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A highly stable optical bench system for the NASA-DLR BECCAL mission

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ABSTRACT

Quantum-optical experiments situated in a gravitationally bound experimental setup are fundamentally limited in numerous ways, such as the gravitational sag experienced by the trapped atoms or the limited free-evolution times of an atomic interferometer. These constraints can be overcome by deploying the experiment in a microgravity platform, such as the International Space Station (ISS). The Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL), a collaboration between NASA and DLR and successor to NASA's CAL mission, aims to achieve just that. Planned as a multi-user experimental facility, it will enable numerous quantum-optical experiments with ultracold atomic clouds of different isotopes of rubidium and potassium in the microgravity environment of the ISS. The optical capabilities of this experiment will be manifold: Atoms can be cooled and trapped using a 2D- and 3D-magneto optical trap (MOT). They can then be loaded into a red-detuned crossed optical dipole trap. Using blue-detuned light, arbitrary painted optical potentials can be applied. Atom interferometry along two separate interferometry axes is also possible. Fluorescence and absorption detection are available for imaging of the atomic ensemble. In this paper, we present a compact and robust optical distribution system which is required to enable this functionality. To this end, we use a combination of fiber-to-fiber coupled optical benches, and fiber-based components. This distribution system needs to withstand the vibrational loads during launch to the ISS, and needs to retain a good fiber-to-fiber coupling efficiency under varying environmental conditions, such as temperature fluctuations, without maintenance, through the multi-year mission time. We have designed a total of ten optical benches, eight for light distribution and two as spectroscopic units. The optical benches make use of our micro-optical bench toolkit based on the glass-ceramic Zerodur, which has mechanical properties akin to aluminium and a negligible coefficient of thermal expansion. The toolkit has been

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flight-tested in various sounding rocket-missions like KALEXUS, FOKUS, MAIUS-1 and will be used in the upcoming MAIUS-2/3 missions. However, as the size and weight budget are more constrained for BECCAL than for previous missions, we had to further compactify the system by mounting optical components on both sides of the optical benches. As these advancements require verification, we have constructed a number of scientific demonstrators, which have undergone rigorous testing.

Keywords: Zerodur, BECCAL, optical bench, laser system, miniaturization, microgravity, quantum optics

1. INTRODUCTION

One prominent example of the benefits of microgravity is atom interferometry. Whereas in gravitational platforms, atoms simply drop out of the experiment frame for too long free evolution times, this limitation does not hold for microgravity platforms. Typically, the resolution of an atom interferometer scales quadratically with the free evolution time, such that this is a major advantage.

There are a great number of different microgravity platforms.[1] While a drop-tower offers good microgravity conditions, the number of experimental cycles that can be run on a given day are usually very limited. Furthermore, the time of one experimental cycle is limited to the range of 10 s.[2] Parabolic Flights are limited by the microgravity quality. Sounding Rockets offer a long continuous experimental time, but usually only for one experimental cycle.

Compared to previously mentioned platforms, a satellite or space-station offers excellent microgravity conditions, and quasi-continuous operation, enabling many long experimental cycles. The DLR-NASA Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) mission is a multi-user facility that will enable quantum optical experiments with different isotopes of rubidium and potassium like atom interferometry aboard the ISS,[3] and a direct successor to NASA's CAL mission.[4–6]

However, this platform comes with several constraints. Firstly, the payload, including optical benches, needs to withstand the mechanical loads during launch. Once placed in the foreseen express rack locker, the experiment needs to run without external maintenance for a timescale of a few years in varying temperature conditions. This is in stark contrast to most lab-based setups, where frequent readjustment of the optics is needed. Furthermore, the payload needs to accommodate most optics used for light distribution that are also found in a lab in a ground-based setup while adhering to the limited weight and size budget of such a mission.

To match these requirements, we make use of our miniaturized optical toolkit specifically designed for such use-cases. The toolkit is based on the glass ceramic Zerodur, which has a negligible coefficient of thermal expansion of $\pm 0.007 \times 10^{-6}\,/\mathrm{K}$[7] and mechanical properties akin to aluminium.[8] Using adhesives with different curing conditions, miniaturized optical components are glued onto an optical bench made from Zerodur. This enables long processing and short curing times,[9] as well as the manufacture of composite components such as fiber couplers and collimators, as compared to bonding methods such as hydroxide-catalysis bonding.[10] During assembly, components are placed successively such that misalignments from the previous component can be compensated by the following component. The toolkit has been applied in previous sounding rocket missions: FOKUS (first launched on 2015-04-23),[11] KALEXUS (launched on 2016-01-23),[12] MAIUS-1 (launched on 2017-01-23)[13,14] and the upcoming MAIUS-2/3 missions.[15]

2. OPTICAL BENCHES FOR BECCAL

The overall system concept and scientific scope for the BECCAL mission has previously been outlined.[3] As a multi-user experimental platform, it will enable a wide range of scientific experiments in the fields of atom interferometry, coherent atom optics, the study of ensembles of scalar and spinor Bose-Einstein particles, quantum gas mixtures, as well as strongly interacting gases and molecules, and may serve as a demonstrator for quantum information applications. Compared to previous sounding rocket and satellite missions, an even more functionally complex experimental apparatus is needed to enable this complex scientific scope, which is especially evident in the number and frequencies of light-fields required: In addition to the light-fields close to atomic resonance used to cool, trap, manipulate and image the atoms, there will be a crossed, red-detuned optical dipole trap at

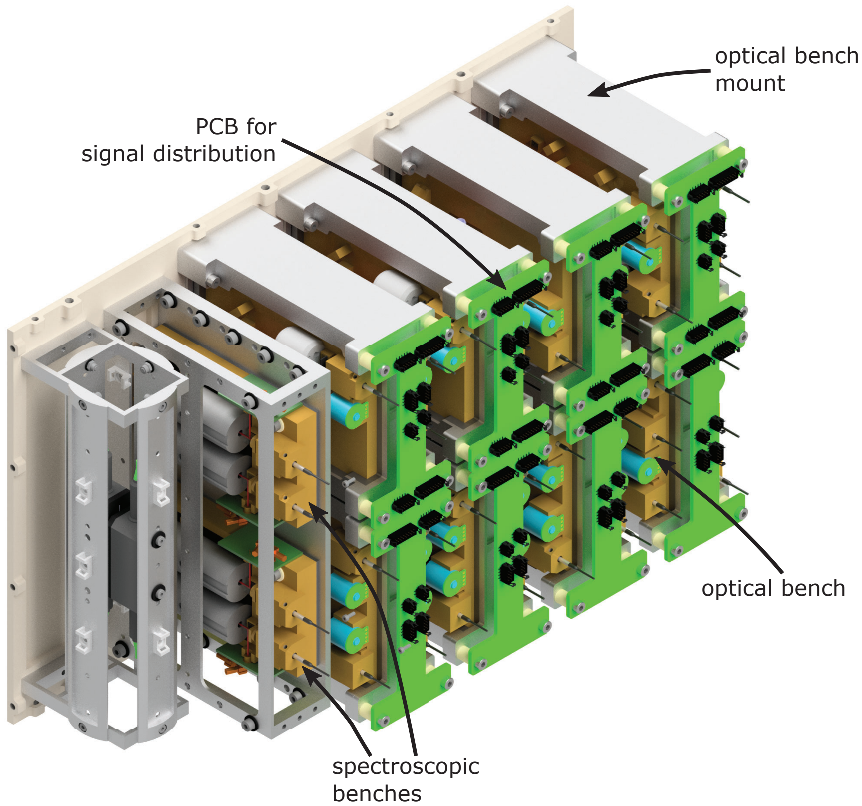


Figure 1. Rendering of the optical benches with mounting.

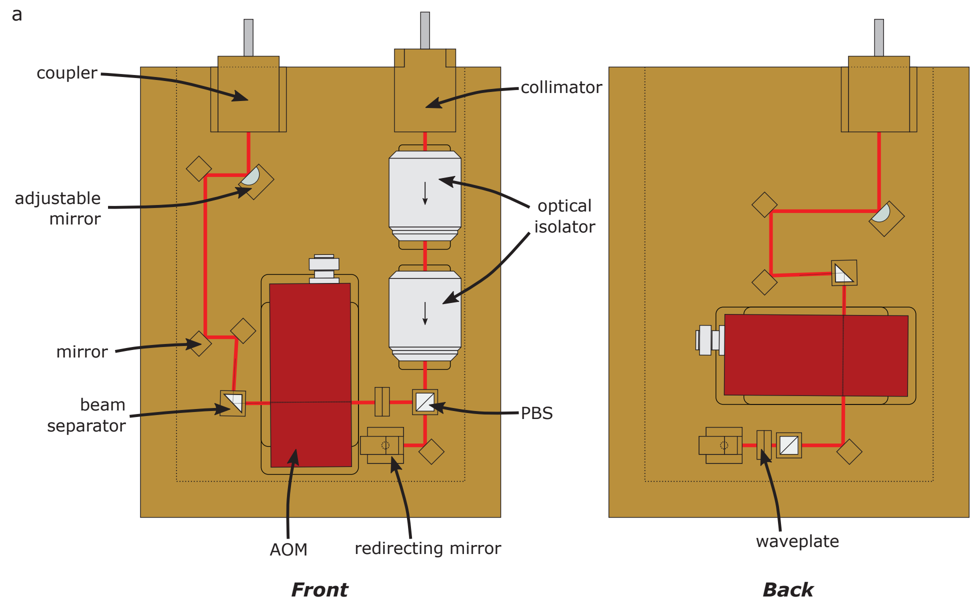
1064 nm, arbitrarily painted, blue-detuned potentials at 764 nm, as well beams for Raman atom interferometry along two separate axes.

As part of the BECCAL payload, we will produce eight optical benches in total for light intensity control and distribution, as well as two optical benches for frequency stabilization. The optical benches, as well as their mounting are shown in Fig. 1. The optical benches used in BECCAL are fiber-coupled, which means they receive light from an optical fiber, which is collimated to free-space using a collimator and then return it to an optical fiber using an optical coupler. In between, a variety of components are used for light manipulation, such as waveplates, polarization beam splitters (PBS) and dichroic mirrors to overlap and split light fields, and acousto-optic modulators (AOM) and shutters for intensity control. We use static and adjustable mirrors to guide the light from one component to the next. Unlike static mirrors, the pointing of adjustable mirrors can be adjusted after assembly of an optical bench, but will be locked into place before launch of the payload.

In contrast to previous sounding rocket missions, we have made some adaptions: To further reduce the form-factor of the optical benches, we mount optical components on both sides of the Zerodur benches. Static mirrors are used to guide light through holes in the optical bench onto the other side. The mounting of the optical benches has also been updated. Previously, optical benches were screwed onto a metal plate with a layer of rubber in-between. For the distribution benches in BECCAL, this is no longer an option as the benches are double-sided. Hence, they are held in place by an aluminium frame that grabs onto the edges of the bench from all sides. A thin rubber layer in-between frame and bench cushions the optical benches by ensuring that the loads from the holder are distributed evenly. This has the advantage that deformations due to local mounting forces are suppressed. Further, in this drawer-like design, all fibers enter and exit the optical bench on one side. This facilitates fiber guiding and enhances modularity. Lastly, we have expanded the toolkit to new wavelengths such as 764 nm and 1064 nm.

3. SCIENTIFIC DEMONSTRATORS

3.1 Optical bench demonstrator



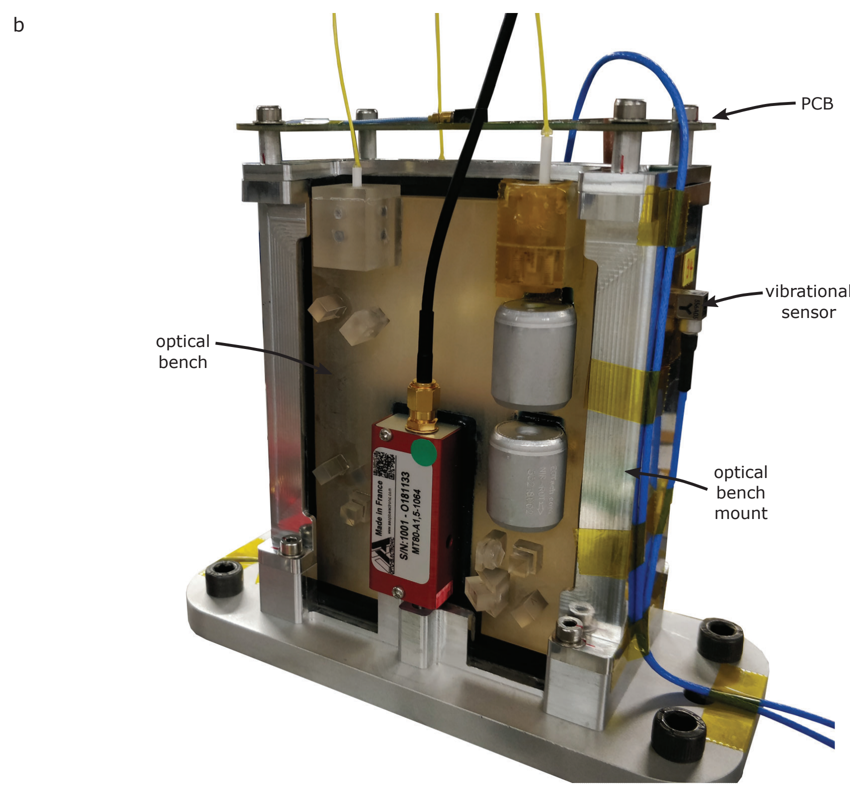


Figure 2. (a) Schematic of the bench layout for the 1064 nm demonstrator bench. The optical beam path is shown in red. (b) Image of the bench demonstrator (front side) as used in the vibration test, including mounting structure. Vibrational sensors were attached to the bench to record the frequency response during the test. A PCB on top of the assembly is used to distribute electronic signals.

To verify the functionality of our optical bench system, we have constructed a scientific demonstrator for the 1064 nm optical bench used to prepare the light fields for the optical dipole traps. The corresponding early layout of the optical bench for 1064 nm is shown in Fig. 2a. As on all optical benches, light is collimated from an optical fiber using a collimator. To avoid back-reflections, the light will first pass an optical isolator. For this particular bench, due to lack of availability of small form factor optical isolators at 1064 nm with a high transmission, we use a conjunction of two commercial optical faraday rotators for 780 nm to achieve a rotation of 45 deg. For all other wavelengths, we can use a single optical isolator. We use a PBS to separate the light field into two for use in a crossed dipole trap. Independent intensity control of each of the light fields is performed by using AOMs in 1st order for fast intensity control, and optical shutters for complete extinction. Both light fields are then coupled back into two separate fibers. A photograph of the demonstrator, including mounting can be seen in Fig. 2b.

To test if the optical bench, including mounting structure, could withstand the rocket launch, a vibration test along three axes was performed, including random vibrations at an exaggerated qualification level of more than 11 g_{RMS} and a half-sine shock for each axis. To assure that the benches retain their optical performance after the launch, the ratio of output to input power for each of the fibered outputs was recorded before and after each test. Bench and mounting structure performed well, without variations of power before and after the test of more than 10%. We attribute the majority of the variations present to a sub-optimal attachment of optical fiber to ferrule, causing a variable bend in the fiber during the vibration tests. As for the final flight model, commercial fibers will be used, this is of no concern.

3.2 Thermal optimization and tests

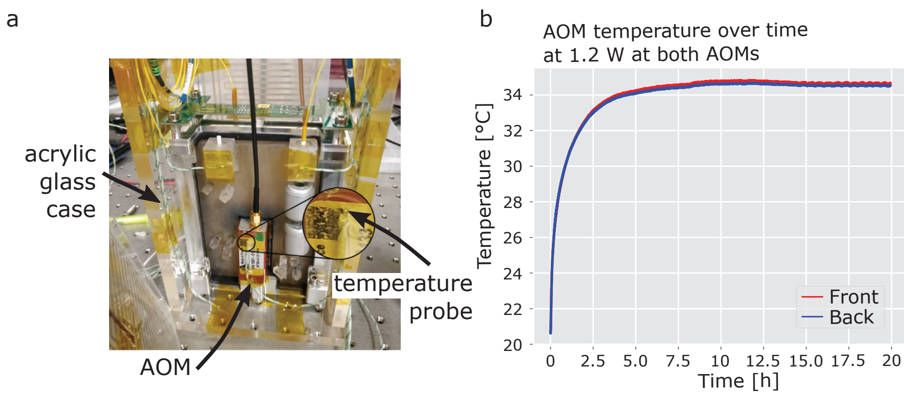


Figure 3. (a) Photograph of demonstrator as used in thermal tests. (b) Plot of the temperature evolution of the temperature probes mounted directly on front AOM (red) and back AOM (blue), at an ambient temperature of 21 °C.

Sounding rocket missions typically have a duration of only some minutes, such that any thermal heat-up during operation of the payload is usually uncritical. The continuous operation of the BECCAL payload imposes new challenges on thermal management. As Zerodur is a poor thermal conductor, we try to carefully limit the amount of heat generated by elements mounted on the optical benches. The two main heat sources are the motor used to actuate the optical shutter blades, as well as the acousto-optic modulators.

To evaluate how the operation of the AOMs affects the temperature of the optical benches, thermal tests on the demonstrator have been performed. To limit the effect of convection, the setup was put in an acrylic glass case. The AOMs were then switched on and the temperature monitored. The setup is shown in Fig. 3a, with the front acrylic glass wall removed for better visibility. Fig. 3b shows the temperature evolution of the AOMs: At a power of 1.2 W, which corresponds to the optimum operating power for AOMs at 780 nm and ambient temperature of 21 °C, both AOMs heated up by roughly 14 K. We are currently performing thermal tests at different operation parameters.

3.3 Mechanical Shutters

For previous sounding rocket missions, stepper motors were used to actuate an opaque blade between two states, one blocking the optical beam, and one letting it pass (see Fig. 4a and b). Most stepper motors, however, require

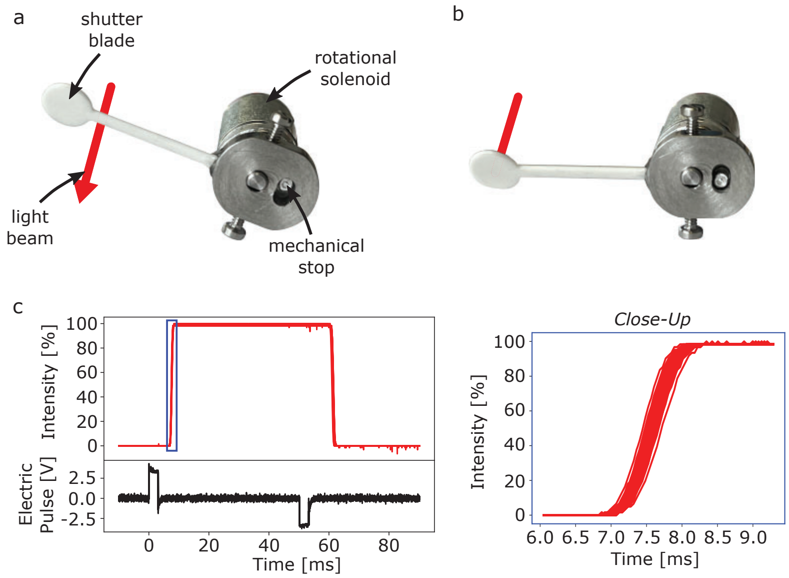


Figure 4. Depiction of optical shutter operating principle: (a) Open state. (b) Closed state. (c) Shutter opening signal. Forward and backward electric pulse (see black line) are applied to the solenoid, and the signal from a photodiode behind the shutter recorded (see red line).

constant power to maintain their position, and thus act as a continuous heat source. Thermal simulations show that stepper motors are thus unsuitable for our experiment, as they produce too much heat. Instead, for BECCAL, we plan to use bi-stable rotational solenoids. These only require power to switch between their two stable rotational states, thus greatly reducing thermal loads.

We are currently testing solenoids from different companies for their suitability. Likely the most important test performed is a test of the response time. Fig. 4c shows the recorded response times for one of the solenoids. The switching time (time between 10 % and 90 % extinction) below 1 ms is well sufficient for our purposes, especially since the shutters are always used in conjunction with AOMs for fast extinction. Solenoids from different companies show similarly quick response times. Note that this is only one of many tests: Next to verifying general electric and physical compatibility, we are currently finalizing an array of tests, such as a determination of detent and holding torque, vibrational tests to see if solenoid and blade can withstand the vibrations during launch, and extended life-time tests.

3.4 Spectroscopy Demonstrator

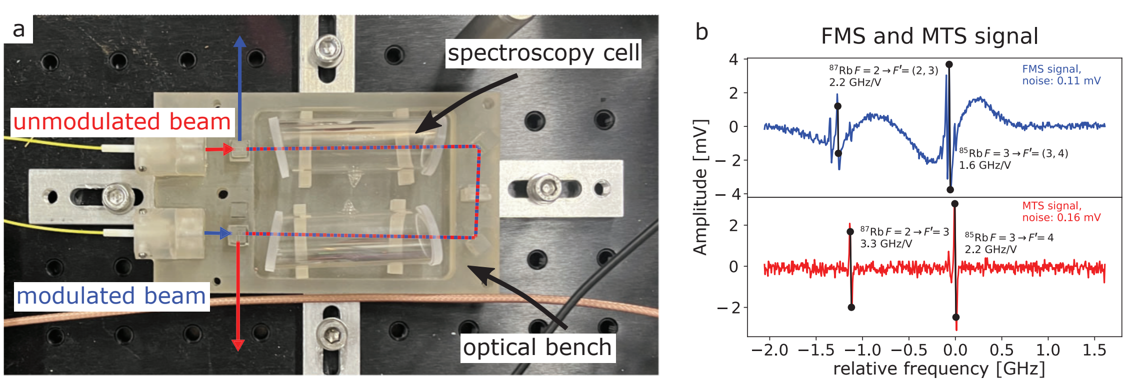


Figure 5. (a) Photograph of the spectroscopy demonstrator. The modulated and unmodulated light beams are illustrated as blue and red lines, respectively. The photodiodes used to record the signals are off-image. (b) FMS and MTS signals recorded using this setup. The relevant transitions and slopes are labeled.

To enable the broad scientific scope of BECCAL, we need precise and flexible frequency control of the scientific light fields, as well as a stable frequency reference. To this end, two spectroscopic benches will be used to enable the stabilization of one master laser each for rubidium and potassium to relevant transitions. The scientific lasers can then be stabilized relative to these transitions via an offset-lock.

A demonstrator of the spectroscopic setup was constructed, which is shown in Fig. 5a. A fiber-optic EOM is used to modulate one of the beams leading to the spectroscopic bench. Both modulated (blue) and unmodulated beam (red) enter the optical bench through separate collimators with perpendicular linear polarization. They then pass two spectroscopic cells filled with the relevant atoms. As the polarization of each beam is rotated by 90 deg between the cells, polarization beam splitters can be used to split off the respective beam to be redirected onto a photodiode. As both modulated and unmodulated beams are recorded and demodulated, this setup enables simultaneous frequency modulation (FMS) and modulation transfer spectroscopy (MTS), which in return enables a stable lock to multiple transitions for each atom.[16,17]

To characterize the spectroscopic setup, we simultaneously recorded FMS- and MTS-signals for various optical and electrical settings. The photodiode PCBs used to record the signals, which are normally glued to the side of the optical benches, were mounted off-image for easy adaption of the electrical parameters. One set of spectroscopic signals is shown in Fig. 5b, including error signal slopes and noise levels of the most dominant transitions. Judging by these parameters, a short-time absolute frequency stability in the sub-MHz-range should be achievable.

4. CONCLUSION

The DLR-NASA BECCAL project requires an optical distribution system that is both small and lightweight and which can withstand the mechanical loads during launch and temperature fluctuations during operation, and remain optically stable for a period of multiple years. In this publication, we have demonstrated how we have adapted and expanded our Zerodur-based optical bench toolkit, which is ideally suited for these environments, for this purpose. The most prominent adaption is the use of double-sided mounting of optical components, leading to further miniaturization, as well as a new mounting strategy. Ten optical benches, eight for light control and distribution, and two as a spectroscopic reference will be part of the BECCAL payload. Tests have been performed on a number of technical demonstrators to assess the feasibility of the adaptions: A technical demonstrator of a double-sided optical bench including mounting was constructed to test the thermal behaviour and mechanical stability, and performed well during a vibrational test. Using the same toolkit, a spectroscopic bench has been produced to successfully perform simultaneous FMS and MTS spectroscopy to enable frequency stabilization to a broad range of optical transitions. Further, to reduce thermal loads, we aim to use rotary solenoids instead of steppers motors to actuate shutter blades. Solenoids from various companies are currently undergoing rigorous qualification testing. With these advancements, the toolkit will help enable the broad scientific scope of the BECCAL mission.

APPENDIX A. ACKNOWLEDGEMENTS

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