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ABSTRACT

Precise wavelength calibration is a persistent problem for highest precision Doppler spectroscopy. The ideal calibrator provides an extremely stable spectrum of equidistant, narrow lines over a wide bandwidth, is reliable over timescales of years, and is simple to operate. Unlike traditional hollow cathode lamps, etalons provide an engineered spectrum with adjustable line distance and width and can cover a very broad spectral bandwidth. We have shown that laser locked etalons provide the necessary stability with an ideal spectral format for calibrating precision Echelle spectrographs, in a cost-effective and robust package. Anchoring the etalon spectrum to a very precisely known hyperfine transition of rubidium delivers cm/s-level stability over timescales of years. We have engineered a fieldable system which is currently being constructed as calibrator for the MAROON-X, HERMES, KPF, FIES and iLocater spectrographs.

Keywords: wavelength calibration, exoplanets, stabilized etalon, radial velocity, Doppler technique, Echelle spectrograph, high-resolution spectroscopy, Fabry-Perot

INTRODUCTION

We have developed a laser locked etalon system for spectrograph calibration capable of delivering a calibration spectrum with stability in the cm/s range[1-3]. In this paper, we describe progress toward a system ready for deployment at a remote observing site, with long-term, low maintenance operation in mind. Since the development of the prototype described in Refs. 1-2, we have set up two systems: (1) the calibrator for MAROON-X (Gemini north), which is largely based on commercial components and is described in Ref. 3, and (2) an updated system based on lessons learned from the prototypes and the MAROON-X system. Below we outline the current system architecture that will be used for calibrators at iLocater (LBT), HERMES (Mercator telescope), FIES (NOT) and KPF (Keck).

SYSTEM COMPONENTS

The hardware of the calibrator system consists of five main components: (1) science etalon, (2) laser, (3) rubidium spectroscopy module, (4) confocal etalon, (5) white light source (see Figure 1). As in the MAROON-X system, we use single-mode fibers to send light between the different subsystems. This makes the subassemblies self-contained and easily interchangeable. To suppress etalon effects inside the fibers, we use angle-polished FC/APC connectors throughout the system. The whole system is controlled by a custom software through a modular National Instruments digital to analog interface, and precision temperature controllers.

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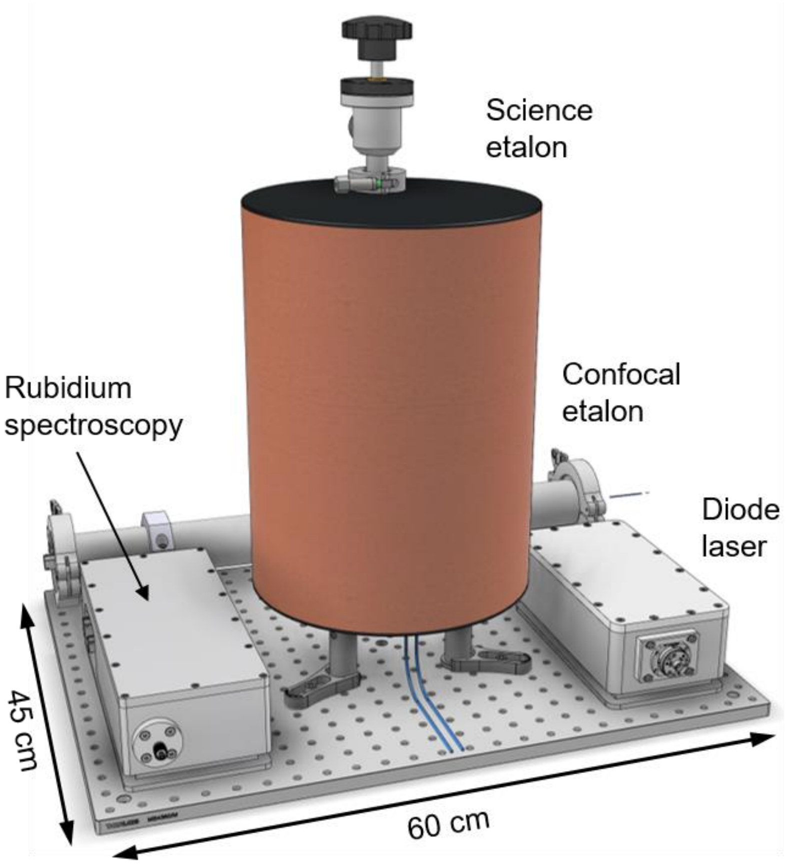

Figure 1: CAD rendering of complete etalon calibrator system. The complete system fits on a 60 x 45 cm breadboard. The commercial white light source is not shown.

Science etalon

The reliability of the science etalon is of key importance for our calibrator. To ensure the best possible long-term stability of the etalon cavity, we have chosen to use Corning ULE glass for the spacers and etalon mirror substrates. ULE has an extremely low coefficient of thermal expansion (CTE), which passes through zero at some temperature not far from room temperature. The temperature at which this zero crossing occurs can be controlled during manufacture. For the science etalon, we select ULE with a zero crossing around 25℃ so that we can stabilize the etalon temperature using a heater. During procurement we make sure to carefully select the material for homogenous CTE, and for low striae for the mirror substrates. The mirrors and spacers will be made from the same piece of ULE for the best CTE match. Like Zerodur, ULE exhibits some shrink, but it is about an order of magnitude smaller than for Zerodur and is not due to a phase change of the material itself. Prior to etalon assembly, the surface stresses of the ULE substrates and subsurface damage will be removed through polishing or etching.

Typically, soft mirror coatings are used in Fabry-Perot etalons to avoid problems with the coatings causing deformation of the mirror substrates through stress. We are using a very small beam, which helps to mitigate these problems to some degree. Careful coating design, and applying a coating to the back of the substrate, further help to keep the surface figure flat. Since we require ultimate long-term stability, and any change in the coating structure will cause shifts of the etalon lines, we plan to use very hard and dense ion beam sputtered (IBS) coatings for the etalon mirrors. These coatings provide excellent optical properties and the lowest possible water adsorption values. Indeed, we see shifts of the etalon lines for several days after pump down of the chamber and after the temperature is stabilized; we believe this to be caused by outgassing of the soft coating. Using IBS coatings requires us to assemble the etalons in-house, since the manufacturers of the substrates and spacers and the mirror coatings are different.

Science etalon enclosure

The science etalon is housed in a vacuum tank to thermally isolate it from the environment and to eliminate line shifts due to air pressure variations. The etalon is mounted vertically and rests on the polished steel ball-ends of three ultra-high precision adjustment screws (Kozak Micro Adjusters) that are mounted in a cup. Light is coupled into the etalon via a single-mode fiber and a reflective collimator (Thorlabs), which is screwed directly into the cup without further alignment mechanisms. The screws allow adjustment of the etalon to ensure that the input beam is perpendicular to the etalon mirrors, minimizing the sensitivity to angular misalignments, which lead to line shifts of the etalon. The transmitted beam is coupled into the output single-mode fiber via a second reflective collimator mounted on a monolithic kinematic mount. The fine adjustment screws are lockable. This arrangement provides the minimum required number of degrees of freedom and the minimum number of interfaces between the incident beam optics and the etalon to ensure the best long-term stability. Figure 2 shows the etalon mechanics.

We currently use reflective collimators from Thorlabs to couple light into and out of the etalon in order to provide wavelength-independent collimation. However, we find that we need to test each individual collimator, as some of them do not produce a collimated beam, or the beam does not exit collinear with the mechanical axis of the unit. The etalon mechanics is mounted inside a standard ISO-KF 160 tube, 275 mm long. We use a home-made vacuum feedthrough for the optical fiber. The etalon mechanics is surrounded by an aluminum heat shield.

We stabilize the etalon temperature extremely precisely using a nested, two-stage temperature control system. We use Kapton heaters to control the temperature of both the vacuum chamber wall and independently a heat shield made from soft aluminium for high thermal conductivity surrounding the etalon optomechanics. The heat shield is maintained ~0.5°C warmer than the chamber wall, which is in turn kept above room temperature. The entire vacuum chamber is surrounded by insulating material. For the tests described here, we simply use a Styrofoam box. Each Kapton heater is controlled by a separate PID loop. We have temperature sensors, but no heating elements, on the etalon holder itself, to monitor the temperature at the etalon. As shown in Figure 3, despite substantial variation in room temperature, well beyond what we would expect inside a temperature-controlled room at a telescope, we achieve a stability of <0.1 mK.

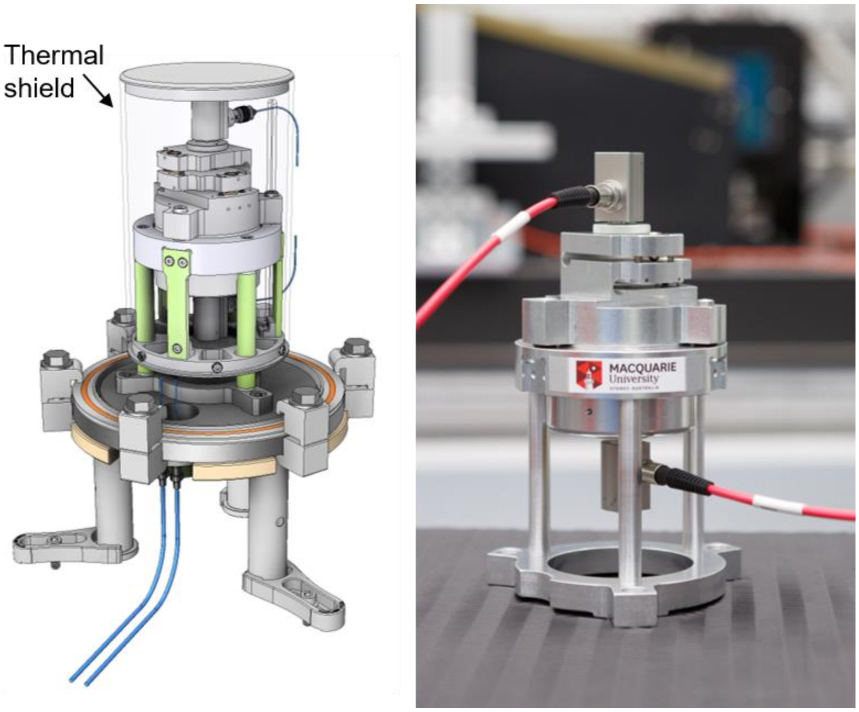

Figure 2: Left: CAD rendering of the science etalon mounting mechanics. The assembly is designed to be mounted inside a standard ISO-K 160 tube (only the lower end flange is shown). Components in green are made from G10 for thermal decoupling. Right: photo of etalon mechanical assembly, which was used for initial alignment of the Veloce spectrograph, part of which can be seen in the background.

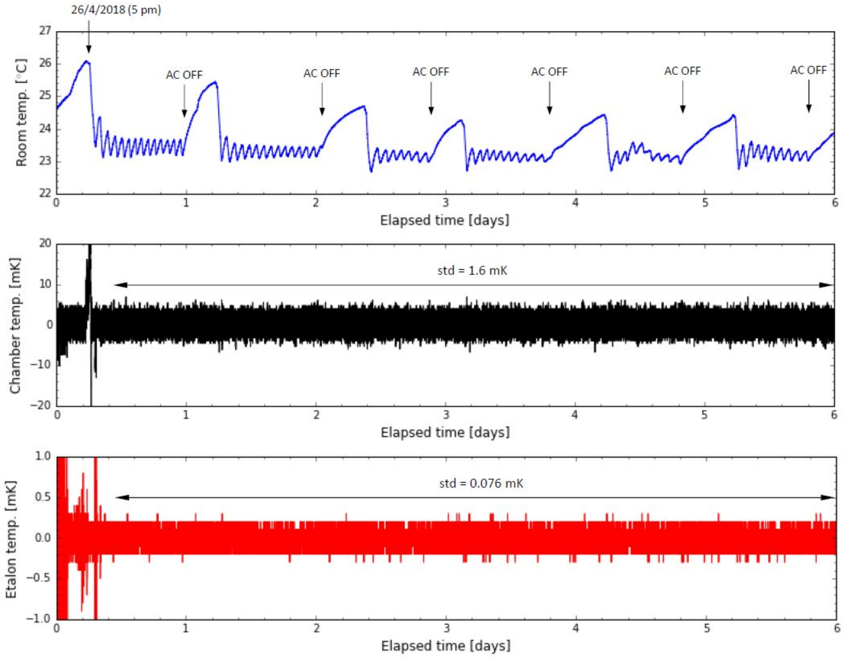

Figure 3: Performance of the prototype thermal control system. Top panel: room temperature. Middle panel: temperature of the vacuum chamber wall. Bottom panel: temperature of the mount that holds the science etalon. For the middle and bottom panels, the quantity plotted is the deviation of the measured temperature from the setpoint.

Lasers

We build our lasers in-house using a Littrow external cavity design derived from that described in Ref. 4. The current lasers are an improved version of our previous ones[1-2], including a stiffer grating mount design based on finite-element modeling, finer adjustment screws, and a hermetic enclosure to eliminate air pressure variations (Figure 4).

We use inexpensive, non-AR-coated laser diodes, which are sufficient to provide the small mode-hope-free scan range we require (typically ~3 GHz). Although our power requirements are moderate, we use 100 mW diodes and run them significantly below the maximum current to prolong their lifetime. Typically, our lasers are operated at 20°C and provide 10 mW output power (outside the window).

Our previous experience using commercial external cavity diode lasers indicated that air pressure variations in the laser cavity were a significant source of frequency drift. By changing the refractive index in the laser cavity, changes in air pressure cause changes in the output wavelength. Since we periodically modulate the laser wavelength by applying a ramp to the piezo, the result of this is that the rubidium lines end up on a different part of the nonlinear piezo-driven laser ramp. To mitigate this problem, we designed hermetically sealed housings for our lasers. The enclosure is made from a solid block of aluminum, with the lid and the exit aperture window sealed via O-rings. We use commercial electrical vacuum feedthroughs and glue them in with Epotek 301-2 epoxy. The lasers are flushed with dry air before closing the lid to avoid problems with condensation inside the laser assembly. A two-stage Faraday isolator is included inside the housing to protect the laser from back reflections; a fiber coupler is mounted on the outside wall.

We use a laser diode driver developed at TU Darmstadt, providing the required modulation inputs in a robust, rackmount system. It exhibits extremely low noise of less than 300 pA/sqrt(Hz) in the frequency range of 10 kHz – 1 MHz, leading to a very narrow laser linewidth which is much smaller than the etalon resolution[5-7]. The driver provides a slow and fast modulation input; we use the slow modulation input to implement a feedforward scheme, in which the current is ramped synchronously with the piezo ramp. This input also allows us to remotely adjust the current setpoint. Using rackmount modules makes it easy to replace a unit if maintenance is required.

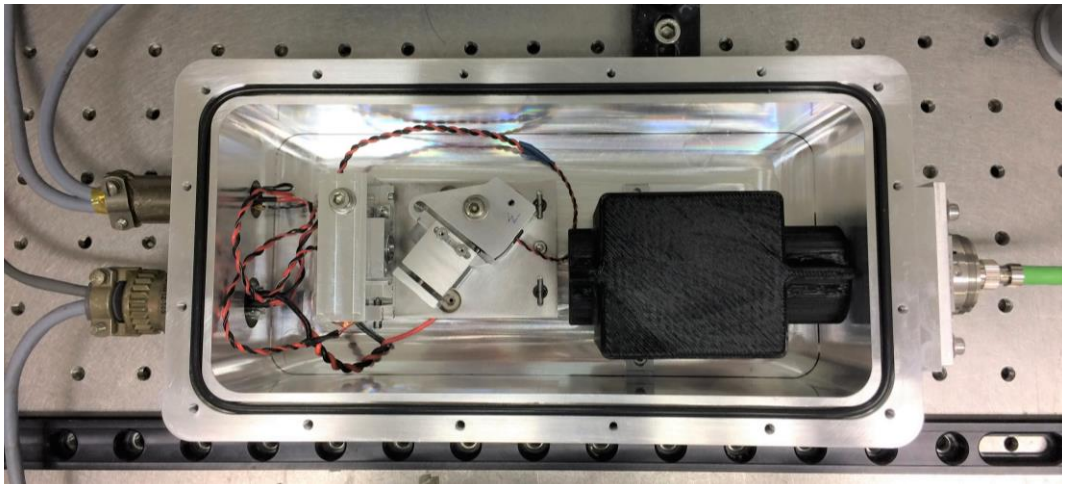

Figure 4: View inside hermetic laser enclosure. The laser cavity mechanics is on the left and the isolator is on the right (enclosed in a plastic protector for transport).

Rubidium spectroscopy module

Our frequency reference is the ^{87}Rb D2 transition at 780 nm, which we probe via saturated absorption spectroscopy[8]. While the transition frequencies of each hyperfine component of this transition are extremely well known[9], the measured frequencies depend on external factors including the Rb cell temperature, pump beam power, beam alignment, and ambient magnetic field[10]. Since the stability of our system is directly determined by the stability of our Rb frequency measurement and as we cannot directly detect systematic errors that stem from line shifts due to changes in the abovementioned factors, we made significant efforts to make our Rb reference measurement setup as long-term stable and decoupled from environmental fluctuations as possible (Figure 5).

We use the simplest possible optical geometry, in which the probe beam is derived by retroreflecting the pump beam from an uncoated glass surface after it has passed through the Rb cell. The optical components are mounted rigidly in a monolithic box-like structure, which is itself kinematically mounted inside a hermetic outer enclosure to isolate it from environmental changes or stress-induced misalignment. The inner box is precisely temperature controlled, and the Rb cell is separately temperature controlled and shielded against stray magnetic fields. The unit is fiber-coupled to make it insensitive to alignment changes. We have added a second beamsplitter to monitor the pump beam power entering the Rb cell, and plan to use this to implement a control loop to keep the laser power constant across the ramp, and to mitigate power changes when the diode ages.

In previous tests, we have seen small changes in the reference wavelength when handling commercial or self-built Rb spectroscopy setups. While still to be tested, we anticipate the new unit with its inner kinematic mounting scheme will significantly improve the mechanical stability over long time scales.

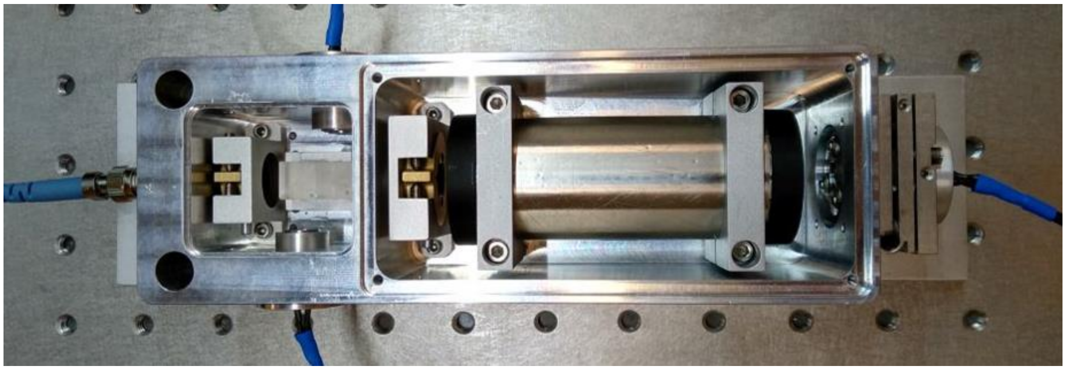

Figure 5: Photo of Rubidium spectroscopy module. The optical fiber input is on the left.

Confocal etalon

We use a 400 mm long confocal etalon to linearize the laser frequency ramp, which is inherently non-linear due to the non-linearity of the piezo. In previous work, the confocal etalon was simply mounted to the optical bench. To decouple the etalon from fluctuations in temperature and air pressure, as well as from vibrations transmitted by the optical table, we have designed a hermetic housing for it based on a standard KF50 tube. Figure 6 shows a CAD rendering of the system. The etalon will be mounted inside the housing using O-rings as radial support for vibration decoupling. The tube will not be evacuated but simply sealed to dampen out air pressure fluctuations.

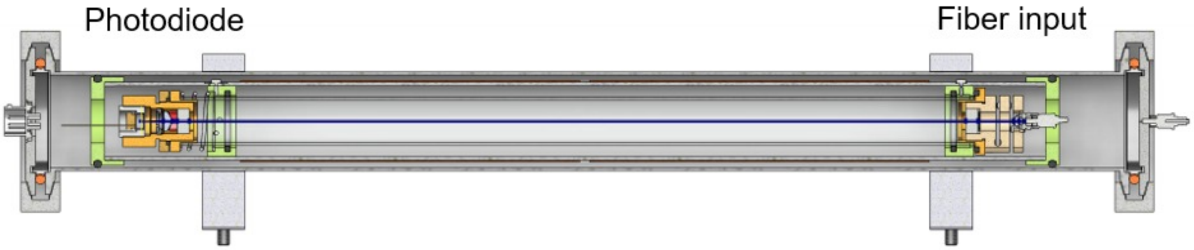

Figure 6: CAD rendering of the confocal etalon mounted inside a KF50 vacuum tube. Light is input via a single-mode fiber and the transmission is monitored by a photodiode mounted on the opposite end of the etalon.

SUMMARY

We have developed a robust, modular system for locking a Fabry-Perot Etalon to a hyperfine transition of Rubidium through saturated absorption laser spectroscopy. The Etalon system can be used as a highly stable wavelength calibrator for high-resolution Doppler spectrographs in the search for extrasolar planets. To build a robust calibrator, we have engineered a system that uses custom, hermetically sealed, temperature controlled subassemblies interconnected with single mode optical fibers. We have previously demonstrated that the internal radial velocity precision of our stabilization scheme is better than 3 cm/s; our improved setup is a major milestone towards deployment and reliable, long term operation at major observatories.

ACKNOWLEDGEMENTS

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