the visible is unknown. Can be affected with prism coupler.

Milestone 1d: Measure the turning point temperature at one wavelength

Using a composite etalon with integrated prism couplers and housed in packaging to control contamination, humidity, and temperature, lock a laser to a single mode of the composite WGM resonator etalon transmission spectrum and heterodyne the locked laser with a stabilized reference laser to measure the frequency drift as a function of temperature. Scan the temperature to identify the thermal turning point.

Risk/Difficulty: Low to Medium – This technique has been demonstrated previously by comparing compensated vs. non-compensated WGM microresonators.

2. **To validate performance in the case of a packaged compensated WGM resonator etalon, we plan the following milestones:**

Milestone 2a: Measure the stability of a packaged composite WGM resonator etalon at two wavelengths – short duration

Using an evacuated, hermetically packaged composite WGM resonator etalon assembly referenced to a frequency comb-locked laser, demonstrate frequency stability of 10^{-11} from 1 s to 10^4 s at two wavelengths in the bandpass between 400 nm and 800 nm separated by at least 200 nm.

Risk/Difficulty: Medium to High - the measurement technique is standard in other etalon development programs and straightforward to implement. Likelihood of achieving the target frequency stability at both wavelengths is unknown and is the highest risk area for the project. The package design is the most critical part of achieving this milestone.

Milestone 2b: Measure the stability of a packaged composite WGM resonator etalon at two wavelengths – long duration
Using an evacuated, hermetically packaged composite WGM resonator etalon assembly referenced to a frequency comb-locked laser, demonstrate frequency stability of 10^{-11} from 1 s to 10^{6} s at two wavelengths in the bandpass between 400 nm and 800 nm separated by at least 200 nm.

Risk/Difficulty: Medium to High – same risk as 2a.

3. To validate performance in the case of a packaged composite WGM resonator etalon on a high-resolution spectrograph:

Milestone 3a: Interface a packaged composite frequency comb-referenced WGM resonator etalon with a high-resolution spectrograph (R ≥ 65,000) and benchmark performance against a stabilized, bulk Fabry Perot etalon
Using an evacuated, hermetically packaged composite WGM resonator etalon assembly referenced to a frequency comb-locked laser and illuminated with a white light source with a band pass filter, measure the relative stability against a bulk Fabry Perot etalon for all lines in the 400 nm to 800 nm bandpass on two separate channels of a high-resolution spectrograph.

Risk/Difficulty: Medium – the stability of the FP etalon used for comparison will have been previously characterized in another facility. The assumption will be that its stability has remained unchanged. Thus, the WGM etalon stability will be a worst case estimate because it is the *relative* drift that will be measured.

Milestone 3b Interface a packaged composite frequency comb-referenced WGM resonator etalon with a high-resolution spectrograph (R> 65,000) and benchmark performance against a highly stable calibration source
Using an evacuated, hermetically packaged composite WGM resonator etalon assembly referenced to a frequency comb-locked laser and illuminated with a white light source with a band pass filter, measure the relative stability against another calibration source for all lines in the 400 nm to 800 nm bandpass on two separate channels of a high-resolution spectrograph.

Risk/Difficulty: Medium – completion requires access to instrument with another higher precision calibration source. Risk is largely programmatic instead of technical.

8 Milestone Data Package

The milestone certification data package will contain the following:

1. A narrative report that includes a discussion of how each element of the milestone was met, with a narrative summary of the overall milestone achievement and its repeatability.

2. A description of the system components and their significant characteristics.
3. A tabulation of the significant system operating parameters.
4. Representative spectrum analyzer traces showing transmitted etalon modes, their spacing, and wavelengths.
5. Spectrometer trace showing the envelope of the etalon transmission spectrum to display intensity uniformity.
6. Allan deviation curves for individual wavelength stability measurements
7. Test environmental condition data
8. Representative spectra of WGM resonator etalon lines and another reference calibration source from a high-resolution spectrograph.
9. Wavelength solution for the spectrograph generated from the etalon calibration lines.
10. A description of the data reduction algorithms, in sufficient detail to guide an independent analysis of the delivered data.
11. A description of the factors that limited the performance during the development program.

9 Success Criteria

The following are the required elements of the milestone demonstration. Each element includes a brief rationale.

9.1 Milestone 1a:

9.1.1 Etalon designed with 10-25 GHz mode spacing

9.1.2 Design of etalon shape with predicted single mode performance

9.1.3 Thermal turning point and compensation factor predicted

Rationale: This milestone sets the design requirements for the fabrication of the WGM resonator etalon.

9.2 Milestone 1b:

9.2.1 Bare etalon fabricated with intrinsic Q-factor of $\sim 10^9$

9.2.2 Coupling prisms procured and integrated with etalon

9.2.3 Single polarization mode verified

9.2.4 Measured line width of ≤100 MHz across the full bandpass of 400 nm to 800 nm

9.2.5 Free spectral range measured to be between 10 GHz and 25 GHz.

9.2.6 >40 dB power contrast for any higher order modes verified.

Rationale: This milestone is a demonstration of the core composite etalon structure to show that the features of line spacing and single-mode-like behavior are achieved.

9.3 Milestone 1b:

9.3.1 Verified coupling variation does not exceed 10 dB across the entire bandpass from 400 nm to 800 nm.

9.3.2 Optical insertion loss of <10 dB across the entire bandpass from 400 nm to 800 nm.

Rationale: Intensity variation of the calibration lines across the bandpass must not saturate some pixels on a spectrograph detector while providing inadequate SNR on others.

9.4 Milestone 1c:

9.4.1 Thermal turning point empirically measured.

9.4.2 Frequency stability while at the thermal turning point measured to be 10^{-10} from 1 s to 1000 s at a single wavelength.

9.4.3 Fiber laser comb stability characterized to better that 10^{-11} Allan Deviation over 10^{6} seconds

9.4.4 Reference laser locked to fiber laser comb over $>10^{5}$ seconds

9.4.5 Sum-frequency generated reference lines at 780 nm and 520 nm with ≥ 100μW at both wavelengths with 300 mW input at 1560 nm.

Rationale: This milestone verifies that the composite WGM resonator has reduced thermal sensitivity, validates laboratory diagnostic tool performance, and determines the initial stability of the etalon

9.5 Milestone 2a:

9.5.1 Packaging enclosure is designed fabricated

9.5.2 Frequency stability of 10^{-11} from 1 s to 10^{4} s demonstrated at two wavelengths in the bandpass between 400 nm and 800 nm separated by at least 200 nm.

Rationale: This milestone demonstrates frequency locking of the etalon to a stabilized reference at two widely separated wavelengths across the bandpass.

9.6 Milestone 2b:

9.6.1 Frequency stability of 10^{-11} from 1 s to 10^{6} s demonstrated at two wavelengths in the bandpass between 400 nm and 800 nm separated by at least 200 nm.

Rationale: This milestone demonstrates long-term stability of the resonator modes

9.7 Milestone 3a:

9.7.1 Successful interface of the stabilized etalon assembly with a spectrograph

9.7.2 Relative frequency drift of several representative WGM etalon lines from the 400-800 nm range to the reference calibration source is $< 3^{-10}$ (10 cm/s) from 10s to 1000s

9.7.3 Power fluctuations of several representative lines is less than 10% over 100 seconds with a white-light source.

Rationale: This milestone demonstrates performance of the full etalon spectrum in a laboratory environment

9.8 Milestone 3b:

9.8.1 Successful interface of the stabilized etalon assembly with a PRV spectrograph at an observatory.

9.8.2 WGM etalon package performance does not degrade from laboratory performance during transport.

9.8.3 Relative frequency drift of WGM etalon lines to the other calibration source lines are $< 3^{-11}$ (1 cm/s) from 10 s to 10^6 s across the bandpass from 400 nm to 800 nm.

Rationale: This milestone validates performance of the etalon in the field.

10 Schedule

As described in our selected NASA Strategic Astrophysics Technology proposal, our project development and test plan have a duration of three years. In short, we plan to accomplish milestones 1a, 1b, and 1c in year 1, milestones 2a and 2b in the second year, and milestones 3a and 3b in the third and final year of the program. Milestones 1 and 2 will be conducted in the laboratory environments of OEwaves, JPL, Caltech, and NIST. Interfacing of the etalon with high resolution spectrographs at telescope facilities shall occur in the third year.

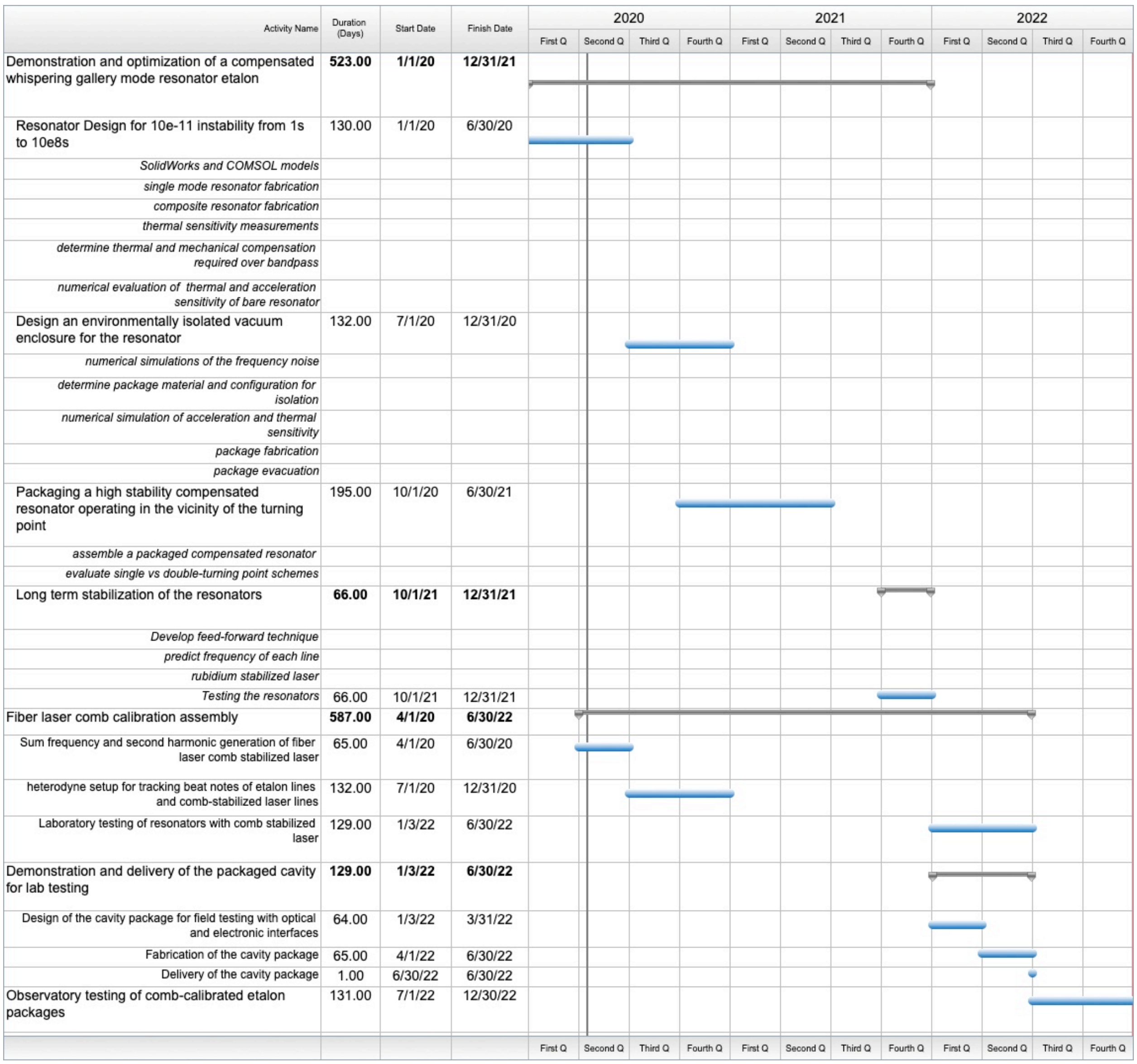


Figure 4 - WGM resonator etalon development and test schedule.

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