Summer Student Program
Project Report

# MONITORING CESIUM FOUNTAIN STABILITY FOR SPECTROSCOPIC FREQUENCY CONTROL

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# 1 Abstract

This report summarizes my work as a CERN Summer Student as part of the ALPHA Collaboration during the summer of 2025. Throughout the summer, I contributed to the collaboration in two main ways: First, I assisted with the repair, tuning, baseline measurement, and experimental campaign for the general ALPHA apparatus. Second, I implemented a data monitoring and analysis framework for the flight parameters of the cesium fountain to be used to identify and diagnose systematic errors as they occur. Each of these contributions were made in pursuit of the overall scientific goal of ALPHA, to probe CPT symmetry using high-precision measurement of antihydrogen. By the end of the summer, antihydrogen production was successfully established in the second of ALPHA's experimental traps and a monitoring program for the cesium fountain flight parameters was successfully initialized and has begun logging to the history stored on MIDAS.

# 2 Introduction to ALPHA

The Antihydrogen Laser Physics Apparatus (ALPHA) experiment is a large-scale international collaboration based at CERN dedicated to studying the fundamental symmetries between matter and antimatter. Its primary focus is on trapping antihydrogen atoms (the antimatter counterpart of hydrogen) and comparing their physical properties with those of ordinary hydrogen. By conducting such comparisons, researchers aim to test foundational principles of physics, such as CPT symmetry and the equivalence principle, with unprecedented precision. ALPHA-2 is an antihydrogen trap that is used for laser spectroscopy of antihydrogen to study the positron structure of antihydrogen atoms. The second trap, ALPHA-g, is used to analyze gravity's affect on antihydrogen and characterize how antimatter reacts to the gravitational force.

To produce antihydrogen, positrons (antielectrons) and antiprotons must first be separately trapped in the form of plasma and then carefully combined. In the ALPHA apparatus, Penning traps are employed to confine these charged plasmas using a combination of strong magnetic and electric fields. Magnets play a crucial role not only in trapping the particles but also in transporting plasma along the experiment's beamline, where precise control over their position and motion is essential.

While each researcher has a specific area of expertise at ALPHA, everyone is expected to become familiar with the experiment and participate in the day-to-day operation of the apparatus. As a summer student, I also enveloped myself in this routine, working an average of three shifts a week to maintain operation of the experiment throughout the summer data collection period of 2025.

## 3 Cesium Fountain Background

### 3.1 Introduction

The pursuit of accurate timekeeping has driven technological progress for centuries, with the latest state-of-the-art innovation resulting in the formal definition of the second based on elemental oscillations measured in atomic clocks. Atomic clocks achieve unprecedented precision by measuring the exact intrinsic oscillations of atoms used for this definition, which occur at fixed and universal frequencies. Unlike mechanical or quartz-based devices, their operation is rooted in quantum mechanics, making them immune to most environmental variations. Among these, cesium fountain atomic clocks represent the current gold standard for primary frequency references in the International System of Units [1].

The earliest cesium clocks, such as the National Physical Laboratory's CS1 in 1955, employed thermal atomic beams. These devices heated cesium to produce a vapor, sending atoms through a microwave cavity at high speeds determined by temperature. While groundbreaking, this method suffered from Doppler broadening and short interaction times, which limited precision [2].

The development of laser cooling in the 1980s—pioneered by Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips—revolutionized atomic timekeeping. Using finely tuned laser light, cesium atoms could be cooled to microkelvin temperatures, reducing their speeds to mere millimeters per second. This allowed far longer observation times and dramatically improved frequency resolution. The innovation led to the modern cesium fountain clock, first implemented in the early 1990s by institutions such as NIST (USA), PTB (Germany), and SYRTE at the Paris Observatory [2].

### 3.2 Principles of Operation

A cesium fountain clock begins with the preparation of pure cesium-133 atoms, which are vaporized and collected in a magneto-optical trap (MOT). Here, three orthogonal pairs of counter-propagating laser beams cool the atoms via the Doppler effect, reducing their temperature to just a few microkelvin above absolute zero in a process known as forming "optical molasses". At such low speeds, the atoms form a dense, slow-moving cloud.

The cooled atoms are then launched upward using a moving optical molasses technique, imparting a controlled velocity of roughly 4 m/s. This motion sends the atoms along a ballistic trajectory, rising under their initial momentum before gravity reverses their motion. As they ascend, the atoms pass through a microwave cavity, where they interact with a field oscillating at around 9.192 GHz. This initiates the first part of a Ramsey interrogation sequence. The atoms then continue upward, slow, and fall back down, passing through the cavity a second time. The two interactions produce an interference pattern of Ramsey fringes that allows the transition frequency to be determined with precision up to $10^{-16}$.

After the second pass, a detection laser measures the proportion of atoms that transitioned to the excited hyperfine state. By adjusting the microwave frequency until maximum excitation is achieved, the clock locks onto the exact hyperfine transition frequency that defines the SI second [1].

### 3.3 Applications for ALPHA

ALPHA uses the cesium fountain to reference all of its laser frequencies in the metrology lab. This guarantees the precision of the excitation wavelenghts used in 1S-2S excitation experiments, which provides a narrower spectrum peak as well as improving the precision of the measurement. In previous ALPHA measurements, a quartz oscillator referenced via GPS offered a precision of two parts per trillion, but this still lagged behind the four parts per quadrillion achieved in equivalent hydrogen experiments. By using the cesium fountain clock, ALPHA can now match — and potentially exceed — the precision of hydrogen spectroscopy, enabling more sensitive tests of CPT symmetry and more stringent constraints on possible differences between matter and antimatter [1].

The clock's usefulness, however, extends beyond ALPHA. The cesium clock's ultra-stable frequency reference can be distributed across CERN to other experiments that require precise timing. This link not only ensures long-term stability and reduces measurement noise for ALPHA, but it also allows other CERN facilities to synchronize more precisely with Coordinated Universal Time (UTC) than is possible via GPS. In the future, the same infrastructure could provide signals from even more stable optical quantum clocks, further improving time synchronization across the laboratory. Such a shared, high-accuracy timing system would benefit a wide range of accelerator operations and experiments, ensuring that all timing-critical measurements are anchored to the same world-class standard. Cesium fountains remain indispensable as primary standards, anchoring the global timekeeping infrastructure and supporting both technological systems and cutting-edge scientific research [3].

## 4 Fountain Monitoring Program

### 4.1 Introduction

The daily operation of the fountain is largely automatic, with intervention only required for systematic checks on a weekly basis and correction of errors in the event of a clock malfunction. However, the historical monitoring of the cesium fountain at ALPHA has not quite matched the standards set by NPL. Systematic errors on the order of $10^{-14}$ could go unnoticed for weeks, and only monthly intervention by trained personnel could correct for these errors. The data analysis for this frequency shift also occurred in an offline fashion using summary files saved by the fountain.

The goal for my project, then, was to implement a monitoring program that would run in real time to alert ALPHA team members when the cesium fountain flight output strays beyond acceptable ranges. This project integrates understanding of the physics behind the cesium fountain with LabVIEW data acquisition and analysis techniques to increase the operational capacity of ALPHA when performing high-precision experiments, and a successful program would be useful well into the future for automated history and monitoring.

Finally, the program also needs to be integrated into the existing ALPHA remote action engine server for the 243 nm system control. This native LabVIEW architecture decentralizes data handling and analysis logic so the overall system is robust to any one subsystem experiencing an unexpected fatal error or PC crash. After learning about the physics behind the cesium fountain, I worked to implement the analysis logic subject to this overarching architecture. What follows is a summary of the purpose of each element of the project and a description of how they interconnect.

### 4.2 Remote Action Engine Framework

The remote action engine framework consists of three primary virtual instruments (VIs) which each contribute to the modularity and consistency of the project. The first of these is the Control Interface VI in the PC_Control library. This VI operates separately from the VIs containing data acquisition and analysis, and it can be run from several computers at once. I edited the front end of this program to include a readout from the cesium fountain flight data. The second important VI is the Main VI in the PC1 library. This VI runs on cpc38 (or any computer with access to EOS; but only 1 instance required). It manages the modules that all run on the computer associated with it, and it can be upgraded with more modules in the future if improved functionality is desired. For my project, this VI was updated to include the cesium fountain module and control its appearance on cpc38. Finally, the last major VI in the remote action engine framework is the CsFountain VI itself, which also runs on the same PC1 computer and is controlled by Main. This VI handles the acquisition and formatting of data, as well as its logging to MIDAS.

### 4.3 VI Diagrams and Descriptions

What follows is a brief description of each VI I created or edited, with images of the larger VIs for reference.

- PC Control/PC_Control.lvlib/Metrology.lvlib/Metrology.vi:

  LabVIEW GUI VI, added CsF TOF data readout

- PC1/PC1.lvlib/Main.vi:

  Main VI for the computer running the CsF analysis, added references and calls to CsFountain.vi

The remainder of the items are found in PC1/PC1.lvlib/CsFountain.lvlib.

- CsFountain.vi: Figure 1

  VI called by Main.vi, used for hourly acquisition, updating FGV, and MIDAS logging

- FGV/CsFountain_FGV_Data.ctl: Figure 2

  Cluster typedef used for storing 48 hours of historical CsF data in LabVIEW

- SubVIs/GetMJDTodayAfter3AM.vi: Figure 3

  Returns the MJD used for TOF file retreival

- SubVIs/GetTOFLastHour.vi: Figures 4 and 5

  File skimmer VI used to obtain most recent hour's CsF data

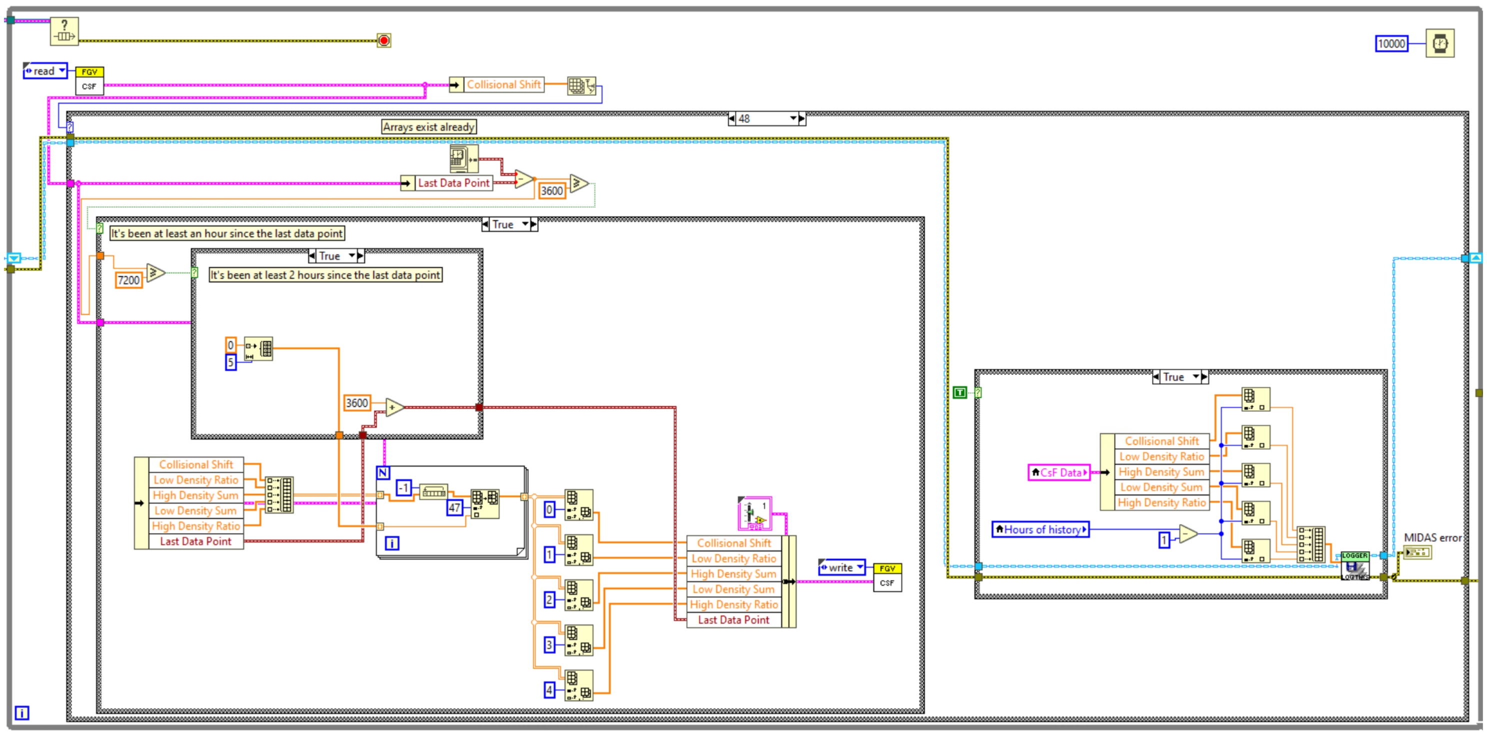


Figure 1: This loop runs every 10 seconds, but only serves to check if it has been an hour since the last data acquisition run. If so, it obtains the most recent hour's data in the left conditional and updates the FGV accordingly. Then, it logs the most recent acquisition to MIDAS with the conditional on the right.

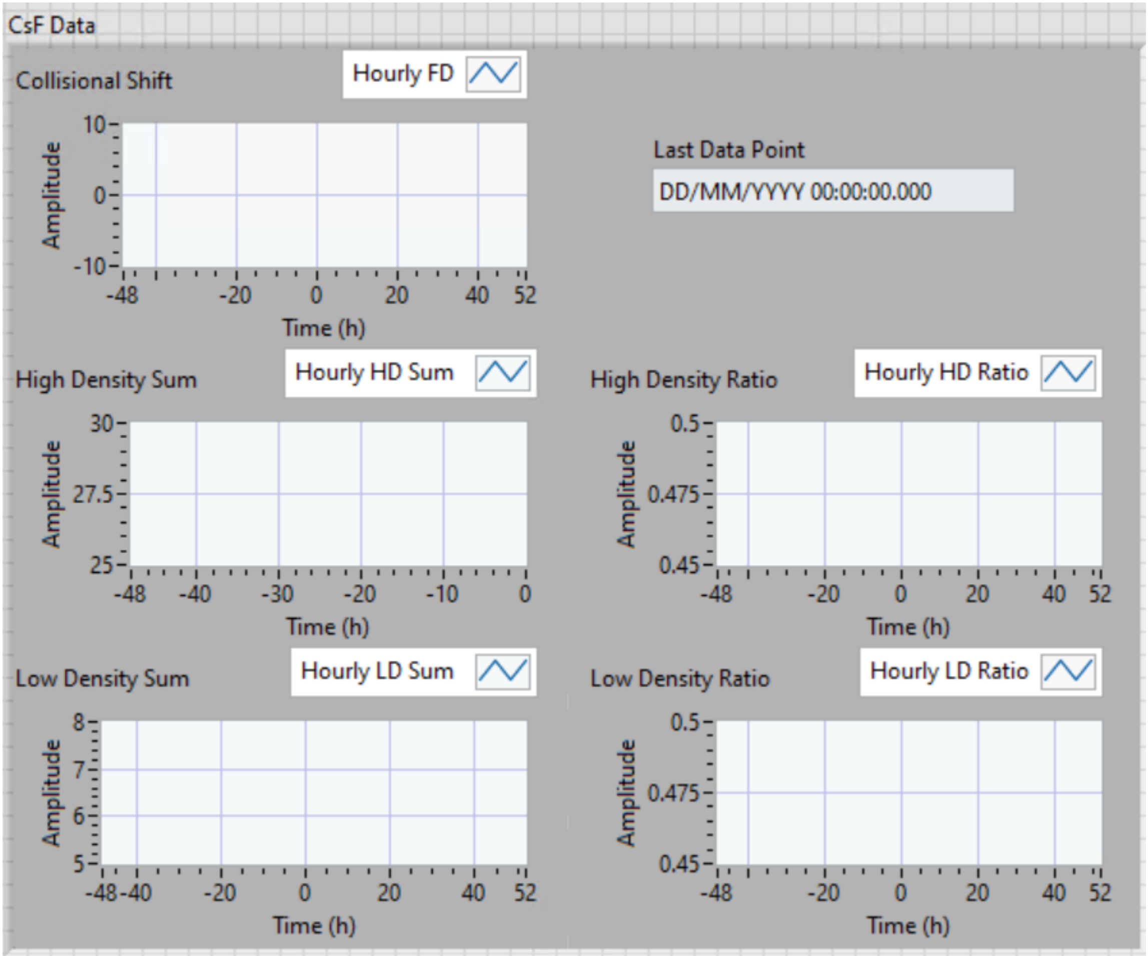


Figure 2: This cluster includes waveform charts for the last 48 hours of data for each of 5 different flight parameters. The FGV structure retains data even after the VI or computer is restarted.

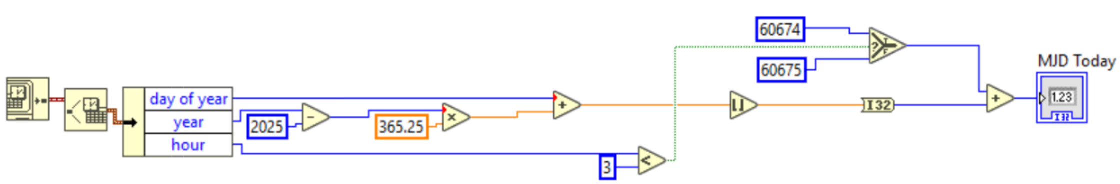


Figure 3: This small VI simply obtains the current MJD to access the correct file. In the future, this program can be simplified if run on a computer with GMT time.

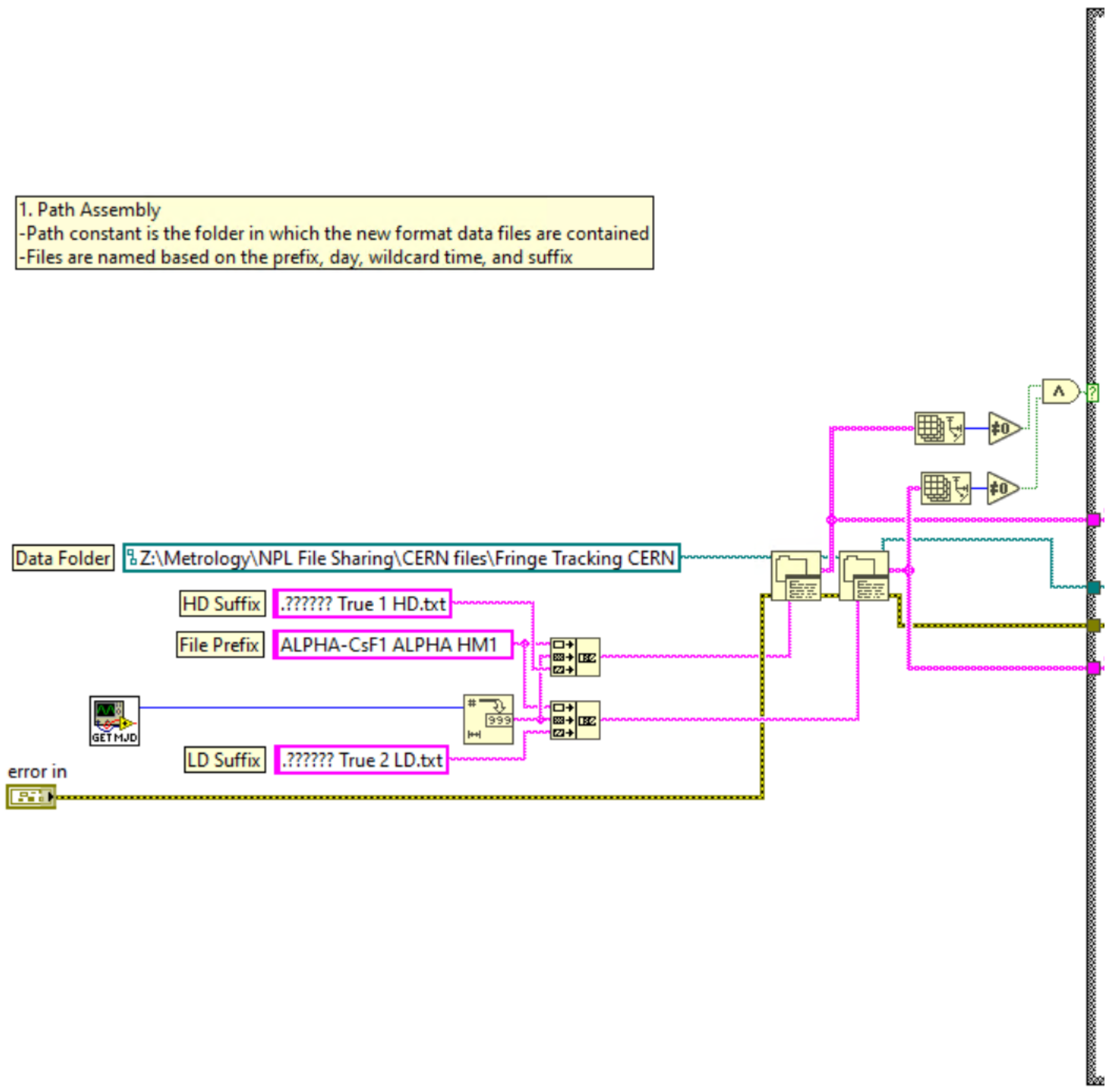


Figure 4: This figure shows the path assembly code for obtaining flight parameters. If any of the file sharing folders or formats are changed, this will need to be updated.

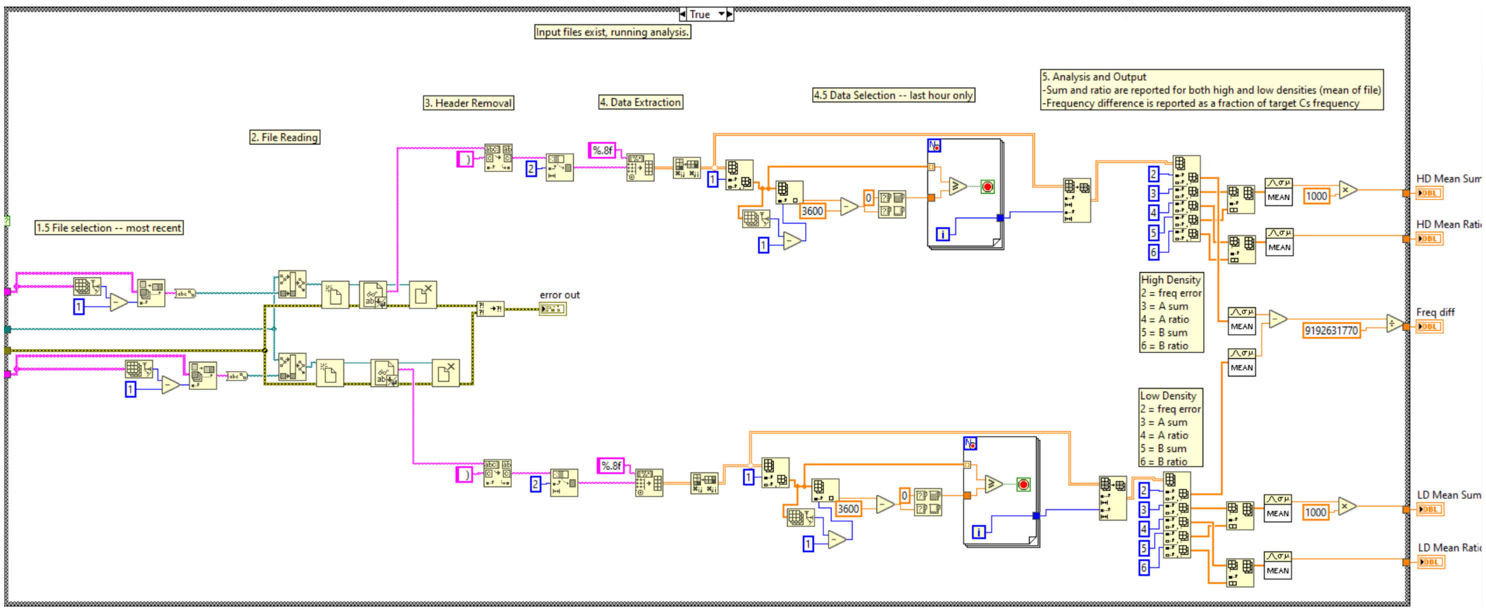


Figure 5: This structure holds the remainder of the data input and analysis software for obtaining the most recent hour's data. Step 1.5 ensures the most recent file is selected. Step 2 extracts the file's data. Step 3 eliminates the header and characteristic information. Step 4 converts the remaining data into a 2D array. Step 4.5 trims the data to only include the final hour. Step 5 performs analysis and reports the results to the output terminals.

## 5 Conclusion

Over the course of the CERN Summer Student programme, my work with the ALPHA Collaboration contributed both to the operational readiness of the experiment and to its capacity for precision measurement. The repair and tuning of the apparatus supported the successful production of antihydrogen in ALPHA's second trap, while the development of a real-time cesium fountain monitoring framework addressed a longstanding gap in frequency stability oversight. By integrating this system into ALPHA's remote action engine architecture, the collaboration now has a robust and automated tool for detecting and responding to systematic timing errors as they occur, improving experimental reliability for future campaigns. Together, these contributions strengthen ALPHA's ability to perform high-precision CPT symmetry tests and further our understanding of fundamental physics. I deeply valued my time working with ALPHA and am grateful for the opportunity to deepen my understanding of experimental physics while contributing to the cutting edge of fundamental research!

## 6 Acknowledgments

I thank my supervisor, Dr. Ginny Marshall, for her guidance throughout the summer and excellent introduction to ALPHA and Europe. I would also like to thank all the members of the ALPHA collaboration who made my summer experience possible. Finally, thank you to the other ALPHA summer students and UMich REU summer students who made the summer memorable in and out of the lab through meals, travel, games, and all our various shared experiences.

## References

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[2] J. Rowlett, "Cesium: A brief history of timekeeping," 2014, https://www.bbc.com/news/magazine-29476893.

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