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Operating and Maintaining NASA's Cold Atom Lab in Space

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Abstract

The Cold Atom Laboratory (CAL) aboard the International Space Station (ISS) is the first multi-user facility for studying ultracold quantum gases in microgravity. Since its launch in May 2018, CAL has enabled groundbreaking experiments with Bose-Einstein condensates of rubidium-87 and potassium-41, leveraging the extended free-fall conditions of the ISS to achieve observation times and temperatures unattainable on Earth. Microgravity enhances the precision of atom interferometry and quantum gas experiments, providing unique opportunities to investigate fundamental physics, including tests of the Universality of Free Fall and studies of quantum matter-wave interactions. Maintaining a quantum laboratory in space presents complex challenges. CAL has continuously evolved through hardware upgrades, software refinements, and robust anomaly response protocols. Lessons learned from CAL's extended mission provide essential insights for future space-based quantum research platforms such as the Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) and other precision measurement initiatives.

Keywords: The Cold Atom Lab, Bose-Einstein Condensate, Quantum, and International Space Station

1. Introduction

Quantum instruments are poised to offer remarkable opportunities for scientific discovery in the coming decades, with applications spanning various fields. However, operating a quantum laboratory in space comes with unique challenges. These cutting-edge instruments often include complex and delicate laser systems, require precise alignments, and demand exceptionally high levels of vacuum, among several other extreme requirements. The Cold Atom Laboratory (CAL), launched to the International Space Station (ISS) in May 2018, is the world's first multi-user quantum science facility designed to study ultra-cold atomic gases in microgravity. By utilizing the continuous free-fall environment of the ISS, CAL enables experiments with Bose-Einstein condensates (BECs) and quantum gases at temperatures below 100 picokelvin—much colder than what is regularly achieved in terrestrial laboratories.

This platform offers several key advantages over ground-based experiments. The microgravity environment allows for extended free-expansion times in a compact instrument, enabling precise measurements of quantum systems without the interference of gravity. These conditions are particularly beneficial for applications such as atom interferometry, where sensitivity increases quadratically with observation time. Additionally, CAL's unique environment has enabled researchers to investigate quantum states of matter with enhanced accuracy. This includes interferometry using rubidium-87 and potassium-41, remote quantum sensing through atom interferometry in space, and studies of quantum gases in bubble-shaped geometries.

However, maintaining a cutting-edge quantum lab in orbit requires continuous monitoring of on-orbit repairs and periodic upgrades. CAL was designed with modularity and flexibility, allowing hardware swaps, firmware updates, and new experimental protocols to be deployed remotely. This capability has been crucial for extending CAL's operational lifespan and enhancing its scientific productivity. Key upgrades have included the installation of a new atom-interferometry-capable science module (SM3) and integrating enhanced microwave sources for dual-species interferometry. These upgrades required astronaut-assisted ISS operations coordinated by the ground team at NASA's Jet Propulsion Laboratory (JPL).

Addressing anomalies and ensuring system reliability is a constant challenge. In 2021, CAL experienced a critical failure when its primary flight computer became unresponsive, necessitating a remote hardware replacement using onboard spare components. Following this incident, additional improvements were implemented to enhance the system's resilience and fault tolerance.

As CAL continues its mission, the facility is a valuable pathfinder for future quantum science platforms in space. Lessons learned from CAL's operation, anomaly resolution, and upgrades will guide the development of successor missions such as the Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) and other planned initiatives to push the boundaries of quantum research in space.

2. Recent Science Achievements

Since its initial commissioning campaign in 2018, over 100,000 BECs have been produced in the CAL flight instrument. Early studies of rubidium BECs produced on CAL already showed significant benefits and unique aspects of the space environment. Free-expansion times exceeding a second were attained using extreme decompression cooling in a magnetic trap to achieve gases with temperatures below 1 nanokelvin. Further, it was demonstrated that, at such low temperatures and in the absence of gravity, a second-order effect allowed trapping of atoms in an otherwise untrappable state [1].

Science campaigns by the Principal Investigator (PI)-led teams have ranged from the maturation of microgravity-enabled tools and techniques for manipulating ultracold gases, which will be needed for future quantum-gas-based mission concepts, to the study of ultracold matter in regimes and topologies that are impossible to achieve on Earth. Notably, techniques were developed using decompression cooling via adiabatic relaxation of magnetic traps to achieve extremely weak traps in microgravity [2]. Shortcut to adiabaticity and delta-kick cooling campaigns demonstrated atom transport with near 70 nm positioning accuracy, release velocities known to the 100 μm/s, and expansion energies corresponding to approximately 50 picokelvin [3]. Evidence of immiscible mixing of rubidium and potassium BECs was also observed for the first time in the absence of gravity [4]. Further, novel "shell-shaped" traps formed by applied RF and magnetic fields allowed CAL researchers to study ultracold atoms filling a bubble geometry for the first time anywhere [5, 6].

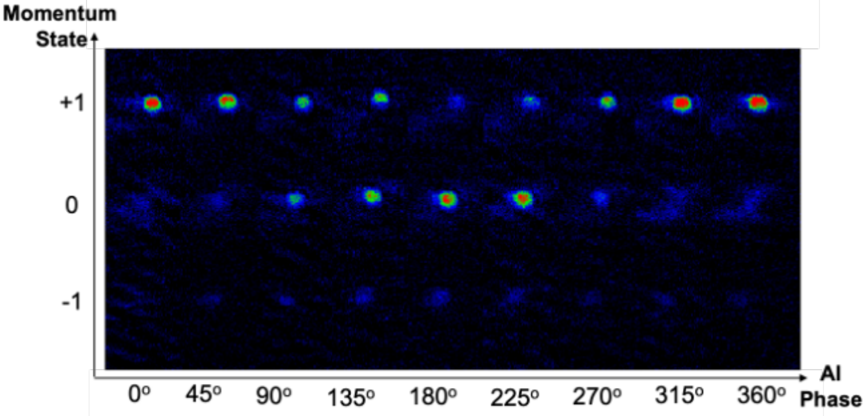

Fig. 1 Demonstration of atoms oscillating between momentum output states (m=+1 and 0) following a three-pulse atom interferometer sequence. The output state is controlled by changing only the phase of the final pulse of the atom interferometer laser. Prior to the readout, an individual atom's wavefunction exists simultaneously in both states. Atoms are also transferred to the m=-1 state attributed to residual transitions which are not suppressed in the gravity-free environment of space.

Precision force sensing using atom interferometry is particularly promising for future space missions that seek violations of the Universality of Free-Fall (UFF), a key tenet of the Einstein Equivalence Principle, and to search for local signatures of Dark Matter and Dark Energy. To mature this technology for space applications, three of the CAL PI-led teams focus on research with the CAL atom interferometer. Already, correlated signals from a dual-species atom interferometer using rubidium and potassium BECs have been demonstrated with CAL [4]. Further, the CAL atom interferometer has been utilized in various configurations to study the sensitivity of the interference fringes to laser frequency and phase, to detect fringes spatially written onto a BEC, and to serve as the first quantum sensor based on BECs in space by measuring vibrations on the ISS [7]. Figure 1 gives an example atom interferometer "fringe" which was produced by applying three laser pulses in a Mach-Zehnder configuration and varying the phase of the final laser pulse between 0 and 360 degrees. Efforts to increase the atom interferometer interaction time (and sensitivity) in a dual-species interferometer are ongoing, with the goal of maturing differential interferometry for a proof-of-principle test of Einstein's equivalence principle.

3. Instrument Operations

3.1 ISS Accommodation

The Cold Atom Laboratory (CAL) is housed within the International Space Station (ISS) as part of the EXPRESS Rack 7 (ER-7) located inside the Destiny Module near the station's center of gravity. This placement provides critical advantages for quantum experiments, offering a highly stable microgravity environment with perturbation-free expansion times far exceeding those achievable on Earth. The ISS offers a relatively benign environment and generous accommodations for space instruments, greatly facilitating the adoption of state-of-the-art technology for space applications. CAL, for example, has a volume of 0.4 m3 and a mass of 233 kg, allowing 565 W of average power, along with water and forced air cooling.

Unlike terrestrial facilities where gravitational forces significantly limit the duration of free expansion, the microgravity environment of the ISS allows CAL to perform experiments with ultracold atoms for extended observation times. This capability is essential for quantum metrology techniques such as atom interferometry, where sensitivity scales with the square of the interrogation time. With freefall times exceeding one second, CAL can achieve temperatures below 100 picokelvin, magnifying quantum effects to unprecedented levels.

However, the ISS microgravity environment is not entirely free from disturbances. Vibrational noise resulting from crew activities, mechanical systems, and external docking events can impact the stability of experiments. Of particular concern are quasi-steady state accelerations (with a frequency below 1 Hz), which ultimately limit observation times. Such accelerations arise from atmospheric drag and distance from the station center of gravity and are typically below 2 micro-g for CAL. Instrumentation attached to CAL, including accelerometers and magnetometers, continuously monitors the effects of the ISS environment to ensure data integrity.

In addition to microgravity, the International Space Station (ISS) is exposed to a complex radiation environment that includes galactic cosmic rays, trapped radiation belts, and transient solar particle events. Although the CAL science module is sheltered by the ISS's structure, radiation-induced noise is still a concern, especially for sensitive quantum states. Ionizing radiation can cause errors in the control electronics, degrade optical components, or interact with the ultracold atomic gases.

3.2 Operational Concept

A two-person operations team manages the Cold Atom Lab (CAL), consisting of a Mission Operations Systems (MOS) Engineer and an Instrument Operator. This team can operate CAL either from the Earth Orbiting Mission Operations Center (EOMOC) at JPL or remotely by connecting to the Real-time Ops Virtual Machine (VM) through Remote Desktop. At the start of each operations day, the MOS Engineer sets up the VM and establishes voice communication with the Huntsville Operations Support Center (HOSC) at the Marshall Space Flight Center (MSFC) using the Internet Voice Distribution System (IVoDS). HOSC provides the Ku-Band IP service, which is essential for communication with the CAL payload on ISS. Real-time communication with the ISS is maintained almost continuously throughout the day using the Tracking and Data Relay Satellite System (TDRSS) network. This near-constant communication allows CAL to carry out its unique operational concept of real-time scientific experimentation aboard the ISS.

The MOS Engineer monitors the IVoDS voice loops throughout the entire operations day to stay informed of other activities on the ISS that might impact CAL operations. When the CAL operations window opens for the day, the MOS Engineer uses IVoDS to contact the Payload Rack Officer (PRO) at HOSC and requests the activation of HPEG (HOSC Payload Ethernet Gateway) Commanding. Real-time commanding of the CAL Flight Instrument is achieved through a combination of UDP/RDP streams from the ISS using HOSC's Ku-Band UDP Direct Downlink service. The UDP stream serves as the conduit for the Flight Instrument to return real-time health and status telemetry, while the Flight Computer is commanded through the Remote Desktop over the RDP stream. The MOS Engineer verifies that HPEG Commanding is active by connecting to the Remote Desktop on the CAL Flight Instrument computer. All commands for the CAL flight software and instrument subsystems are executed during this Remote Desktop session.

After connecting to the Remote Desktop and enabling HPEG Commanding, the MOS Engineer hands over control of the Flight Instrument to the Instrument Operator. The operator initializes the instrument flight software and deploys the subsystems needed for science operations. The operator locks the laser subsystems, initializes the cameras, powers on the Tapered Amplifier Drivers, and sets the appropriate current for the atom dispensers. The operator will then verify that laser cooling of atoms has been achieved by executing a sequence to cool Rubidium atoms in a magneto-optical trap (MOT), then turning off the quadrupole magnetic field and allowing the temperature of the atoms to drop below 100 μK. After this has been confirmed, the operator will demonstrate that a Bose-Einstein Condensate (BEC) can be achieved. Doing this requires an additional evaporative cooling stage using an RF or microwave field. The atoms will begin to condense around a critical temperature of about 100 nK. The operator executes a sequence to produce a BEC about 12-13 times in a row to calibrate the system.

Each day, PI Science teams work with the JPL CAL scientists to provide science definition tables in order to run experiments using the CAL instrument. These tables are given to the MOS Engineer, who verifies that they follow all flight rules with an automated checker script. The MOS Engineer then uploads the tables from the ground system at JPL to the Flight Instrument computer using the HOSC CFDP (CCSDS File Delivery Protocol) tool, which transmits files to the ISS over the DTN (Delay/Disruption Tolerant Networking) service provided by the MSFC Tele¬science Resource Kit (TReK) software suite.

After the tables have been uploaded, the Instrument Operator runs them on the Flight Instrument using a timed series of commands. Executing this sequence produces a pair of images — an absorption and a reference image — which are automatically downlinked from the Flight Computer to the ground system via CFDP. On the ground system, the Instrument Operator can analyze the images using the JPL-developed image analysis tool, which calculates the optical densities for the expanded cloud of ultracold atoms from the absorption images, then performs a two-dimensional fit to determine how many atoms are present in the image, what fraction of the atoms are BECs, and the size and position of the atom cloud. This data is recorded in the daily operations log and can be provided to the PI Science Teams as requested. The Level 1 and 2 science data, including the raw absorption and reference images, are uploaded to the NASA Physical Science Informatics (PSI) archive for delivery to the external PI Science teams. CAL operations often produce several hundred image pairs daily in these experimental runs. Over the course of a month, two to three thousand experimental runs are performed on flight.

In addition to the images generated by the PI Science experiments, the CAL Flight Instrument also produces telemetry files and event record files (EVRs). If these files cannot be transmitted to the ground immediately, they are stored on the flight instrument. The MOS Engineer downlinks all these files from the Flight Instrument using CFDP, allowing them to be collected and archived by the CAL Ground Data System.

At the end of each day's experimental runs, the Instrument Operator follows several steps to power down the systems: they turn off the Tapered Amplifier Drivers, set the atom dispenser currents to zero, unlock and switch off the laser systems, and then shut down the instrument flight software. Once the flight instrument is back in its idle or "Standby" mode, the Instrument Operator hands control over to the MOS Engineer. The MOS Engineer then verifies that the instrument is in a safe state and contacts the Payload Rack Officer (PRO) at HOSC via the IVoDS system to request the disablement of HPEG commanding. After this process, the MOS Engineer checks out with the Operations Controller (OC) at HOSC and reports on the day's activities.

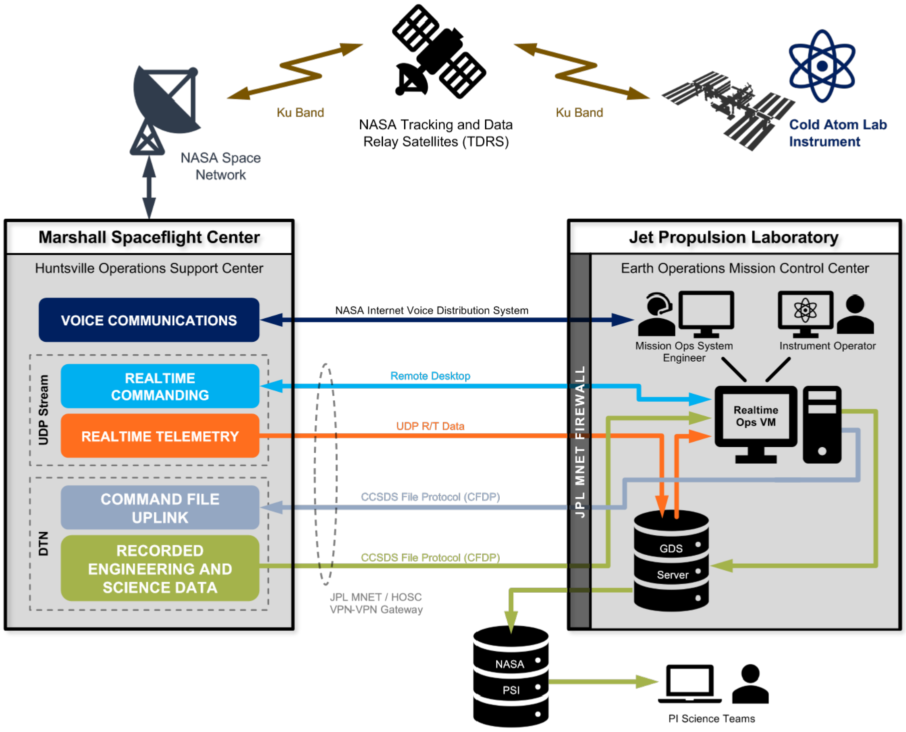

Fig. 5 CAL Mission Operations Architecture.

Anomalies, Repairs, and Upgrades

When an anomalous situation is encountered during CAL operations, the first step is always to ensure that the instrument is returned to a safe state. Once this is done, the Operations Team can proceed to categorizing the error — typically, this is either command error (operator error, faulty timing within an experimental definition table, or a single-event upset (SEU) induced miscommand), network communication error (e.g. DTN outage), or a hardware or software fault in the Flight Instrument. If the issue is due to a command error, a procedural note is made and, depending on the severity, an Incident Surprise, Anomaly (ISA) report may also be filed.

If the issue is determined to be network-related, there are steps that the operator/MOS on console follow to attempt to resolve the issue on their own. First, if it appears to be a network/connection issue, the MOS can ping various access points to determine where the breakdown is occurring. Depending on which pings succeed/fail, the MOS will either notify HOSC or restart the DTN nodes on the ground/flight computers. If, instead, the issue appears to be due to software error, as in the case of "missed" images or lack of atoms/low atom numbers, the operator can check laser locks and re-run calibration tables. If the issue persists, the operator will escalate the investigation to involve the scientists assisting with that day's operations, or further up to project management, depending on severity. The operator will also check previous ISA reports — if the same symptoms have been seen in the past and there are steps for resolution, the operator can follow those steps, while documenting the reappearance of that anomaly. If the anomaly appears to be due to hardware or software failure, the operator will notify the appropriate Cognizant Engineer(s), and the Cog-E and Project Management teams will become involved in the anomaly investigation and resolution. If deemed necessary, an ISA report is filed to document anomaly evidence and resolution steps.

Over CAL's almost seven-year lifetime, there have been 93 ISAs, with 79 of those fully documented, completed, and closed out. 14 remain open and under investigation.

3.3 Emergency Offsite Commanding Plan

For daily operations, CAL is reliant on JPL's server ecosystem of secure servers, virtual private networks (VPN), and virtual machines (VM) to ensure a secure data connection to HOSC and to Flight Instrument. However, in the event of a catastrophic failure of JPL infrastructure, such as during the 2025 Eaton Fire, CAL would lose the ability to both command and receive telemetry data from the Instrument.

To mitigate this risk, CAL has partnered with HOSC to install a VM server with a backup command VM at the HOSC data center. The backup command VM has been imaged with the same Tele¬science Resource Kit (TReK) software suite that enables CAL operators to interface with the CAL Flight Instrument.

In the event of an unexpected loss of service at JPL, the operations team is able to use a VPN to securely log onto the emergency backup VM and use it to command the instrument or downlink telemetry data. However, the physical distance between JPL and the HOSC data center increases latency, which complicates real-time command execution. As a result, this contingency plan is primarily intended for emergency commanding, e.g. to return the instrument to a safe state if instrument operations are interrupted due to a local event.

3.4 In-Situ Repairs and Upgrades

In 2018, the CAL payload was launched with a strategy for replacing its limited-lifetime components while in orbit. This strategy includes the replacement of optical amplifiers, lasers, specific flight computer parts, and alkali-metal dispensers, which are used to dispense atoms that form the building blocks of Bose-Einstein condensates (BECs). This capability allows the project to extend its scientific operations beyond the initial three-year primary mission. The CAL Operations Team continuously monitors telemetry data of these consumables to detect early signs of end-of-life behavior and to assess the health and status of the hardware systems rigorously.

When a consumable or replaceable component is determined to have reached its end of life, CAL will collaborate with the International Space Station Payload Operations Integration Center (POIC) to develop and qualify procedures for the safe and successful replacement of the component.

Additionally, the modular architecture of the CAL Flight Instrument provides unique opportunities not only to service malfunctioning or expired components but also to enhance operations by installing updated hardware with new functionalities.

3.5 Enhanced Science Module

The Cold Atom Laboratory (CAL) has undergone several hardware upgrades to enhance its scientific capabilities and extend operational life during its mission. One of the most significant upgrades involved the installation of a new atom-interferometry-capable science module, known as Science Module 3 (SM3), delivered to the ISS aboard the SpaceX CRS-19 resupply mission in December 2019. This new module was specifically designed to support advanced experiments with ultracold atoms, including dual-species interferometry, to test the UFF.

SM3 represented a substantial enhancement over its predecessor, featuring enhanced magnetic field control, and optimized optics for conducting high-precision interferometry experiments. SM3 was built with the capacity to produce and manipulate both rubidium-87 and potassium-41 simultaneously, enabling new classes of quantum measurements with unprecedented precision. Additionally, the module included custom-designed atom chips to provide better control over magnetic traps and enhanced cooling capabilities.

Installation of SM3 required a complex hardware replacement operation performed by the ISS crew in January 2020. The procedure, coordinated by the CAL Operations Team at NASA’s Jet Propulsion Laboratory (JPL), involved twelve separate crew activities over a nine-day period. During installation, astronaut Christina Koch successfully integrated the new module into the CAL infrastructure, ensuring compatibility with existing power, data, and cooling interfaces. Placement operation performed by the ISS crew in January 2020. The procedure, coordinated by the CAL Operations Team at NASA’s Jet Propulsion Laboratory (JPL), involved twelve separate crew activities over a nine-day period. During installation, Koch successfully integrated the new module into the CAL infrastructure, ensuring compatibility with existing power, data, and cooling interfaces.

Following installation, the CAL Operations Team verified the vacuum integrity of SM3 through telemetry analysis and demonstrated laser-cooled atoms within days. By uploading new experimental protocols tailored to SM3's unique atom chip geometry, the team confirmed the upgraded instrument's successful generation of Bose-Einstein condensates (BECs). This module demonstrated robust performance over the next three years, leading to numerous achievements including dual-species cooling experiments, and pioneering studies of atom interferometry in space.

3.6 Upgraded Microwave Frequency Source

Shortly after CAL's launch to the ISS in May 2018, the ground operations team noted that microwave evaporation, a critical process for sympathetically cooling potassium and rubidium atoms simultaneously to Bose-Einstein condensates (BECs), was not functioning as expected. Initial attempts to produce BECs using microwave evaporation yielded poor results, with significantly reduced efficiency compared to ground-based tests. An extensive investigation revealed that the issue was caused by excess noise originating from the microwave generation hardware, specifically within the microwave frequency source, referred to as "Slice 7." This noise prevented the precise removal of only the hottest atoms required for effective evaporative cooling of rubidium atoms.

A new Slice 7B was designed to address this issue and provide more microwave power output. The installation of Slice 7B was performed by astronaut Megan McArthur, who utilized a Microsoft HoloLens mixed and augmented reality headset to assist with the complex procedure. This marked the first demonstration of augmented reality technology to facilitate hardware maintenance on the ISS, allowing ground-based engineers to provide real-time guidance and visual cues to the astronaut. Following the successful installation of Slice 7B, the CAL operations team validated the performance of the new hardware by achieving efficient evaporative cooling of rubidium atoms to form BECs. Moreover, Slice 7B enabled the successful production of potassium BECs, ultra-cold K-39 samples, and dual Bose condensates via sympathetic cooling. Each of these results was a first-ever demonstration in space.

3.7 CPU Controller Failure and SSD Replacement

During science operations on 12 August 2021, the CAL Operations Team lost communication with the Flight Computer, and were unable to re-connect even after multiple remote power-cycles of the payload. Based on power draw telemetry, provided by HOSC, it was determined that the most likely cause was failure of either the PXI-8108 CPU controller or the solid-state drive (SSD) that stored the Flight Computer OS and Flight Software.

The CAL team partnered with the ISS crew to retrieve the ORU PXI-8108 from stowage on the space station and replace the original controller on 28 August 2021. The newly installed controller was then reconfigured by the ISS Network Team for operation on the ISS network. The CAL Operations Team proceeded to re-establish communication between the ground and the Flight Instrument, and the FSW Team then updated the Flight Computer with the latest version of the FSW. CAL was able to resume nominal operations on 3 September 2021.

A separate R&R procedure was performed on 16 December 2021 after the boot partition of the newly installed SSD became corrupted after less than three months of operation. Due to the headless design of the Flight Computer, it was determined that the best course of action was to replace the installed SSD with a separate ORU SSD. A replacement SSD was then delivered to ISS on SpaceX CRS-23. The CAL Team was able to leverage the procedures of the previous R&R in August to replace the corrupted SSD on 16 December 2021 and verify nominal telemetry after the integrity of the Flight Computer was confirmed. After confirming the functionality of all subsystems, the Operations Team proceeded with a successful checkout of the rubidium subsystem and was thereafter able to resume science operations.

3.8 Vacuum Anomaly

CAL's first science module, somewhat confusingly named SM-2 (its companion, SM-1, was deployed in our testbed), achieved several pioneering scientific milestones. These included studies of the first Bose-Einstein condensates formed in an orbiting laboratory, research on quantum gases in spherical "bubble" topologies, and demonstrations of very low temperatures, precision control, and extended observation times. The unit was eventually replaced by SM-3, a significant upgrade that enabled groundbreaking experiments in atom interferometry and the formation of dual-species Bose-Einstein condensates. This new system operated in orbit for more than three years but started to experience issues with its rubidium and potassium sources. Consequently, it was replaced by SM-3B, which was essentially a direct replacement of the prior module. However, SM-3B introduced one new feature: the ability to produce a larger-volume atom trap, included as a technology demonstration. Our goal was to utilize this new trap to facilitate the demonstration of larger Bose-Einstein condensates.

The SM-3B module performed exceptionally well during ground testing, surpassing all previous science modules by most metrics. It was launched on August 2, 2023, aboard NG-19. After the system was installed and powered on by October 12, we observed anomalous telemetry from our ion pump controller, indicating significantly higher ion current than expected. This suggests a higher base pressure in the system. Given that there are known mechanisms in which ion current can remain high even with low base pressure, we proceeded with the instrument check-out. While we successfully established laser cooling, the resulting magneto-optical trap was weaker than normal and had a poor lifetime. Both issues align with indications of higher pressure, confirming the ion pump telemetry findings.

Several possible root causes for this problem were identified, including a vacuum leak, a defective ion pump, a faulty ion pump controller, a poor cable connection, or an elevated level of helium within the chamber. It is important to note that ion pumps are not efficient at pumping helium, and the International Space Station (ISS) is known to have elevated helium levels.

We conducted an astronaut checkout to confirm the cable connection. Additionally, by connecting a separate ion pump controller that was already on the station, we were able to eliminate the pump controller as a source of the issue. Our team also developed an advanced laser cooling-based test that allowed us to roughly confirm and calibrate the current readings of the ion pump controller. In this test, the magneto-optical trap itself served as a vacuum sensor, based on the principle that background atoms at increased pressures reduce the loading rate and lifetime of the magneto-optical trap [8]. Once the ion pump readings were confirmed, we performed leak-up tests with the power shut off for varying lengths of time. This resulted in data regarding the level of vacuum as a function of time, which indicated that we were most likely dealing with a leak.

It became evident that we could not use SM-3B for meaningful scientific work, so the team swiftly shifted focus to getting a replacement unit launched as soon as possible. We had two potential science modules on hand: SM-1, a reliable workhorse from our testbed, and SM-2, which had just returned from nearly two years in orbit. Although neither module supported atom interferometry experiments, both were in good working order (albeit somewhat outdated) and capable of conducting significant scientific work until a new module could be built. SM-1 was chosen as the least risky option and was quickly prepared for launch. It was successfully launched on SpaceX-30 and installed on March 21, 2024. prepared for launch. Within two weeks, the lab was once again producing Bose condensates, and ready for PI Science.

4. Conclusion

The Cold Atom Laboratory (CAL) has demonstrated that cutting-edge quantum science can be successfully conducted aboard the International Space Station (ISS) despite the inherent challenges of operating a complex atomic physics instrument in orbit. Over its extended mission, CAL has enabled experiments that push the boundaries of quantum physics, including the first observation of a BEC in an orbiting lab, the first demonstration of a dual-species condensate in space, and pioneering experiments in atom interferometry and with quantum gases in novel topologies.

The microgravity environment of the ISS offers distinct advantages for precision measurements and fundamental physics experiments, including extended free-fall times, the ability to manipulate quantum gases with minimal external interference, and the opportunity to perform unique tests of the UFF using dual-species interferometry. However, maintaining a high-performance quantum laboratory for long periods in orbit requires continuous monitoring, responsive troubleshooting, and innovative solutions to unforeseen problems.

CAL's extended mission has highlighted the potential and complexity of space-based quantum research. Numerous anomalies have forced the team to develop robust anomaly response protocols and innovative approaches to troubleshoot an aging yet vibrant facility. As CAL continues its operations, it serves as a scientific instrument and a pathfinder for future missions. The insights gained from addressing anomalies, upgrading hardware, and overseeing overall system performance will inform the design of upcoming missions such as the Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) [9], the Quantum Gravity Gradiometer [10], and other precision measurement initiatives.

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