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Gudmundur K. Stefansson[a,b,c], Frederick R. Hearty[a], Paul M. Robertson[a,b,d], Eric I. Levi[a], Suvrath Mahadevan[a,b], Tyler B. Anderson[a], Andrew J. Monson[a], Chad F. Bender[a,b], Samuel P. Halverson[a,b], Yiting Li[a], Lawrence W. Ramsey[a,b], Arpita Roy[a,b], Christian Schwab[e], Ryan C. Terrien[a,b,f], Matthew J. Nelson[g], and Basil Blank[h]

[a]Department of Astronomy & Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA, USA, 16802;
[b]Center for Exoplanets & Habitable Worlds, The Pennsylvania State University, University Park, PA, USA, 16802;
[c]Leifur Eiriksson Foundation Fellow;
[d]NASA Sagan Fellow;
[e]Macquarie University, Sydney, Australia;
[f]NRC Fellow, NIST/University of Colorado, Boulder, CO, USA;
[g]The University of Virginia, Charlottesville, VA, USA;
[h]PulseRay, Inc., Beaver Dams, NY, USA

ABSTRACT

We present recent long-term stability test results of the cryogenic Environmental Control System (ECS) for the Habitable zone Planet Finder (HPF), a near infrared ultra-stable spectrograph operating at 180 Kelvin. Exquisite temperature and pressure stability is required for high precision radial velocity ($< 1\,\mathrm{m/s}$) instruments, as temperature and pressure variations can easily induce instrumental drifts of several tens-to-hundreds of meters per second. Here we present the results from long-term stability tests performed at the 180 K operating temperature of HPF, demonstrating that the HPF ECS is stable at the 0.6 mK level over 15-days, and $< 10^{-7}$ Torr over months.

Keywords: Doppler spectrographs, near infrared spectrographs, temperature-controlled instruments, pressure controlled instruments

1. INTRODUCTION

The prolific Doppler radial velocity (RV) method has lead to the discovery of hundreds of exoplanets in the past two decades. Further investments in the field of Doppler spectroscopy have been suggested in the literature,[1,2] both to further independent discoveries, and to ensure timely RV follow-up of exciting transiting exoplanet targets found by past (e.g., Kepler[3]), current (e.g., K2[4]), and future (e.g., TESS[5]) transit missions. Such followup measurements are vital for deriving mass estimates for these planets, and will prove to be immediately useful for prioritizing the target list for future transit spectroscopy with JWST.[6] In the context of this paper, observing M-dwarfs in the near infrared (NIR) to search for rocky planets in the Habitable Zone (HZ) offers many advantages. First, M-dwarfs are the most numerous stars in the galaxy, and it is in the NIR where the flux density of M-dwarfs peaks. Second, the low luminosity of M-dwarfs moves the HZ closer in to the host

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E-mail: gudmundur@psu.edu

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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star relative to Solar-type stars, and the low stellar mass of M-dwarfs further increases the RV amplitude of HZ planets, making a rocky planet in the HZ detectable with $\sim 1\,\mathrm{m/s}$ Doppler precision. This is why many NIR instruments (e.g., the Habitable zone Planet Finder (HPF),[7] CARMENES,[8] SPIRou,[9] and IRD[10]) are now being built and commissioned to achieve $\sim 1\,\mathrm{m/s}$ RV precision.

The Habitable zone Planet Finder is a high resolution (R=50,000) NIR Doppler spectrograph, to be commissioned at the 10m Hobby-Eberly Telescope at McDonald Observatory in Texas in early 2017. HPF has a goal Doppler RV precision of 1 m/s, with a 3 m/s baseline requirement. The main science goal of HPF is to detect rocky exoplanets in the HZ around nearby mid-to-late M-dwarfs. The operating temperature of HPF is 180 K, driven by the choice of a Teledyne Hawaii-2RG NIR detector array with a 1.7 micron cutoff. Further details on HPF and the HPF survey have been described elsewhere.[7, 11, 12]

Exquisite temperature and pressure stability of the spectrograph optical train is a fundamental requirement for high precision ($\sim 1\,\mathrm{m/s}$) RV spectrographs, as temperature and pressure variations inside the instrument can easily induce systematic Doppler drifts of several tens to hundreds of meters per second. Temperature variations lead to differential flextures between the spectrograph optics, and variations in pressure lead to index of refraction changes in the air within the spectrograph, both of which degrade the instrumental RV precision. The HPF spectrograph has a dedicated Environmental Control System (ECS), designed to minimize these error sources. Similar to the successful HARPS spectrograph,[13] HPF reduces environmentally caused RV errors by enclosing the full optical train in a thermally stabilized vacuum environment, isolating the optics from ambient temperature and pressure variations. The HPF ECS design has been detailed in a previous SPIE Proceeding.[14]

This paper focuses on describing results from long-term stability testing of the HPF ECS at the 180 K operating temperature. This ECS has demonstrated $\sim 0.6\,\mathrm{mK}$ temperature stability over 15-days, and $< 10^{-7}$ Torr pressure stability over months, even without the addition of the planned external passive thermal enclosure. We show that the HPF ECS is meeting both its short-term and long-term temperature and pressure stability requirements.

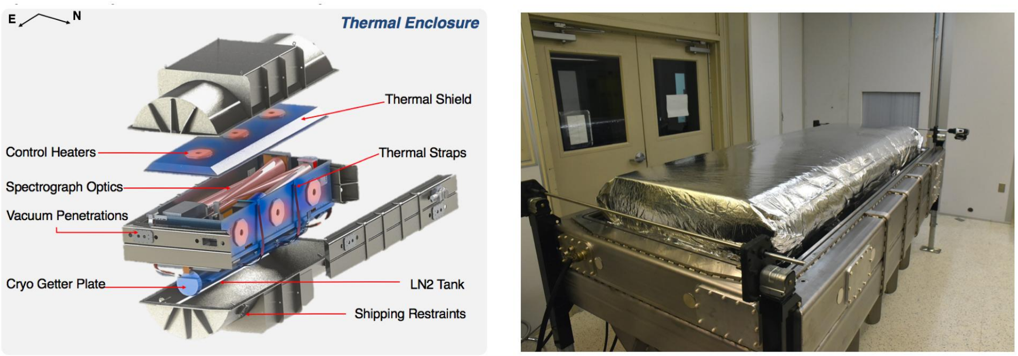
This environmental control system is versatile, capable of stabilizing large-scale Doppler spectrometers at a range of different temperatures from 77 K to $\sim 300\,\mathrm{K}$, with minimal modifications. Elsewhere in these Proceedings we discuss empirical long-term stability of the HPF ECS operating at elevated room temperatures of 300 K (as opposed to the 180 K operating temperature presented here), demonstrating nearly identical thermal control precision and temperature stability.[15] For this reason, this ECS can be used as a blueprint to stabilize other precision RV instruments—and this ECS is already being implemented for the NN-EXPLORE NEID spectrograph for the 3.5m WIYN Telescope at Kitt Peak.[15] The applicability and versatility of this ECS to stabilize other instruments is detailed elsewhere in these Proceedings.[16]

This paper is sectioned as follows. Section 2 gives an overview of the HPF ECS, and outlines its temperature and pressure requirements. Section 3 describes the stability test setup, and results from long-term stability testing are presented in Section 4. Section 5 gives a top-level summary.

2. THE HPF ENVIRONMENTAL CONTROL SYSTEM

2.1 Overview

Figure 1 gives an overview of the HPF cryostat, and the HPF ECS. Figure 1a shows an exploded view of the HPF cryostat, with the spectrograph optics, detector, and liquid nitrogen (LN2) tank fully contained within the cryostat vacuum boundary. An actively temperature controlled radiation shield with surface-mounted control heaters (red "stop-sign" heaters in Figure 1a) surrounds the optics, and is responsible for maintaining the optics at the 180 K operating temperature. A set of 16 copper thermal straps couple the radiation shield to the LN2 tank, sized to over-cool the radiation shield down to nominally 170 K; the control heaters actively heat the temperature of the shield from 170 K to the final 180 K operating temperature with milli-Kelvin stability. A set of Multi-Layer Insulation (MLI) blankets surrounds the radiation shield (see Figure 1), LN2 tank, and copper thermal straps, reducing radiative thermal coupling between the cryo-cooled components of the HPF ECS and the warm surroundings. At the observatory, the HPF cryostat will be placed in a dedicated thermal enclosure in the HET Spectrograph Room to passively reduce high-frequency temperature fluctuations.



a) b)

Figure 1. An overview of the HPF ECS: a) An exploded view of the HPF cryostat and ECS; b) an image of the HPF cryostat, and radiation shield covered in MLI blankets. Photo taken at the HPF Integration Lab at Penn State (upper cryostat lid removed; no thermal enclosure).

2.1.1 The HPF Temperature Monitoring and Control System

The HPF Temperature Monitoring and Control System (TMC) is responsible for keeping the radiation shield at the 180K operating temperature of HPF with milli-Kelvin stability long-term. Figure 2 gives an overview of the system. The system is composed of 14 control heaters mounted on the sides of the radiation shield, along with dedicated temperature sensing and driving electronics.

The TMC is composed of two completely separate temperature measurement systems: a Temperature Control System (TCS; green in Figure 2), and a Temperature Monitoring System (TMS; blue in Figure 2). The 14 control heaters have associated with them two temperature sensors mounted in the center hole of the control heater: one TCS sensor and one TMS sensor. The TCS sensor is used to drive the control heater in a Proportional-Integral-Derivative (PID) loop, to maintain the control heater at a fixed set-point temperature. The TMS sensor is exclusively used to monitor long-term temperature drifts in the TCS feedback loop, providing a fully

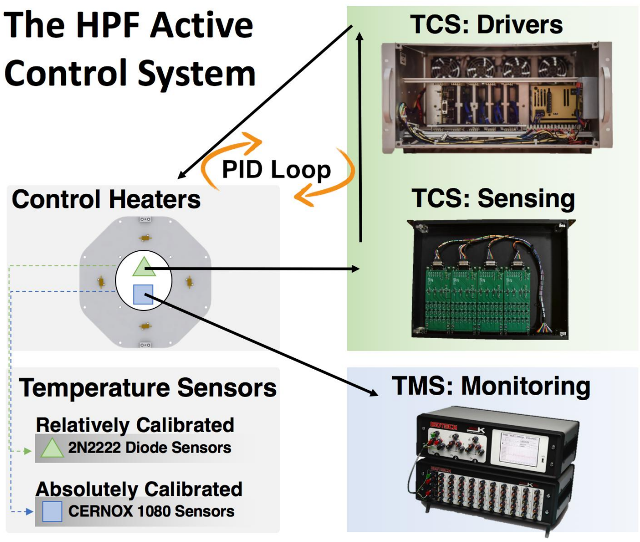


Figure 2. Overview of the HPF Temperature Monitoring and Control System (TMC), responsible for keeping HPF stable at the 180K operating temperature with milli-Kelvin precision long-term. The system consists of two completely separate sub systems: a custom-built TCS system, and a commercial TMS system. Each control heater has associated with it two temperature sensors, one sensor from each temperature sensing system, TCS and TMS.

independent measurement of the long-term thermal stability of the ECS. However, in the case of a TCS sensor failure, a TMS sensor can be used in the PID loop and control electronics. This provides a fully redundant and robust control system.

The TMS system uses a commercial MicroK 250 extremely low-noise thermometry bridge from Isotech. We chose to use LakeShore CERNOX 1080 resistive thermometers in the TMS due to their exquisite sensitivity at 180 K (0.1 mK measurement precision when coupled with the MicroK). The temperature sensors were absolutely calibrated by LakeShore Cryotronics. This system is used in a 4-wire configuration to minimize noise.

The TCS electronics are custom fabricated PCBs. The temperature sensing relies on measuring the voltage drop of a diode under excitation by a low forward current ($\sim 10\,\mu$A), sensitive to temperature. The sensor used is a 2N2222 bipolar junction transistor, behaving as a diode when just two leads—the emitter and base pair—are excited. These sensors are relatively calibrated to the absolutely calibrated TMS sensors.

2.1.2 Vacuum System

HPF uses two separate systems for vacuum operations.

The first system is only used during maintenance, composed of a turbo-molecular pump, backed up by a scroll pump. These two pumps are responsible for bringing the HPF vacuum pressure from ambient pressures to the $\sim 10^{-6}$ Torr level.

The second vacuum system is responsible for keeping the HPF vacuum pressure stable at the $< 10^{-7}$ Torr levels long-term (months to years), with minimal power draws and no moving parts. This system is composed of two different vacuum pumps. The first pump is a porous cryogetter similar to the cryogetters used in the APOGEE NIR spectrograph.[17] The getters are composed of LN2-chilled activated charcoal, directly mounted to the HPF LN2 tank, one getter on each end of the LN2 tank (see Figure 1). These getters are oversized, carrying ~ 1 L of activated charcoal each, an amount capable of maintaining the APOGEE cryostat at $< 10^{-6}$ Torr vacuum over years.[14, 17] The second pump is a NexTorr D-100 pump from SAES getters, a compact vacuum pump integrating a Non-Evaporable-Getter element, and a small ion pump to provide high pumping speeds for both active gases (e.g., hydrogen), and inactive gases (e.g., helium, argon, etc.). The NexTorr's high hydrogen pumping speeds (100 L/s) is the principal reason for its inclusion in the HPF vacuum system, as the HPF stainless steel cryostat out-gassed non-negligible amounts of hydrogen in the initial vacuum pumpdown cycles. This hydrogen out-gassing problem of the HPF cryostat, and its solution, will be discussed further in Stefansson et al. 2016 (in prep).

2.2 HPF ECS stability requirements

Table 1 summarizes the main requirements for the HPF ECS at the 180 K operating temperature. The aim of the long-term environmental stability tests presented in this paper is to verify that the HPF ECS can meet these requirements. The requirements were determined using a thermal RV error budget methodology, similar to the one described elsewhere in these Proceedings,[18] in order for HPF to reach its RV precision goal of $1 - 3$ m/s.

Table 1. A summary of the HPF ECS stability requirements.

Stability	Requirement
Temperature: Long-term	10 mK
Temperature: Short-term	3 mK requirement; 1 mK goal
Pressure: Long-term	$< 10^{-7}$ Torr

3. TEST SETUP OF LONG-TERM STABILITY TESTS AT 180K

Figure 3 shows an overview photo of the HPF ECS test setup during long-term stability testing at the 180 K operating temperature in the HPF Integration Lab. The integration lab is a class 10,000 clean room, temperature controlled by a standard lab HVAC system to 293 ± 0.2 K. The spectrograph optics had not been integrated with the cryostat during this test. Although HPF will be placed in a passive thermal enclosure once commissioned at HET, the test results presented here did not use a thermal enclosure.

Figure 3. The HPF cryostat during long-term stability testing. The scroll and turbo pumps are only used during initial vacuum pumpdowns. They were turned off during long-term stability testing, leaving the charcoal getters and NexTorr pump to maintaining the vacuum. No additional thermal enclosure was used.

4. RESULTS FROM LONG-TERM ENVIRONMENTAL STABILITY TESTING

4.1 Long-term Temperature Stability

Figure 4 shows our results from a 15-day temperature stability run, showing the temperature as recorded by the TMS CERNOX temperature sensor on the middle of the optical bench. The optical bench is stable to ∼ 0.6 mK RMS over this 15-day interval. The inset plot shows the temperature drift of the bench during a 24 hour period where the peak-to-valley of the optical bench is well within a 1 mK band. The peak-to-valley drift band across the whole 15-day period is contained within a ±1.5 mK band. Comparing these results with Table 1, we see that the HPF ECS is meeting its temperature stability requirements.

We do observe low-amplitude small-scale drifts on the optical bench. The main cause of this temperature drift is due to daily LN2 fills. The LN2 in the LN2 supply Dewar is kept at high pressure, increasing its saturation temperature, and this warmer LN2 introduces a mild temperature spike in the HPF LN2 tank. We minimize this transient by depressurizing the HPF LN2 tank for a few minutes before and after each LN2 fill. Depressurizing

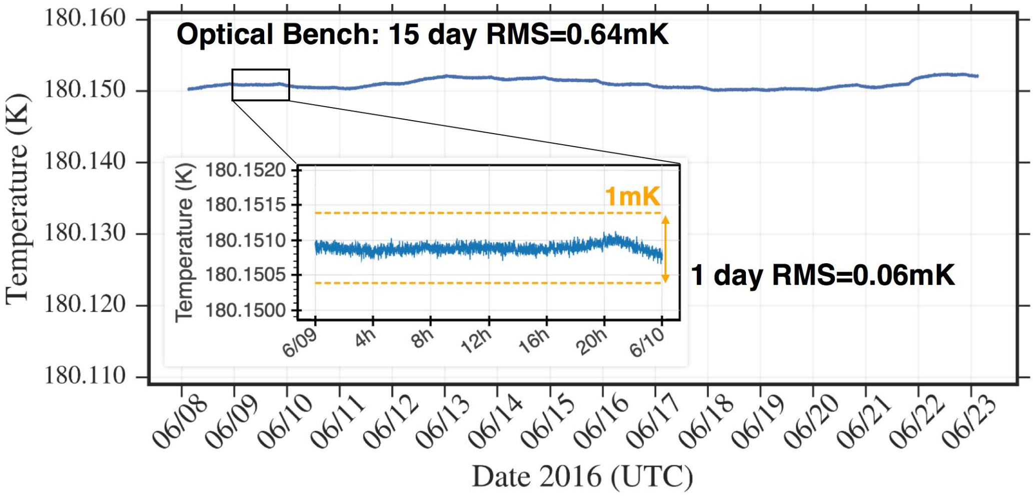


Figure 4. Long-term temperature stability of the HPF optical bench, demonstrating ∼ 0.6 mK stability over 15-days. The HPF ECS is meeting its temperature stability requirements.

the HPF LN2 tank momentarily lowers the saturation temperature of the LN2, compensating for the warmer LN2 from the supply Dewar. Throughout this 15-day period in Figure 4 the LN2 tank fills were done manually every day with this timed sequence. A dedicated LN2 autofill system (required for automatic fill operations at the observatory), capable of optimizing the LN2 filling sequence further, will further minimize the effect of this transient. This system will perform the LN2 fills daily every morning, having the transient occur long before nightly science operations.

4.2 Long-term pressure stability

Figure 5 shows the long-term pressure stability of HPF during a single 2.5 month vacuum cycle, using the LN2 chilled charcoal getters and NexTorr pump, demonstrating that the HPF ECS is capable of maintaining a $< 10^{-7}$ Torr pressure stability long-term. The periodic (bi-daily or daily) pressure spikes up to the $\sim 10^{-6}$ Torr level are due to daily/bi-daily LN2 fills during this period. As warm LN2 from the pressurized supply Dewar is fed through the HPF LN2 feed lines, the LN2 feed lines momentarily warm up and vibrate, causing molecules cryocondensed to the cold feed-lines to enter the gas phase. The trace amount of gas is promptly pumped out by the cryogetters and NexTorr pump. These transients are short (a few minutes), and have minimal effect on the pressure stability of HPF. The HPF LN2 tank will be filled daily each morning, long before observations are taken the following night. We conclude that HPF ECS is currently meeting its pressure stability of $< 10^{-6}$ Torr long-term, as is described in Table 1.

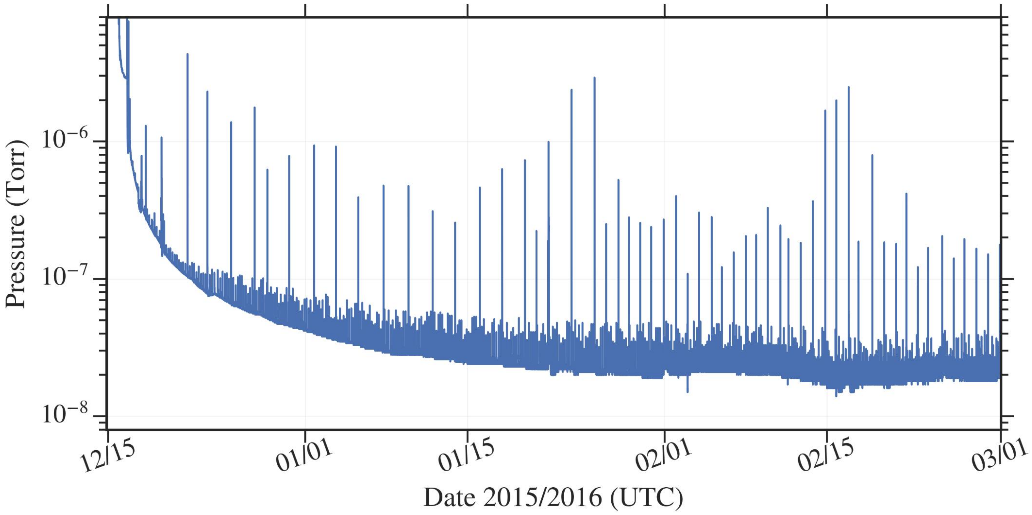


Figure 5. Long-term pressure stability of HPF. The periodic spikes from $\sim 10^{-7}$ Torr to about $\sim 10^{-6}$ Torr are due to daily/bi-daily LN2 fills during this period.

5. SUMMARY

This paper discusses the results from long-term stability testing of the HPF Environmental Control System (ECS), focusing on the achieved temperature and pressure stability at 180 K. This ECS has demonstrated 0.6 mK temperature stability over 15 days, and $< 10^{-7}$ Torr pressure stability over months, without a planned external passive thermal enclosure. These results show that the HPF ECS is meeting its temperature and pressure stability requirements. Based on this successful demonstration of the HPF ECS, this system is being adapted for use with the NEID optical spectrometer at the 3.5m WIYN Telescope at Kitt Peak, operating at 300 K.

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