Inertial Navigation using Atom Interferometry

Jimmy Stammers
Imperial College London

A dissertation submitted for . . .

Abstract

This thesis describes work I did during my PhD…

Declaration

This dissertation is the result of my own work…

Jimmy Stammers

Acknowledgements

Some people worth thanking…

Preface

This thesis describes my research on various aspects of…

Contents

List of figures

List of tables

Chapter 1

Introduction

- atom interferometry experiments for precision measurements of inertial forces
- inertial navigation suffers from long-term bias drift
- recent experiments have demonstrated measuring acceleration in environments of interest to navigation

Chapter 2

Theory

- Describe general principles of light-matter interaction
- Specific cases for laser cooling (doppler/sub-doppler) and Raman transitions
- Lead into atom interferometry
- Perhaps split this into two shorter chapters

2.1 Overview

2.2 Light-Matter Interactions

2.3 Laser Cooling of Rubidium-87

2.4 Raman Transitions in Rubidium-87

2.5 Light Pulse Atom Interferometry

Chapter 3

Experimental Setup

This chapter provides a description of the hardware that makes up the experiment. Over the course of the project, the complexity of the experiment necessarily increased. The setup is presented in a bottom-up approach, starting from the most fundamental components, to provide a clear overview of the system.

To-Do:

- Figures describing each of the lasers
- Describe 3D and 2D MOT setups
- Imaging systems
- Microwave synthesisers
- Raman Assembly
- MOT light distribution

3.1 Chapter Overview

The first two sections describe the two commercial laser systems used in this experiment. The μQuans laser system which generates the light used for cooling and repump in the 2D and 3D Magneto-optical Traps (MOTs), referred to as the MOT light. The design and operation of this laser is given in Section 3.3. A secondary laser system, built by MSquared, is used to generate light to drive Raman transitions between two hyperfine ground states in Rubidium-87 (^{87}Rb)[1], otherwise referred to as Raman light. This is described in Section 3.4.This is followed by a description of the vacuum chamber in Section 3.2 which contains both the 2D Magneto-optical Trap (MOT) (Section 3.2.1) and the 3D MOT (Section 3.2.2).

[1]The μQuans laser also has a pair of lasers designed for driving Raman transitions, but these are not used in this experiment. Section 3.4 gives an explanation for this.

3.2 Vacuum Chamber

3.2.1 The 2D MOT

3.2.2 The 3D MOT

3.2.3 Imaging Systems

CCD Camera

Photodiode

3.3 The μQuans Laser System

To-Do:

- Laser Schematic
- Plots of lock signals
- DDS Serial communication
- Power output, stability
- Ref for error signal generation by current modulation
- Measure master error signal variance for frequency stability??

All the MOT light in this experiment was generated by the μQuans laser [**?**]. μQuans is a French laser company that is a spin-off from the Institut d'Optique and Observatoire de Paris. Consequently, their technology has been developed over a long history of performing experiments into atom interferometry using Rubidium. A schematic of this laser system is shown in Figure 3.1. The μQuans laser is comprised of four 1560nm **ecdls!**s (**ecdls!**s) which are frequency-doubled to produce light at wavelengths close to 780nm. The telecommunications industry, which relies heavily on light in the 1530-1565nm wavelength band for optical communications, has motivated a rapid development in low-noise, robust lasers. In particular, this has enabled a design which does not require free-space optics and is much more resilient to effects such as temperature changes and vibrations, when compared to more conventional 780nm laser systems. The μQuans laser contains one master laser [2], which is locked to the $F = 3 \rightarrow F' = 3, 4$ crossover point in Rubidium-85 (^{85}Rb), and serves as an absolute frequency reference. The other three slave lasers are used for output. The first one is used to provide lightAll the MOT light in this experiment was generated by the μQuans laser [?]. μQuans is a French laser company that is a spin-off from the Institut d'Optique and Observatoire de Paris. Consequently, their technology has been developed over a long history of performing experiments into atom interferometry using Rubidium. A schematic of this laser system is shown in Figure 3.1. The μQuans laser is comprised of four 1560nm **ECDLs!**s (**ECDLs!**s) which are frequency-doubled to produce light at wavelengths close to 780nm. The telecommunications industry, which relies heavily on light in the 1530-1565nm wavelength band for optical communications, has motivated a rapid development in low-noise, robust lasers. In particular, this has enabled a design which does not require free-space optics and is much more resilient to effects such as temperature changes and vibrations, when compared to more conventional 780nm laser systems. The μQuans laser contains one master laser [3], which is locked to the $F = 3 \rightarrow F' = 3, 4$ crossover point in ^{85}Rb, and serves as an absolute frequency reference. The other three slave lasers are used for output. The first one is used to provide light for cooling, as well as repump light by modulating the phase of this laser using an Electro-optic Modulator (EOM). The other two make

[2] see Section 3.3.1 for more details
[3] see Section 3.3.1 for more details

up a pair of lasers for driving Raman transitions. One laser is frequency-offset locked to the master and the other is phase-locked to the first, to ensure that the relative phase between the two lasers is constant. It should be noted that this Raman laser was not used in this experiment, so will not be discussed in great detail. Each of these slave lasers is amplified in an Erbium-Doped Fibre Amplifier (EDFA) before being frequency doubled in a Periodically Poled Lithium Niobate (PPLN) and passed through an Acousto-optic Modulator (AOM) which is used to control the output power during the experiment. for cooling, as well as repump light by modulating the phase of this laser using an EOM. The other two make up a pair of lasers for driving Raman transitions. One laser is frequency-offset locked to the master and the other is phase-locked to the first, to ensure that the relative phase between the two lasers is constant. It should be noted that this Raman laser was not used in this experiment, so will not be discussed in great detail. Each of these slave lasers is amplified in an EDFA before being frequency doubled in a PPLN and passed through an AOM which is used to control the output power during the experiment.

3.3.1 Absolute Frequency Reference

The purpose of the master laser is to provide an absolute frequency reference so that the frequency of the output lasers can be controlled by comparing the difference frequency between them and the master. Lasers with linewidths narrower than their natural linewidth can be achieved by using a servo to stabilise their frequency and is essential for any experiment that requires laser light of a precise frequency. The frequency reference for the master is obtained using saturated absorption spectroscopy inside a Rubidium vapor cell. The sub-Doppler features in this spectrum are insensitive to temperature changes, and under sufficiently weak laser power have linewidths close to the natural linewidth of Rubidium ($\Gamma \sim 2\pi \times 6$MHz). Figure 3.2 shows the

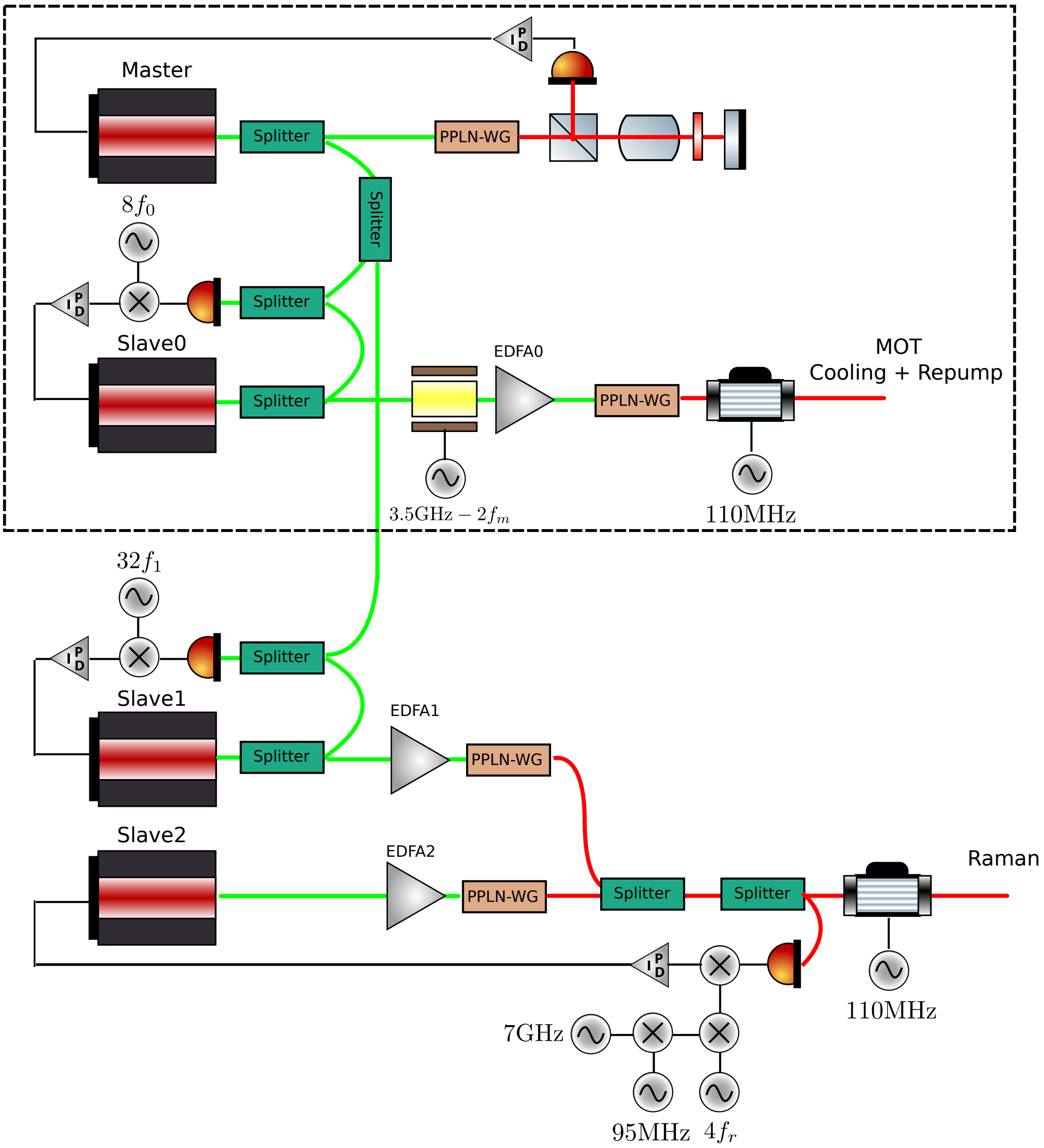

Figure 3.1: Schematic of the μQuans laser system. Each output laser is derived from a 1560nm ECDL (shown in green) which is amplified using an EDFA and then frequency-doubled to 780nm using a PPLN crystal. A master laser is locked to the 3,4 crossover in ^{85}Rb and the output lasers are offset-locked to their corresponding frequencies. The dashed region indicates the components used for generating light for the MOTs, which was the only function of this laser for this experiment.

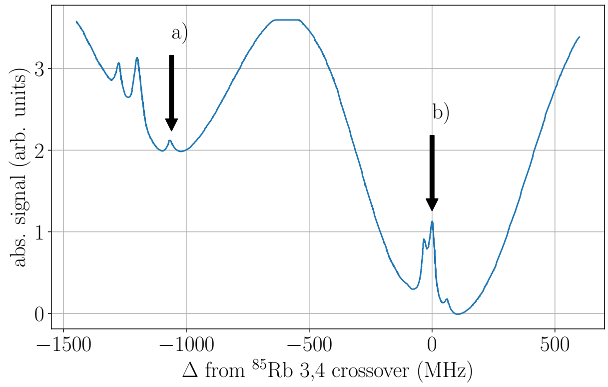

Figure 3.2: Saturated absorption spectroscopy using the Rubidium vapour cell in the μQuans laser. The absorption features indicated are a): the $F = 2 \rightarrow F' = 3$ transition in ^{87}Rb and b): the crossover resonance between the $F = 3 \rightarrow F' = 3$ and $F = 3 \rightarrow F' = 4$ transitions in ^{85}Rb which is used to lock the frequency of the master laser.

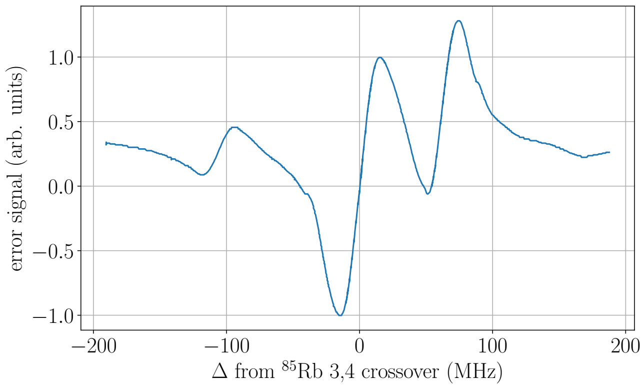

Figure 3.3: Error signal obtained by modulating the laser current. Close to the lock point, the signal is approximately linear. This signal is used in a feed-back loop to correct for frequency changes of the master laser.

saturated absorption spectrum using the μQuans master laser. This is obtained by fine adjustment of the temperature of the master External-Cavity Diode Laser (ECDL). The laser is set to lock to the crossover resonance between the $F = 3 \rightarrow F' = 3$ and $F = 3 \rightarrow F' = 4$ transitions in ^{85}Rb (indicated as b)), which is the strongest feature in the spectrum as well as being relatively close the the cooling transition in ^{87}Rb (indicated as a)). Some form of feed-back onto the master laser is required to keep its frequency fixed. The simplest way to achieve this is to use a signal that is linearly proportional to the deviation in frequency from the set-point, if one exists. The frequency of the laser is modulated by weakly modulating the current to the master ECDL. **a**dd more detail about the error signal lineshape The error signal shown in Figure **??** is obtained by demodulating the absorption signal using a lock-in amplifier. In fact, this current modulation is always present on the master laser and the saturated absorption spectrum shown previously has been processed to average out the effects from this fast frequency modulation. In addition to proportional feed-back from the error signal, the servo that controls the master frequency also contains an integrator to compensate for long-term drifts. Typically, these arise from external temperature changes and if unaccounted for, they could cause the laser to unlock. In the conditions of our laboratory, where the temperature is externally controlled, this has never occurred.

3.3.2 Generating MOT light

3.3.3 Raman light

3.3.4 Real-time Frequency Control

3.4 The M-Squared Laser System

To-Do:

- Schematic
- Raman PLL phase-noise
- Laser Control

- DCS module

3.4.1 Laser Specifications

3.4.2 The DCS Control Module

3.4.3 Frequency Control of the Raman Lasers

3.4.4 Controlling the Phase Difference

3.5 Raman Optical System

3.5.1 Vacuum design

3.5.2 Raman Beam Collimator

3.5.3 Retro-reflection Assembly

3.5.4 The MEMS Accelerometer

3.6 MOT Light Distribution

3.6.1 Optical Fibre Network

3.6.2 Power Control

3.7 Microwave Field Generation

3.7.1 Setup

3.7.2 Wind-Freak Microwave Synthesiser

Chapter 4

Computer Interface

4.1 Overview

- New MOTMaster software to control experiment
- Control system diagram
- Interfacing with muquans/msquared lasers
- Acquiring data from experiment — axelsuite

4.2 MOTMaster

4.2.1 Hardware Abstraction

4.2.2 Voltage Pattern Generation

4.2.3 Timed Serial Communication

4.2.4 Analogue Voltage Acquisition

4.2.5 Interfacing with External Software

4.3 External Laser Control

4.3.1 Muquans Interface

4.3.2 M-Squared Interface

Browser-based Control

Remote JSON Protocol

4.4 Processing Experimental Data

- Describe real-time processing and visualisation of data

4.4.1 Image Processing

4.4.2 Photodiode Voltages

4.4.3 MEMS Accelerometer

Chapter 5

Preparing Atoms for Interferometry

This chapter presents the work that went towards the initial stages of the experimental sequence, where the main objective is to prepare a sufficiently cold ensemble of ^{87}Rb in the same quantum state.

5.1 Chapter Outline

To-Do:

- Discuss loading atoms in 3D MOT from 2D
- Characterisation of the moving frame optical molasses
- Various schemes for preparing atoms into $|1, 0\rangle$. *m*ention velocity selection here or in next chapter?

5.2 Preliminary Trapping

5.2.1 Loading from the 2D MOT

5.2.2 3D MOT Characteristics

Loading Rate

Temperature

5.3 Launching and Further Cooling

5.3.1 Optical Molasses

5.3.2 Launching the Atoms

5.4 State Preparation

5.4.1 Schemes for Preparation

5.4.2 Optical Pumping Scheme

5.4.3 Improving State Purity

Driving Microwave Transitions

Chapter 6

Acceleration-Sensitive Interference

This chapter describes the work towards realising an atom interferometer and subsequently measuring accelerations.

6.1 Chapter Outline

To-Do:

- Raman spectrum, identifying each transition
- Characterisation of velocity-selective pulse and each interferometer pulse using Rabi oscillations.
- Making a three-pulse atom interferometer
- Improving acceleration sensitivity and correlating vibrations using MEMS

6.2 Raman Spectroscopy

6.3 Individual Pulse Characterisation

6.3.1 Velocity-Selective Pulse

6.3.2 Interferometer Pulses

6.4 Three-Pulse Atom Interference

6.5 Measuring Accelerations

6.5.1 Vibration Sensitivity

Chapter 7

Outlook

This final chapter describes some of the next steps and further work

7.1 Combining with classical accelerometers

- Discuss schemes for combining multiple sensors - Kalman filtering
- Extend this to inertial navigation
- Steps towards overcoming sensitivity-bandwidth trade-off.

7.2 Extending to senstivity along three axes

- New chamber design
- Improvements to MSquared laser
- Required knowledge of gravitational axis for accurate navigation

Acronyms

CCM Centre for Cold Matter

^{87}Rb Rubidium-87

^{85}Rb Rubidium-85

MOT Magneto-optical Trap

AOM Acousto-optic Modulator

EOM Electro-optic Modulator

PM Polarisation-Maintaining

QWP Quarter-wave Plate

HWP Half-wave Plate

MFD Mode Field Diameter

PPLN Periodically Poled Lithium Niobate

PLL Phase-Locked Loop

FPGA Field-Programmable Gate Array

EDFA Erbium-Doped Fibre Amplifier

ECDL External-Cavity Diode Laser

TTL Transistor-transistor Logic Circuit

NI National Instruments

DAQ Data Acquisition

ADC Analogue-to-Digital Converter

DAC Digital-to-Analogue Converter

HAL Hardware Abstraction Layer

SPI Serial Programming Interface

DDS Direct Digital Synthesiser

PBS Polarising beam-splitter

DRO Dielectric Resonator Oscillator

CCM Centre for Cold Matter

^{87}Rb Rubidium-87

^{85}Rb Rubidium-85

MOT Magneto-optical Trap

AOM Acousto-optic Modulator

EOM Electro-optic Modulator

PM Polarisation-Maintaining

QWP Quarter-wave Plate

HWP Half-wave Plate

MFD Mode Field Diameter

PPLN Periodically Poled Lithium Niobate

PLL Phase-Locked Loop

FPGA Field-Programmable Gate Array

EDFA Erbium-Doped Fibre Amplifier

ECDL External-Cavity Diode Laser

TTL Transistor-transistor Logic Circuit

NI National Instruments

DAQ Data Acquisition

ADC Analogue-to-Digital Converter

DAC Digital-to-Analogue Converter

HAL Hardware Abstraction Layer

SPI Serial Programming Interface

DDS Direct Digital Synthesiser

PBS Polarising beam-splitter

DRO Dielectric Resonator Oscillator