Optical Mass Gauging Using Modified Michelson Interferometer

Marshall Space Flight Center

Kristina Barile, Harvard University • Meera Chander, Massachusetts Institute of Technology • Christopher Navarro, University of Texas at El Paso • Luke Saindon, University of Maine

Principal Investigator: Kevin Pedersen (ER23)

ER Propulsion Systems Department

Introduction

In a microgravity environment, it can be challenging to determine the mass/volume of liquid propellant in a tank due to unpredictable fluid behavior. Although other methods exist to accomplish this task, compensations must be made due to unfavorable balances between weight, cost, and uncertainty of these systems. This thus exemplifies a technology gap for accurate in-space propellant gauging for spacecraft as well as cryogenic fuel depot applications.

As a different approach, we have constructed a proof-of-concept optical mass gauging experiment. A piston-bellows system stimulates a change in volume – and thus density – to an amount of ullage gas in a propellant tank. This manifests as fringe movement detected by a modified Michelson interferometer. By measuring the number of fringes that pass our detector, we can calculate the volume of the ullage and thus the volume of propellant.

? What are fringes?

Regions of constructive and destructive interference of light waves (background image).

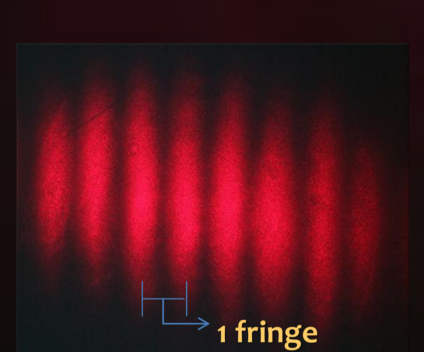
Primary Objectives

- Design, construct, test proof-of-concept
- Establish repeatability of this method
- Quantify the uncertainty
- Compare results with alternatives to this method and further improve this system

How It Works

Waveforms of light converge to constructively or destructively interfere.
Constructive: waves out of phase by an integer multiple of their wavelength
Destructive: waves out of phase by a half-integer multiple of their wavelength

In our modified Michelson interferometer, a laser source is separated into two beams. One beam travels through a control of air, while the other travels through a test cell of ullage. These beams ultimately merge again to form an interference pattern with fringes.



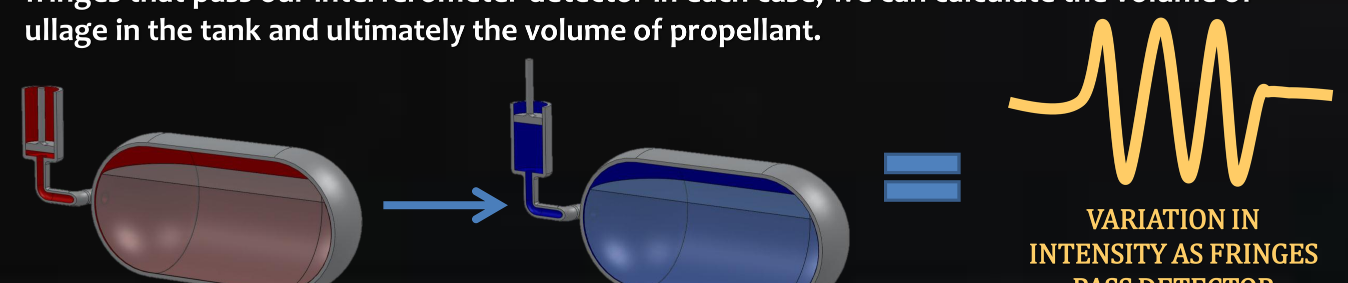
The physical path lengths of each separated beam are nearly identical. However, the beams differ in optical path length (the product of the physical/geometric length and the index of refraction of the medium through which they propagate), as air and the ullage have different indices of refraction. A continuous change in optical path length will form continuously changing interference patterns – the fringes move; in other words, the regions of constructive and destructive interference change. These changes can be detected with a photodiode, which outputs voltage and detects changes in light intensity caused by the bright and dark regions of the moving fringe pattern.

We produce change in optical path length by using our piston-bellows system. This increases or decreases the volume occupied by the ullage, thus directly affecting pressure, density, and index of refraction.

PISTON STROKE → ΔP → $\Delta \rho$ → Δn → Δm

(ΔP, $\Delta \rho$, Δn: OF THE ULLAGE; Δm: FRINGES IN INTERFERENCE PATTERN)

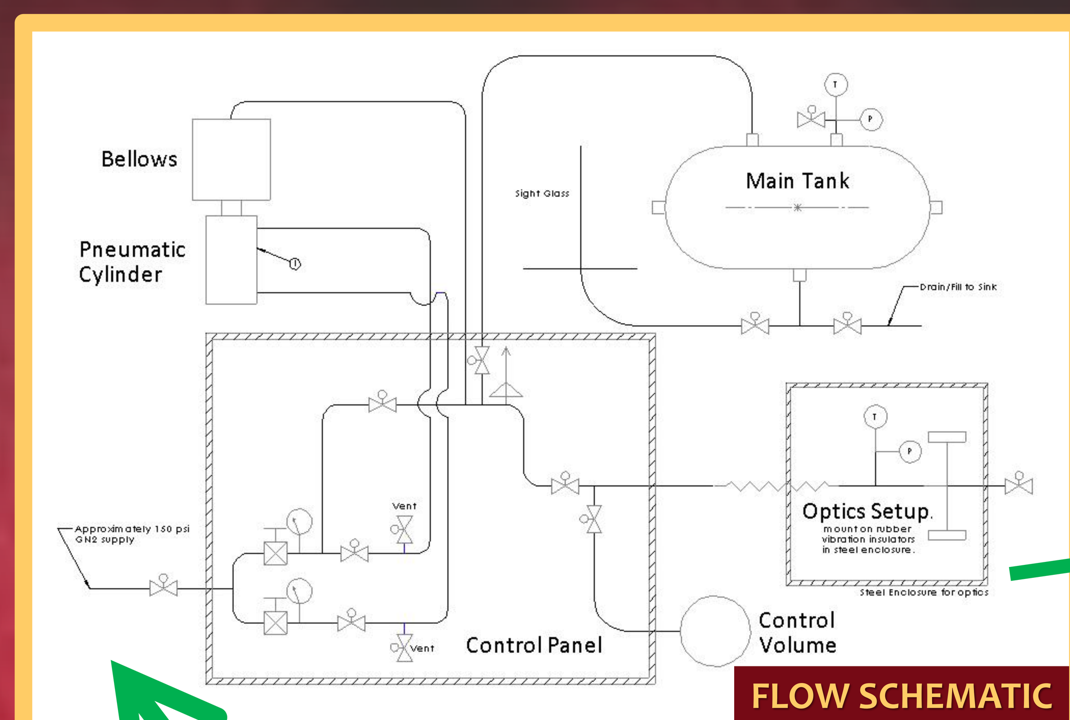
As per a mathematical derivation, we ran several expansion/compression cycles with different parts of our system isolated, as shown under Test Cycle Cases. After measuring the number of fringes that pass our interferometer detector in each case, we can calculate the volume of ullage in the tank and ultimately the volume of propellant.



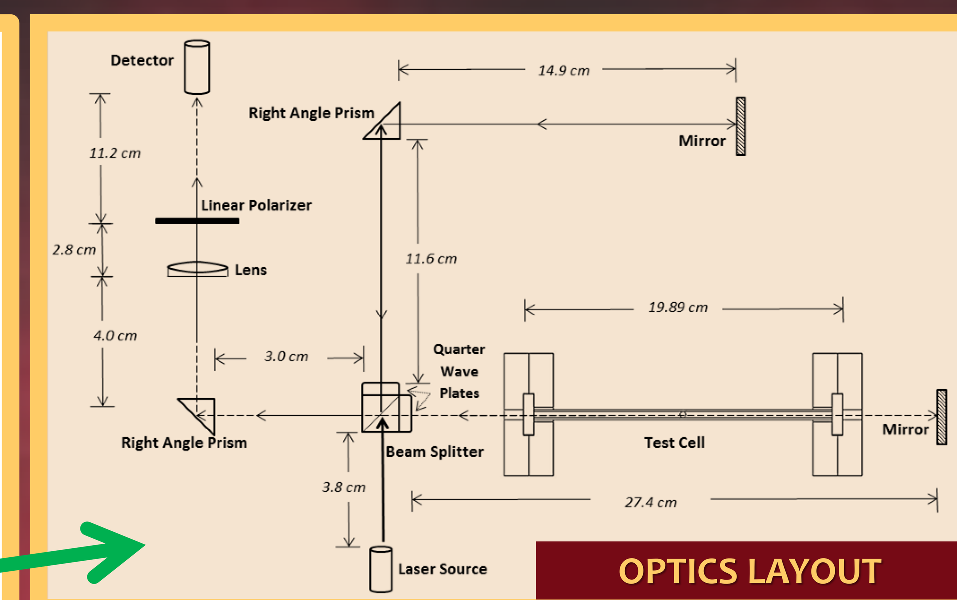
Project Process

Understand Theory → System Design → Hardware Acquisition → Stress Analysis → Hazards Analysis → System Set-Up → Test Procedure → Test Readiness Review → Data Acquisition → Data Analysis

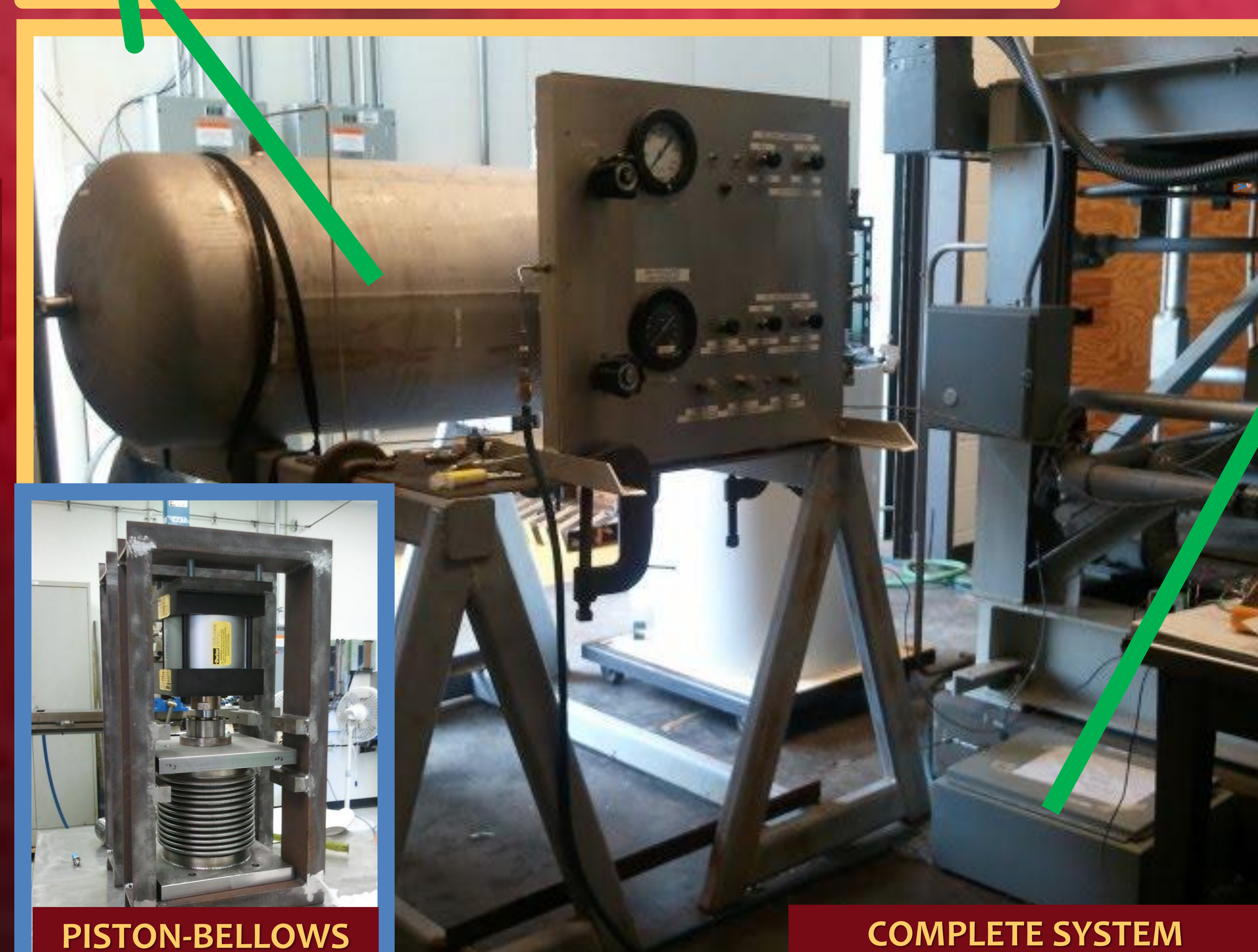
System Set-Up and Design



FLOW SCHEMATIC

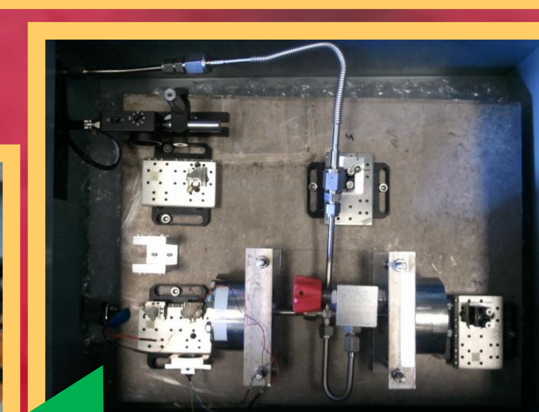


OPTICS LAYOUT



PISTON-BELLOWS

COMPLETE SYSTEM



Test Cycle

CASE 1

$$V_{total} = V_{system} + V_{control} \pm V_{piston}$$

CASE 2

$$V_{total} = V_{system} \pm V_{piston}$$

CASE 3

$$V_{total} = V_{system} + V_{control} + V_{tank} \pm V_{piston}$$

CASE 4

$$V_{total} = V_{system} + V_{tank} \pm V_{piston}$$

System Details

- Tank Volume: 25202.5532 in³
- 5 mV Class II laser
- ΔV of bellows: 36.61 in³
- Control Volume: 27.827 in³
- System Volume: 59.632 in³
- Test Pressure: 70 psig

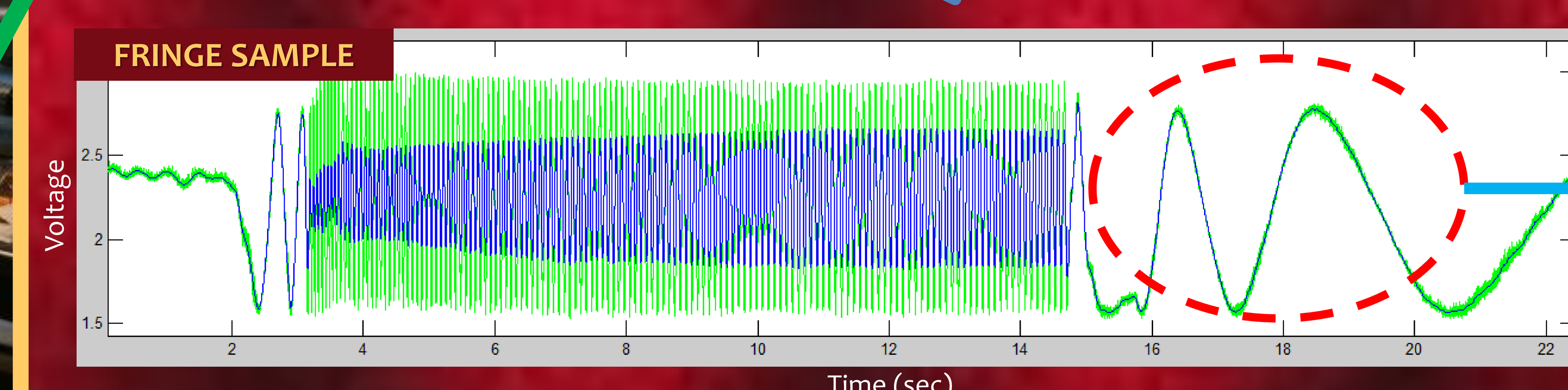
Data Analysis

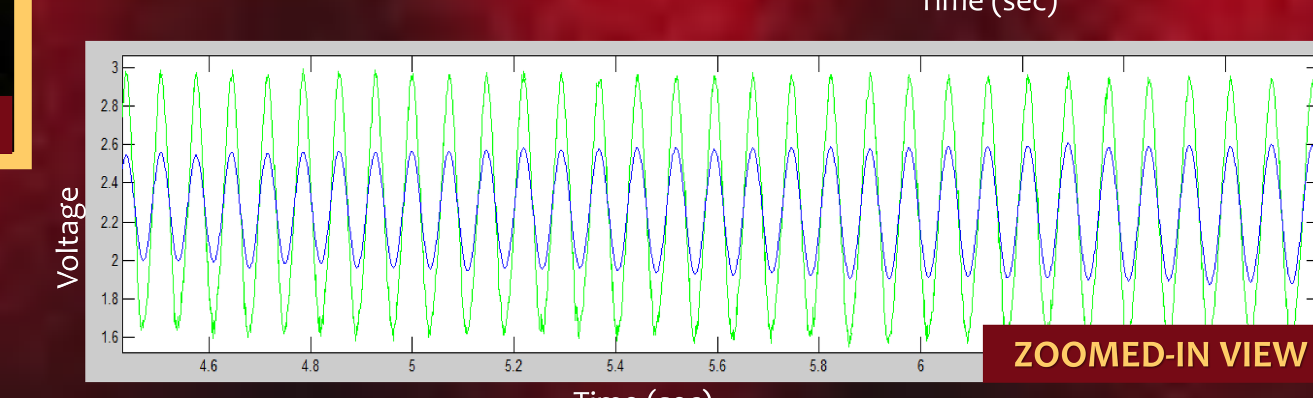
$$V_u = \left[\frac{\Delta m_3}{\beta_{3,4}\Delta m_4 - \Delta m_3} - \frac{\Delta m_1}{\beta_{1,2}\Delta m_2 - \Delta m_1}\right] V_c$$

$$V_p = V_t - V_u$$

Ullage and propellant volume equations – no dependence on equations of state

FRINGE SAMPLE





ZOOMED-IN VIEW

Original data points (40k samples)

Averaged data for peak counting

Secondary effects observed due to system anomalies:

- *Thermal effects*
- *Mechanical (valve) effects*
- *Material effects*

Acknowledgements

A very special thank you to…

Kevin Pedersen, Patrick McRight, Charles Pierce, John Wiley, Valentin Korman, William Witherow, Jack Chapman, William Stein, Jonathan Williams, James Richard, Adam Kimberlin, Kurt Polzin, Zachary Koch, Christopher Burnside, CDA Technicians, ER23 Colleagues

…for their support and mentorship.

STUDENTS FUNDED BY THE MAINE, MASSACHUSETTS, AND TEXAS SPACE GRANT CONSORTIA

Harvard University • Massachusetts Institute of Technology • UTEP • The University of Maine

Conclusions

By measuring fringe movements and approximating ullage volumes, we can see the promise of this approach despite its current limitations. Accuracy of calculations becomes difficult as ullage volume increases, and accurate predictions of propellant mass become more critical. The interferometer also displays a distinct sensitivity. It can measure small fringe shifts due to thermal, material, and compressibility effects. In addition, the interferometer can detect if a pressure drop is occurring inside the system. This may prove useful overall as a method for investigating leaking systems.

To further validate this particular system, additional analysis must be done with cryogenic fluids and microgravity testing; system automation will further improve fringe counting methods. Optical mass gauging is nonetheless proving to be a non-invasive, accurate, and reliable method of mass gauging that can be applied to future spacecraft and depot fueling systems in microgravity applications.