Development of the Science Data System for the International Space Station Cold Atom Lab

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Abstract— **Cold Atom Laboratory (CAL) is a facility that will enable scientists to study ultra-cold quantum gases in a microgravity environment on the International Space Station (ISS) beginning in 2016. The primary science data for each experiment consists of two images taken in quick succession. The first image is of the trapped cold atoms and the second image is of the background. The two images are subtracted to obtain optical density. These raw Level 0 atom and background images are processed into the Level 1 optical density data product, and then into the Level 2 data products: atom number, Magneto-Optical Trap (MOT) lifetime, magnetic chip-trap atom lifetime, and condensate fraction. These products can also be used as diagnostics of the instrument health. With experiments being conducted for 8 hours every day, the amount of data being generated poses many technical challenges, such as downlinking and managing the required data volume. A parallel processing design is described, implemented, and benchmarked. In addition to optimizing the data pipeline, accuracy and speed in producing the Level 1 and 2 data products is key. Algorithms for feature recognition are explored, facilitating image cropping and accurate atom number calculations.**

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1. INTRODUCTION

The Cold Atom Laboratory (CAL) is a multi-user system for the study of ultra-cold atoms in a microgravity environment. CAL is scheduled to be an internal payload on the Internation Space Station in 2016. CAL's mission goals include demonstating the following capabilities for the first time in a space enviroment: laser cooling of Rubidium (Rb), laser cooling of Potassium (K), magnetic trapping, evaporative cooling, and the production of Bose-Einstein Condensates (BECs) [1, 5]. Being situated in a microgravity environment will allow for greater than five second interraction times with dual-species BEC as well as achieving temperature less than 1 μK. The primary science data products for the mission will be images of the observed BEC clouds.

The Science Data System (SDS) is responsible for ground post-processing of the CAL science data products when it is in flight. The Science Data System will provide science data products that will be used to calibrate and monitor the performance of the system once in flight. The SDS will also provide preliminary science measurements, such as optical density, atom number, condensate fraction, and BEC temperature, to the various scientists who will be using CAL to run sequenced experiements.

In this paper, we present an overview of the CAL Science Data System. The mission operations concept, including mission phases, is described in Section 2. Section 3 details the design and architecture of both the Mission System and the SDS. Section 4 describes the various science products that the SDS is responsible for. Section 5 discusses the current implementation of the Science Data System's post-processing software. Results and analysis of preliminary testing of the SDS with current CAL BEC data are detailed in Section 6. Finally, conclusions are in Section 7, and plans for future work are outlined in Section 8.

2. MISSION CONCEPT

The CAL mission has a primary lifetime of one year. Mission phases will include: Installation, Checkout, Validation, Science Operations, and Decomissioning. CAL will be remotely operated from JPL during its lifetime except for Initial Payload Installation and Installation of Orbital Replacement Units.

Installation

Installation begins with the arrival of CAL at the ISS, and ends with successful communications between the CAL instrument and the Ground Data System (GDS). ISS crew members will perform the installation. Installation will include the initial powering up of the CAL Instrument, a basic communication test between CAL and the GDS, and an instrument status provided to GDS.

Checkout

Checkout will have a length of six weeks. During this time, the CAL instrument will be powered on and off multiple times and all instrument modes will be exercised. This will help the CAL team verify the following capabilities: ISS Command and Data Handling Interface for Health and Status, Instrument Commanding and Configuration, Science Data Collection, Science Data Downlink to GDS, and Command Logging. During checkout, near real-time downlinks of data and uplinks of commands are planned.

Validation

Validation will have a length of 12 weeks and will consist of the Project Scientist validating the Instrument and collecting required science data. These validations will be performed in near real-time, with near real-time communications between the CAL Instument and JPL, as well as near real-time data analysis. The Project Scientist will work closely with the CAL operators. The nominal length of each experiemnt will be 1 minute, and CAL will only be run during crew sleep time, as the Instrument is sensitive to vibrations.

Science Operations

The primary science operations phase will have a length of 34 weeks, potentially followed by a secondary science operations phase. The Instrument will be operated for at most eight hours per day, during crew sleep time. During this phase, principle investigators from the Science Team will be allocated blocks of time for their experiments to be run on the CAL Instrument.

Nominally, science data will be downlinked in non-real-time during non-science operations from the ISS to the GDS. Aggregate downlink data rates of 10 Mbps are currently supported by the ISS, while an increased rate of 100 Mbps is expected to be implemented in 2014. Uplink rates of 800 bps per payload are currently supported by the ISS, while aggregate uplink rates of 25 Mbps are planned for 2014.

Decommissioning

When the CAL mission is complete, the Instrument will be powered off and decomissioned. CAL may be sent down in a vehicle inteneded to burn up in the atmosphere. Alternatively, CAL may have its mission lifetime extended using Orbital Replacement Units, which provide replacement parts or new capabilites.

3. SYSTEM DESIGN

Mission System Architecture

An overview of the CAL Mission System Architecture is shown in Figure 1.

Once CAL is in flight, communications will be provided by the Space Network, which includes a geosynchronous Tracking and Data Relay Satellite System (TDRSS). The ISS Payload Operations Center is located at the Huntsville Operations Support Center (HOSC) at Marshall Space Flight Center. All communications with CAL will go through HOSC, shown in Figure 1. Recurring command uplink and downlink windows will be scheduled with the Space Network to support CAL operations. Payloads that utilize the Space Network for communications experience a Loss of Signal and Acquisition of Signal during each TDRSS handover, several times per day.

Science Data System

The Science Data System will be located at JPL and is responsible for processing the raw, Level 0 data produced by the CAL instrument into Level 1 and Level 2 data products as well as archiving this data. The Level 0 data will consist of three (3) images and associated meta data for the given experiement. In a given experiement, a laser will shine on the BEC atom cloud and the image acquisition system will take an absorption image (I_a), followed by a background image (I_b). Periodically a reference image (I_r) will be taken with the shutter closed. Science metadata will include a time

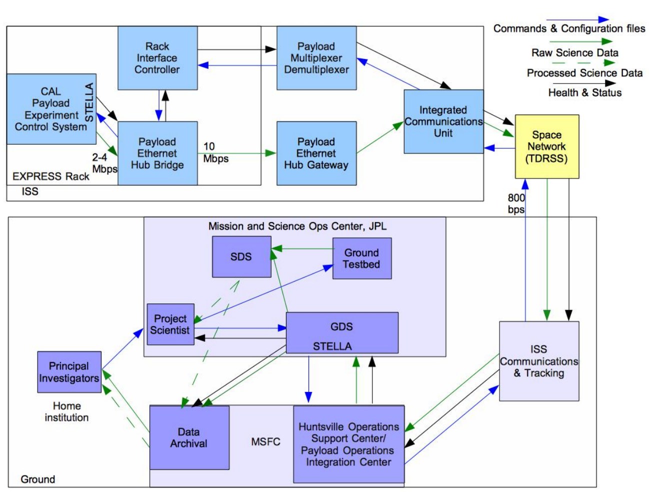

Figure 1 - CAL Mission System Architecture

stamp and CAL Instrument configuration information.

Level 1 data is the computation of the optical density from the three types of images: absorbtion, background, and reference images. These images are used to compute the optical density using the formula below.

$$Optical\ Density = \alpha \cdot \ln \frac{I_b - I_r}{I_a - I_r} + \beta$$

Level 2 data can be obtained from processing the Level 1 optical density image and will consist of the following science products:

- Atom number, including associated Gaussian fitting and cropping
- Condensate Fraction and associated fits
- Temperature
- 3D Magneto-Optical and Atom-Chip Trap lifetimes

An overview of the CAL Mission products is shown in Figure 2.

Per the mission requirements, a given days' worth of science data must be processed and made available to the science teams within 24 hours.4. Science Products

Level 0 Science Products

The Level 0 Science Products will consist of two images, an absorption image with the atom cloud and one without the atom cloud present. There will be a third reference image taken periodically that will be used to remove noise generated internally by the camera. Each of the Level 0 images is a 2048 x 2048 pixel TIFF image with 12-bit resolution.

Level 1 Science Products

From the Level 0 images, a single image with pixel values corresponding to the optical density of the given experiment can be derived. From this image, all of the Level 2 science measurements can be obtained. This requires knowledge of the atom cloud's position within the image, as well as how big it is. A region of interest (ROI) is defined with the atom cloud near the center. The ROI can be automatically defined by a feature recognition algorithm, or it can be defined by the user operating the SDS. In cases where the feature recognition algorithm fails or when the scientist prefers to define a region of interest, the user has the ability to do so.

Level 2 Science Products

From the optical density ROI, various science measurements can be computed, including atom number, Gaussian widths, temperature, and condensate fraction. These products are produced by creating a profile of the cloud in both the x- and y-directions and by summing the optical densities along each axis.

From these two profiles, various fits can be applied to the data, providing useful information about the size, shape, and thermal properties of the cloud. From two 1-dimensional Gaussian fits, one can determine the width of the cloud in both the x- and y-directions. Below is the fomula fit to the data in order to obtain the gaussian width (σ) in a given direction:

$$y_G = \alpha * e^{-\frac{(x-x0)^2}{2\sigma^2}} + \beta$$

From 1-dimensional Thomas Fermi fits, one can determine the widths of the condensate and thermal components of the atom cloud, as well as determine the condensate fraction and temperature of the cloud.

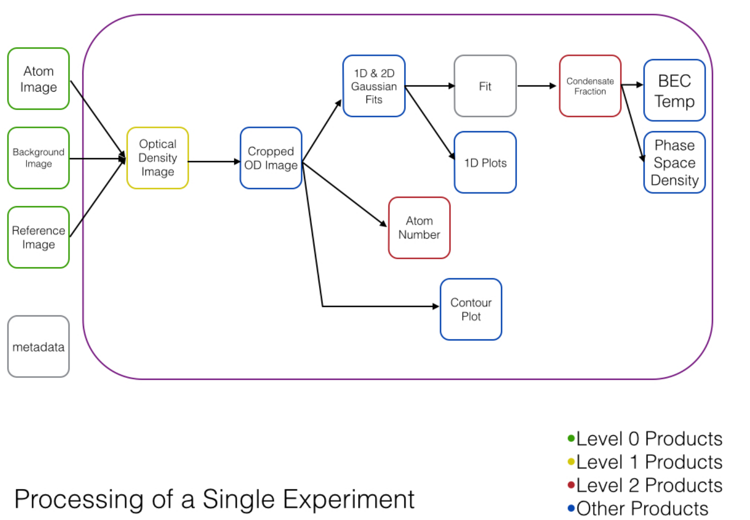

Figure 2- Science Data Products

An example cropped region of interest is shown in Figure 3**.** This data was fit to a biomodal distribution, and an example of this fit is shown in Figure 4, where the Thomas-Fermi fit is in red and the Gauss fit is in blue.

From these fits, atom number, condensate fraction, and temperature can be computed. Currently, only atom number and condensate fraction have been calculated. Atom number is computed by summing the optical density matrix that comprises the region of interest. The formula for this method is described below, where k denotes the dimension of one pixel in meters [3]:

$$N = k^2 \sum_i Optical\ Density_i$$

To compute atom number from the various fits, the area under each curve is integrated over the range $(-\infty, \infty)$. For the Thomas-Fermi fit, the atom number is calculated for both the thermal and condensate components. These two numbers are used to compute the condensate fraction:

$$Condensate\ Fraction = \frac{N_{TF}}{(N_{TF} + N_G)}$$

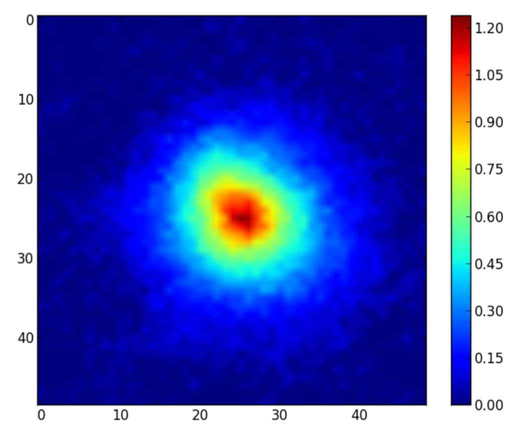

Figure 3- Optical Density Region of Interest

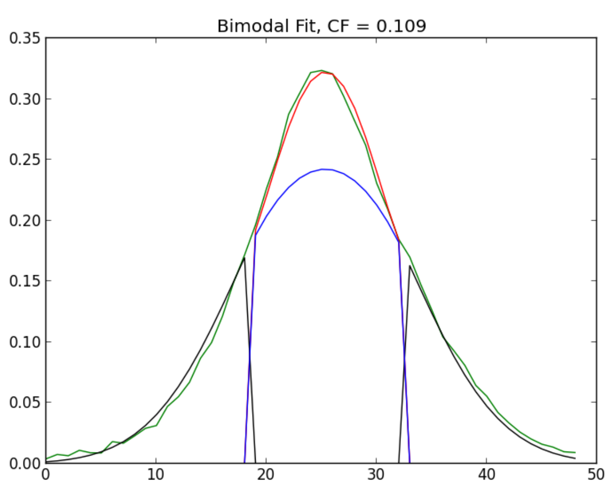

Figure 4- Bimodal Fit

5. CURRENT IMPLEMENTATION

Software Architecture

An overview of the Science Data System's current software architecture is shown in Figure 5. The current implementation can be run in two different modes: one mode where a single experiment is processed, and the other where a series of experiments with the same instrument conditions can be averaged and then processed.

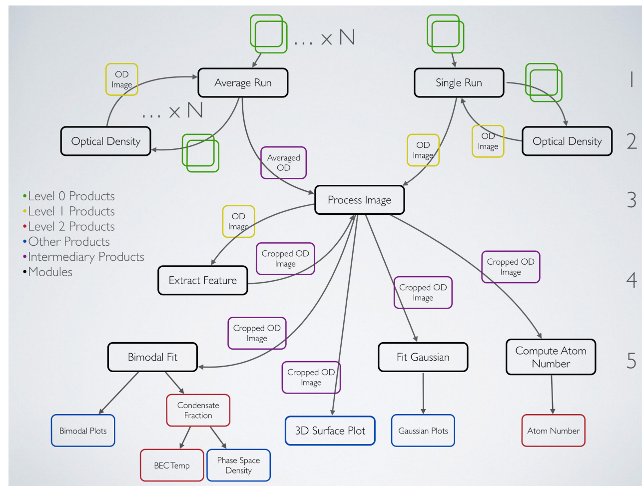

Figure 5 – CAL SDS Software Architecture

A single module handles the processing of the Level 0 data into the Level 1 optical density image, while many modules handle the processing of the Level 1 optical density image into the various Level 2 science data products, as detailed in Figure 5.

A feature recognition module was designed using functions from an image processing library, allowing for automatic detection and cropping of the optical density image to a region of interest containing the atom cloud. This process is done by first applying a Gaussian filter to the optical density image, as the laser used to illuminate the atom cloud is Gaussian in form. This process reduces noise and helps to separate the atom cloud feature from the background. A feature recognition algorithm is utilized to determine the edges of the atom cloud feature. A 2-dimensional Gaussian fit is applied to this region of interest, yielding the width (sigma) of the cloud in both the x- and y-directions. With these Gaussian widths, the region of interest can be cropped to a factor of sigma; using a value of 7 σ seems to align the closest with how the scientists would manually crop the images.

Once the region of interest is defined, various modules perform computations to generate the Level 2 science products. The 1-dimensional fits are computed using a Levenberg-Marquardt Algorithm that utilizes gradient decent to rapidly and robustly solve non-linear least squares problems [6]. For the Gaussian widths, a simple Gaussian formula is applied to compute the other products that depend on both the thermal and condensate components of the cloud a Thomas-Fermi fit is applied.

In addition, a parallel processing architecture for processing multiple experiments has been outlined and a prototype version has been implemented. Since each pair of images can be processed into an optical density image independently from the other images, multiple images to be averaged can be processed into Level 1 data separately, a natural parallel process. Parallel processing will become crucial once CAL is in flight, as it will be necessary to maintain real-time analysis for the Project Scientist operating the instrument during the validation phase, as well as to process a day's worth of data in the required turn-around time constraint during the science operations phase.

6. ANALYSIS

Initial benchmarking of the prototype system has been performed. In the future, parallel processing architecture will be implemented for processing multiple images at once, but the results from processing a single image so far have been promising. In testing the system, it takes approximately .75 seconds to produce the optical density image (Level 1 product) from two 2048 x 2048 pixel images.

The automatic atom-cloud-detection step takes approximately 1.5 seconds, depending on how noisy the image is. If there is more extraneous noise, the algorithm has to sort through more features when looking for the atom cloud. Averaging multiple images or producing better images can improve the signal-to-noise ratio, potentially decreasing the number of features needed to search through. The average time it takes to generate all of the fits, including outputting the plots to files, is about 1.5 seconds as well. In total, it takes under 3 seconds to run the analysis for a single experiment, giving the science team near-real time feedback.

In addition to the required science products, there is the option to generate a 3D surface plot of the Region of Interest, providing a visual aid for the scientists when looking at the numbers. This is the most intensive process, as it takes approximately 3 seconds to produce, depending on the size of the region of interest.

7. CONCLUSIONS

The CAL Science Data System has been designed and a protoype version has been implemented, validated, and briefly benchmarked. Determining an appropriate region of interest has been a challenge, as there is no automated way to accurately definine a perfect crop. Methods have been implemented in order to best mimic what the scientists would deem as the best crop, and further refining of this autocropping feature need to be done.

This system will be used in both assisting the GTB in their research both before flight and during flight. The software will be the framework for the SDS in flight and will provide necessary Level 1 and 2 data products to the Project Scientist as well as the Science Teams.

8. FUTURE WORK

In addition to the current products that the prototype computes (atom number, condensate fraction, and Gaussian widths), the SDS will produce the following products:

- MOT lifetime
- Magenetic chip trap lifetime
- Temperature

Moreover, planned improvements to the current SDS implementation include:

- Graphical user interface for operation and feedback
- Data archival
- Interfacing with the ISS Physical Science Informatics system for data archival and distribution to principal investigators
- Script for automatic data processing initiation

9. ACKNOWLEDGEMENTS

The authors would like to acknowledge the CAL Ground Testbed team for providing BEC images used for software testing.

This research was carried out at the Jet Propulsion Laboratory, California Institue of Technology under a contract with the National Aeronautics and Space Administration. Government sponsoship acknowledged.

REFERENCES

[1] David Aveline, "Experiements in Cold Atom Optics Toward Precision Atom Interferometry," Ph.D. Dissertation, Physics, University of Southern California, Los Angeles, Ca, 2011.

[2] Steck, D. Rubidium D-line data. Unpublished. http://steck.us/aklalidata/ (2003).

[3] Daniel M. Farkas et al., "Production of Bose-Einstein Condensates at a 1 Hz Rate," ColdQuanta, August 29, 2013. arXiv:1403.4641

[4] G. Reinaudi, T. Lahaye, Z. Wang, and D. Guéry-Odelin, "Strong saturation absorption imaging of dense clouds of ultracold atoms," Opt. Lett. 32, 3143-3145 (2007).

[5] Sengupta, A. et al., "Cold Atom Laboratory Mission," Proceedings of the IEEE Aerospace Conference, Big Sky, Mt, 2014.

[6] "Scipy.optimize.curve_fit." Scipy.optimize.curve_fit — SciPy V0.14.0 Reference Guide. Web. 4 Sept. 2014.

BIOGRAPHIES

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