Atom interferometer analog of the double slit experiment

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Motivation-Gradiometers for Navy applications

Atom interferometers (for magnetic field measurements)

Making the atom beam-splitter: Raman transitions in real atoms in arbitrary magnetic fields

Interferometer Experiments ....
Outline - Interferometer Experiments

- Single Pulse
  - Time Domain
  - Frequency Domain

- Double Pulse
  - Time Domain
  - Frequency Domain

- Triple Pulse
  - Time Domain
  - Frequency Domain

- Outlook

- Conclusions
Airborne Magnetic Noises

MAD ~ 1/2 Hz

Spectral Density (nT/Hz)

Frequency (Hz)

~ fT/Hz^{1/2}

MAD ~ 1/2 Hz

NIST

Welch

Budker

Romalis

UVa

Nov 12, 2012
P2000 Gradiometer Test
Memorial Airfield, Chandler, AZ.
April 27, 2003

Truck did 4 passes (2 in each direction) at 30 MPH using cruise control at each gradiometer distance.

Memorial Airfield Runway 31/13

03 Ford Expedition

Visual Markers

Fixed Distance = 150'

"HammerHead" Wing
‘Fixed Sensor’
P2000 Sensor #1

Vector Mag
GPS Receiver
GPS Antenna

150’ Aircraft Cable

200’ Sensor Cable

P2000 System 1 & 2
and recording systems

Thorpe SEEOP 33’ Trailer

Yamaha YG2800I
2800 Watt Inverter Generator

P2000 Sensor #2
‘Moving Sensor’

Run 1, 10’
Run 2, 20’
Run 3, 40’
Run 4, 60’
Run 5, 80’
Run 6, 100’
Gradiometer (Reference sensor)

Fluctuations are all geomagnetic noise!

filtered UTF (BP=0.001-10 Hz) : separation (ft)=80; 17.4481-17.5067 hr;
Gradiometer (Reference sensor)

Truck drive-bys -- dual mags difference of filtered UTFs [bird - ref] (BP=0.001-10 Hz) : separation (ft)=80; 17.4481-17.5067

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Technical Overview of AI sensors

\[ |c_{e,p+\hbar k}(2T + \tau)|^2 = \frac{1}{2} [1 - \cos (\Delta \phi - \delta \tau/2)] \]
We have shown...

A proposal for a gradient magnetometer atom interferometer

J.P. Davis and F.A. Narducci*

Journal of Modern Optics

- For uniform B field
  \[ \Delta \phi = 0 \]

- For gradient B-field
  \[ \Delta \phi = -k_{eff} \left( g + \frac{\mu dB}{m dz} \right) T^2 \]

An inherent gradiometer
State-space interferometer

\[ \Delta \phi = \frac{\Delta S}{\hbar} = \frac{\mu_B}{\hbar} \left( g_{F'}m_{F'} - g_{F}m_{F} \right) \left( \frac{\partial B}{\partial z} \right) v_o T^2 \]

\[ = \frac{\mu_B}{\hbar} \left( g_{F'}m_{F'} - g_{F}m_{F} \right) \left( \frac{\partial B}{\partial z} \right) \frac{\Delta z}{2} T \]

\[ _{^{35}}^{1}Co-\text{propagating Raman beams for Doppler-free, acceleration free configuration} \]

\[ _{^{35}}^{1}\text{Coherent superposition of magnetic sublevels} \]

Same picture allows us to see how this runs as a magnetometer (possibly with stationary atoms)
Raman Resonances

Now controlled by ground state decoherence time which can be made very small
Raman resonances in arbitrary fields
A real atom: $^{85}$Rb

11 different Raman resonances!
Experimental Arrangement

- Trapping Beam
- Sat Abs
- ECDL
- HWP
- AMP
- AO1
- MOT
- Beat note

Graphical representation of the experimental setup with labeled components and connecting lines.
Timing sequence

- Gradient
- Reump Field
- Trapping Fields
- Raman
- Probe

Rf frequency changes from shot to shot
Raman Spectra-Arbitrary Field

\[ \frac{1}{T_{\text{pulse}}} \]

\[ \dot{a}^* \dot{\hat{T}} \]
Selection Rules

“Even” transitions driven by
x-y polarization
\( \sigma \) polarizations
\( \Delta m = 0 \)

“Odd” transitions driven by
\( \sigma \) polarizations
\( \Delta m = 1 \)

Here, z is defined by the direction of the magnetic field

\( g \) factor between ground states changes sign
Six Peaked Spectrum
Five Peaked Spectrum

No deadzone

\[ \sum_{k=0}^{\infty} \rho_{kk} \text{ (arb. units)} \]

Freq (kHz)

Longitudinal
Double Pulse Experiment
(Ramsey)
Time Domain
Raman Transfer (Cycling)
Timing sequence

- Gradient
- Reump Field
- Trapping Fields
- Raman
- Probe

Pulse length changes from shot to shot

Time (msec)
Rabi cycling: 0 peak (Expt.)

Intensity (arb. units)

Time (µs)
$|c_2(t_1 + T + t_2)|^2 = \left[2\frac{\Omega^+}{\Omega^*} \left[\frac{\Omega^*}{2\Omega_g} \tilde{c}_2(t_1)e^{i\delta(t_1+T)} - \frac{\Omega^-}{\Omega_g} \tilde{c}_1(t_1)\right] e^{i\Omega_+ t_2} \right. \\
\left. + 2\frac{\Omega^-}{\Omega^*} \left[\frac{\Omega^+}{\Omega^*} \tilde{c}_1(t_1) - \frac{\Omega^*}{2\Omega_g} \tilde{c}_2(t_1)e^{-i\delta(t_1+T)}\right] e^{i\Omega_- t_2} \right]^2$ \\

$\Omega_{\pm} = \frac{1}{2} (\delta \pm \Omega_g) \quad \Omega_g = \sqrt{|\Omega|^2 + \delta^2}$

Picture two lasers beating against each other where here the Raman fields plays the role of the first laser and the atomic ground state transition plays the role of the second laser.
Timing sequence

- Gradient
- Repump Field
- Trap fields
- Raman
- Probe

Time between pulses changes from shot to shot.
$f = 1.517862 \text{ GHz}$

$T =$ delay time between pulses
$f = 1.517863 \text{ GHz}$

$T =$ delay time between pulses
\( f = 1.517864 \text{ GHz} \)

\[ T = \text{delay time between pulses} \]
$f = 1.517865 \text{ GHz}$

$T = \text{delay time between pulses}$
\( f = 1.517866 \ \text{GHz} \)

\[ T = \text{delay time between pulses} \]
f=1.517867 GHz

T=delay time between pulses
f=1.517868 GHz

T=delay time between pulses
$f = 1.517869 \text{ GHz}$

$T = \text{delay time between pulses}$
$f=1.517870 \text{ GHz}$

Graph showing the relationship between time (in usec) and some data points, with labels:

- $T = \text{delay time between pulses}$
For a magnetometer, the center frequency would not be at zero
Rabi Cycling: +1 Peak (Expt.)
Double Pulse on magnetic transition

![Graph showing a double pulse on a magnetic transition. The graph plots the sum of certain quantities over time (in microseconds).]
Double Pulse Experiment
(Ramsey)
Frequency Domain
Timing sequence

Rf frequency changes from shot to shot

- Gradient
- Repump Field
- Trap fields
- Raman
- Probe
Inspiration from optics/clocks

\[ \Delta x \sim \frac{1}{2 \text{ slit width}} \]

\[ \Delta x \sim \frac{1}{2 \text{ slit separation}} \]
Two-photon detuning (kHz)

\[ \Delta \nu = \frac{1}{\Delta T_{pulse}} \]
Two-photon detuning (kHz)
Triple Pulse Experiment
Time Domain
Timing sequence

Timing between last two pulses changes
Triple Pulse Experiment
Frequency Domain
Timing sequence

- Gradient
- Reump Field
- Trapping Fields
- Rf frequency changes shot to shot
- Raman
- Probe
Evidence of gradiometer

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Similar Bfield – changing spatial gradient

An atom interferometer gradient magnetometer
Just for fun.....
Work to be done….

• Systematic measurement of output vs.
  – Magnetic field
  – Gradient magnetic field

• Atom fountain arrangement

• Sensitivity
Optical pumping
Conclusions

- Single Pulse
  - Time Domain
  - Frequency Domain

- Double Pulse
  - Time Domain
  - Frequency Domain

- Triple Pulse
  - Time Domain
  - Frequency Domain

“Demonstration” of a gradient magnetometer atom interferometer
Questions?
Gradiometers can remove distant noise

**Diagram:**
- **Spectral Density (nT/Hz^{0.5})**
- **Frequency (Hz)**
- **MAD**
- **ELF**
- **Deep**
- **Buffeting**
- **Geology**
- **Shallow**
- **Platform Maneuver**

**Noise Sources:**
- **CPA=2000 ft**
- **3 \times 10^8 nT-\text{ft}^3 Dipole**
- **ASQ-208**
- **Swell**
- **P-2000**

**Legend:**
- **Noises**

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Technical Overview of AI sensors

\[ |c_{e,p+\hbar k}(2T + \tau)|^2 = \frac{1}{2}[1 - \cos(\Delta \phi - \delta \tau/2)] \]
State-space interferometer

- Co-propagating Raman beams for Doppler-free, acceleration free configuration
- Coherent superposition of magnetic sublevels

Same picture allows us to see how this runs as a magnetometer (possibly with stationary atoms)

\[
\Delta \phi = \frac{\Delta S}{\hbar} = \frac{\mu_B}{\hbar} (g_{F'} m_{F'} - g_F m_F) \left( \frac{\partial B}{\partial z} \right) v_o T^2
\]

\[
= \frac{\mu_B}{\hbar} (g_{F'} m_{F'} - g_F m_F) \left( \frac{\partial B}{\partial z} \right) \frac{\Delta z}{2} T
\]
Components for the atom optics

\[ |c_{e,p+\hbar k}(2T + \tau)|^2 = \frac{1}{2} [1 - \cos(\Delta \phi - \delta \tau/2)] \]
Raman Transfer (3-level atom)

Very narrow resonance!!
Atom Beamsplitter

\(\pi\) pulse - all the population is transferred

\(\pi/2\) pulse - half the population is transferred
Raman Spectra-Arbitrary Field

\[ \sum_{F=\text{arb. units}} (\rho_{ii}) \]

Detuning (kHz)
Raman Transfer (Cycling)
Rabi cycling: 0 peak (Expt.)
Rabi Cycling: +1 Peak (Expt.)

+1 transition: Case 2

Intensity (arb. units) vs. Time (μs)
For a magnetometer, the center frequency would not be at zero.
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Single Pulse

Double Pulse
Triple Pulse Experiment
Time Domain
Similar Bfield – changing spatial gradient
Backups
Two level atom reminder

- Natural Linewidth
- Powerbroadened Linewidth

\[ \hbar \omega_0 \]

\[ \hbar \omega_L \]
Square vs Gaussian Pulses

Square Pulse

Gaussian Pulse