Remote Magnetometry with Mesospheric Sodium

ONR Remote Atmospheric Magnetometry Workshop
25 April 2014

FASORtronics LLC
Contract N00014-14-C-0110

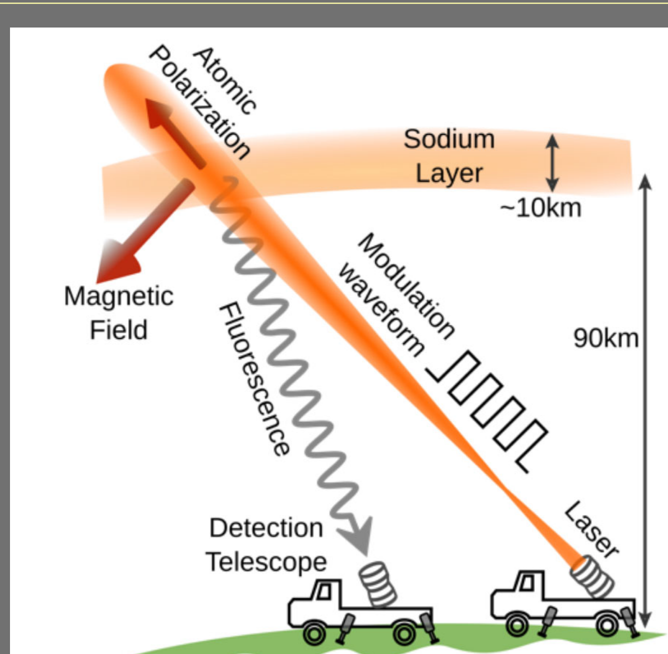
Tom Kane *Craig Denman* *Paul Hillman*

Goals of Talk

- Understand measurement sensitivity
- Scaling rules for sensitivity
- Technology of experiment
- Update on experimental program
- Magnetometry and guidestar laser technology

Laser Remote Magnetometry using Natural Sodium

- The Sensor
  - sodium atoms in the mesosphere
  - 3000-5000 atoms/cm^3
  - 90 kilometer altitude
- Laser Interrogation of atoms
  - pulse laser near Larmor frequency (~350kHz)
  - detect returned photon fluorescence
- Laser similar to astronomical “guidestar” lasers



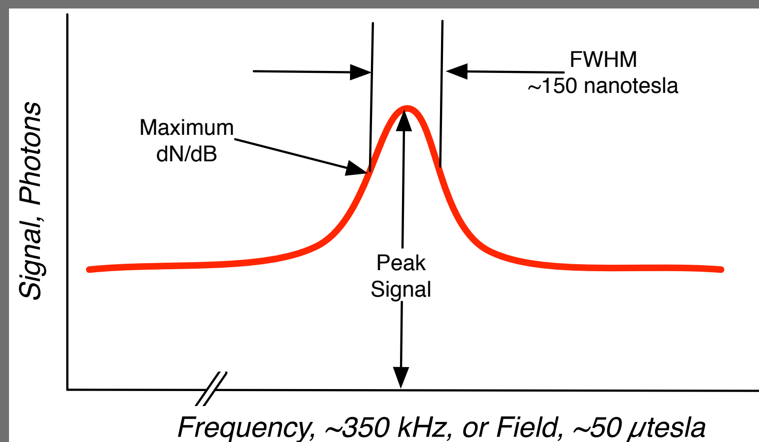
J.M. Higbie, et al, arXiv:0912.4310v1 [physics.atom-ph] 22 Dec 2009

FASORtronics

The 350 kHz Larmor frequency corresponds to a 0.5 Gauss (50 μTesla) magnetic field, which is near the high extreme over the earth. This frequency is proportional to the B field.

Photon Limited Sensitivity

- N = expected number of photons collected during measurement
- √N = standard deviation in number of photons, “shot noise”
- 1/√N = fractional uncertainty



Magnetic field change equivalent to shot noise:

Roughly: ΔB = (1/√N) / (dN/dB / N)

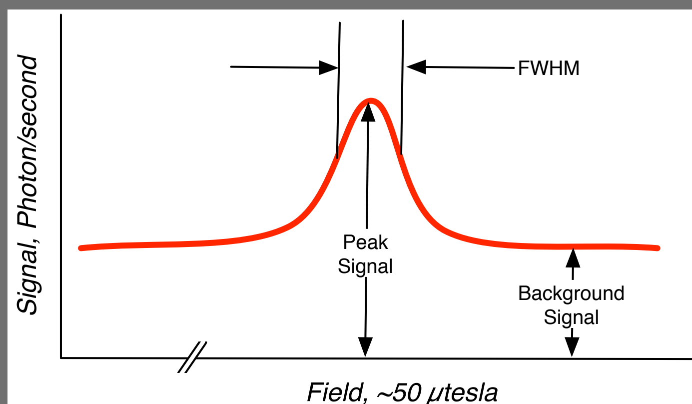
(1/1000) / (1%/nanotesla) = 0.1 nanotesla

FASORtronics

The resonance is expected to be about 1 kHz wide, corresponding to about 150 nTesla. The point of steepest slope will have a slope of about 1% of signal per nTesla. With 1 million photons detected, and only shot noise, there is measurement uncertainty of 0.1%. Thus with 1 million photons detected, the magnetic field change equivalent to shot noise is about 0.1 nTesla. This case is for an optimized laser.

Sensitivity of Mesospheric Sodium Magnetometry

$$\mathrm{nT}/\sqrt{\mathrm{Hz}} = \frac{4\sqrt{3}\,FWHM}{9}\,\frac{\sqrt{Peak + Back}}{|\,Peak - Back\,|}$$



The equation is the shot-noise-limited sensitivity, assuming a Lorentzian lineshape. *FWHM* is the full-width at half-maximum of the resonance, in units of nTesla. *Peak* and *Back* are the signals at the peak of the resonance, and away from the resonance, in units of photons per second.

What Determines Linewidth?

- Rate of Loss of polarized atoms
  - 1 / Linewidth ≈ Decay time of polarized atoms
  - Collisions with molecules
  - Atoms moving out of laser beam
  - Laser beam moving
- Rate of build-up of polarized atoms
  - Too much laser intensity broadens linewidth
  - There is an optimum

The two types of collisions

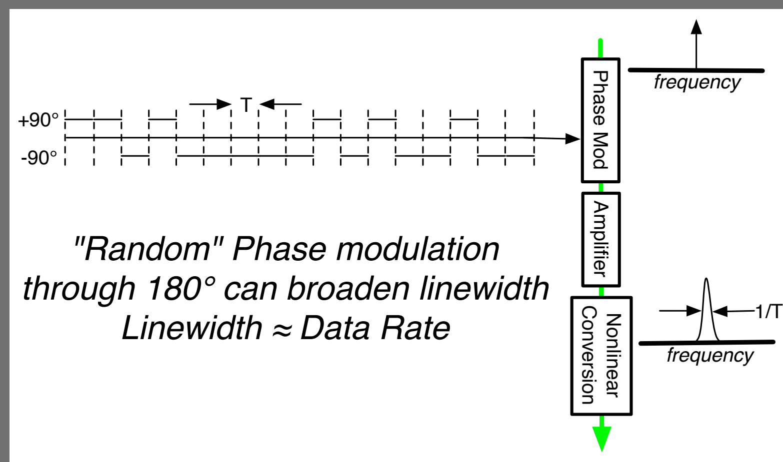
- All collisions change velocity
  - Atom is “lost” only if laser is single-frequency
  - 50 microseconds mean time between collisions @ 100 km
- Only some collisions change spins (polarization)
  - Collisions with oxygen (O_2)
  - Atom is lost
  - 250 microseconds mean time between collisions with O_2
- Collision rate is linear in pressure
  - Mesospheric pressure 10^{-6} of sea level

FASOR tronics

The linewidth of the resonance is determined by how long an atom sees the laser light before its spin is randomized. For a narrow-band laser, the atom stops being pumped by the laser light after any collision, because its velocity is changed to where its Doppler shift puts the laser light outside the sodium absorption. But with a broadband laser, the Doppler shift does not stop the pumping process,because light is present over the whole Doppler-broadened laser line. For a broadband laser, only collisions with oxygen will stop pumping, since the oxygen will exchange angular momentum with the sodium atom. Thus a broadband laser can narrow the linewidth by a factor of 5, improving magnetic sensitivity.

If Laser Linewidth ≥ Atom Doppler Linewidth

- Longer Lifetime applies
- ~1 GHz easily created by phase modulation
- Fiber-coupled, waveguide phase modulators



Phase modulation of the laser can broaden linewidth in a very controllable way. However, high-frequency phase modulators are not available in bulk form. They are available in waveguide form, which is not compatible with power above a few milliwatts, or with visible light. An architecture which phase-modulates at low power, in the infrared, and then amplifies and frequency-converts afterward, can provide broad linewidth, at high power, at 589 nm.

Optimum Intensity

- Intensity too low:
  - Time to polarize atom >> spin exchange time
  - Few atoms polarized
- Intensity too high:
  - Time to polarize atom << spin exchange time
  - Polarization saturates; linewidth broadens
- Low value of optimum intensity leads to cheap, simple launch telescope
  - Commercial asphere lens is adequate

FASORtronics

Launch telescope can be about 100 mm diameter.

Effect of Laser Spectrum

Laser Spectrum	Optimum Average Intensity*	nanoteslas/ √Hz @ 2 watts avg.	nanoteslas/ √Hz @ 20 watt avg.
Single Frequency	0.2 watt/ m^2	6	2
Single Frequency + Repump	0.6 watt/ m^2	2.5	0.8
Broad Linewidth + Repump	8.5 watt/ m^2	0.34	0.11

*Average Intensity = time averaged over modulation cycle

Modeling: Rochester Scientific pulsed code

FASOR tronics

Our initial work will be with a 2 watt laser, narrow linewidth, with no "repump" sideband. Expected sensitivity is near 6 nTesla/√Hz. A 20 watt laser, with optimum spectral properties, could go down to 100 picoTesla /√Hz.

Factors Extrinsic to Atoms

- Goal: Return of order 10^6 photons per second
  - Atomic density
    - Scatter fraction
  - Collection geometry
    - Range & telescope aperture
  - Laser power
  - Detector efficiency

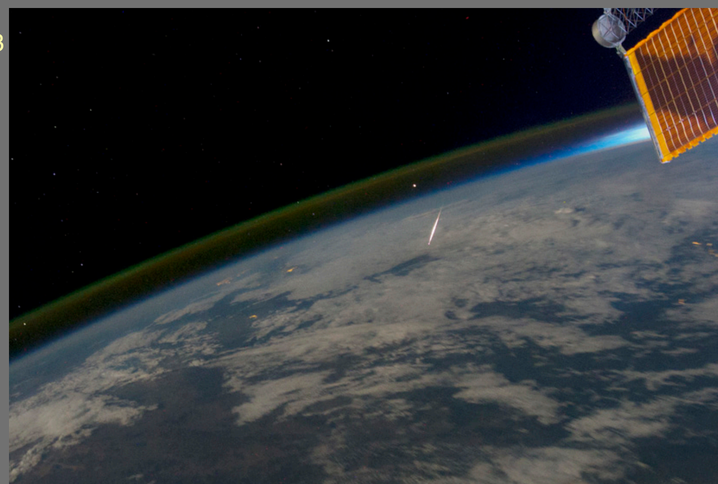
FASORtronics

Collection Geometry

- Fraction of light collected, if isotropic scattering
  - $D^2 / (16 z^2)$
    - D = receive telescope diameter (1.5 meters for us)
    - z = range to sodium atoms (139 km for us, 45° angle)
    - $D^2 / (16 z^2) = 7.3 \times 10^{-12}$
- Not isotropic; backscatter enhancement is in range 2 to 4.
  - 2 because of dipole nature of scatter from unpolarized atom
  - For ideal laser (re-pump plus linewidth broaden) another ~2X from a polarized atom

Sodium Layer

- "Column Density" - per area
  - 40 million atoms/mm^2
  - Volume: 4 atoms/mm^3
- Fraction of light scattered: 4%
- Total worldwide sodium: 800 kilograms
- Lifetime in mesosphere
  - Weeks



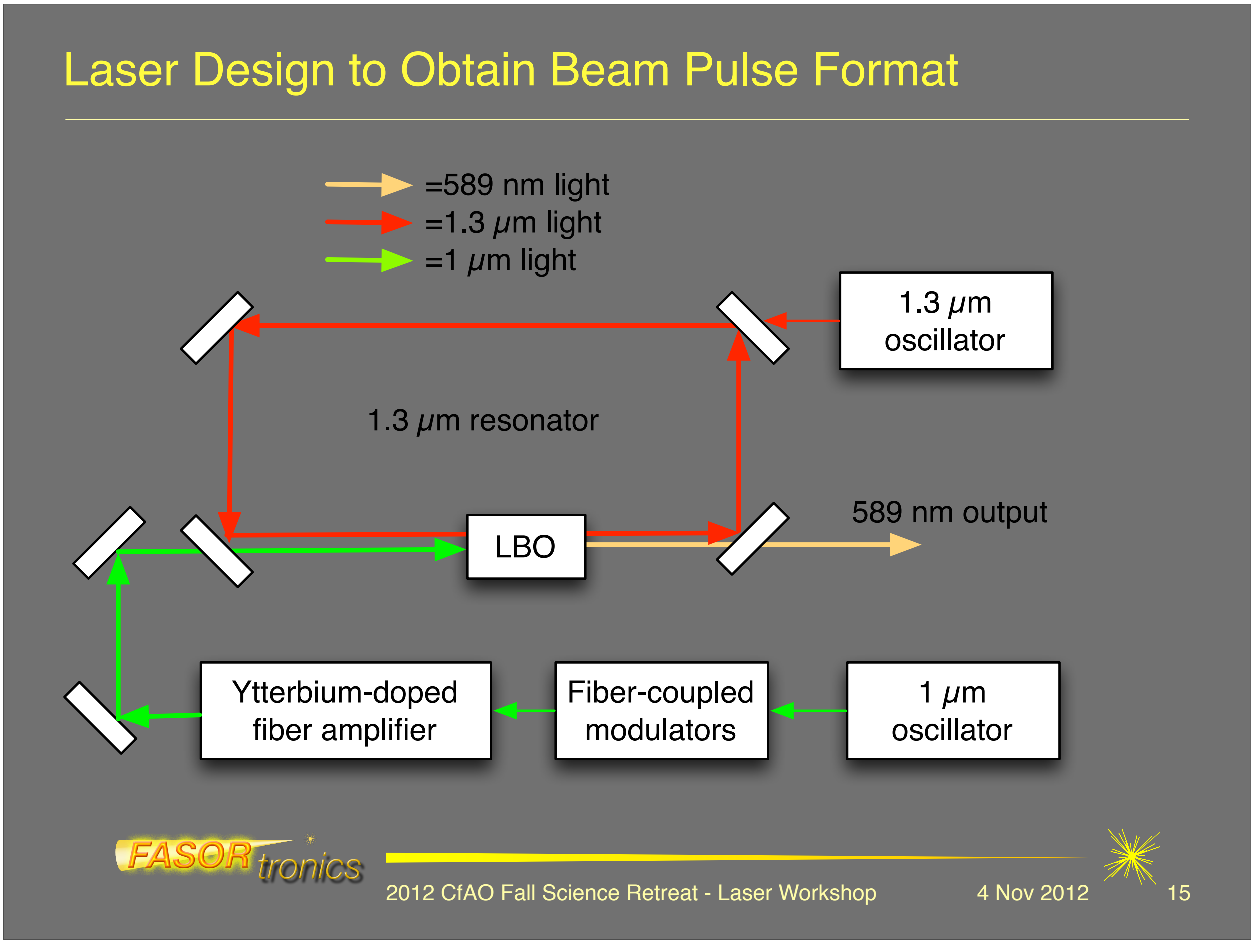
FASOR tronics

Laser Power & Detection Efficiency

- 50 watts is state-of-art for 589 nm
- Our project:
  - 10 watts x 20% duty cycle = 2 watts

FASOR tronics

In a later phase we hope to upgrade to 20 watts of transmitted power.



Friday, April 25, 2014

This fiber / YAG "hybrid" design will provide an efficient laser pulsed at the right frequency for magnetic measurements. Since the 1 μm light is converted in a single pass, and is not resonant, its modulation will be passed directly to the generated 589 nm light, rather than stripped off by the filtering properties of the resonator. Thus any modulation at 1 μm appears directly at 589 nm. So a broad linewidth, or sidebands, can be generated using low-power, infrared phase modulators, and transferred to the high-power 589 nm.

Photodetectors that are shot-noise limited

- Detection Efficiency: 27%

Detector Type	Minimum shot-noise-limited signal		Efficiency
	picowatt	photon/sec	
Standard Photomultiplier	≤0.005	≤15,000	20%
Cooled, GaAsP Photomultiplier	≤0.005	≤15,000	39%
Avalanche Photodiode	4	12 million	70%
Multi-Pixel Photon Counter	≤0.04	≤120,000	27%
Standard Photodiode with Transimpedance Amplifer	100	300 million	80%

FASOR tronics

Friday, April 25, 2014

With an expected signal of about 1 million photons per second, we cannot use an ordinary photodiode, but must use a device with internal gain. We will use a multi-pixel photon counter, with quantum efficiency of 27%.

Our Team: FASORtronics + University of Arizona

Steward Observatory's 61" Kuiper Telescope

FASORtronics

University of Arizona partners: Michael Hart and Randy "Phil" Scott

The Telescope: University of Arizona 61-inch “Kuiper”

~ 1.55 meter

FASOR tronics

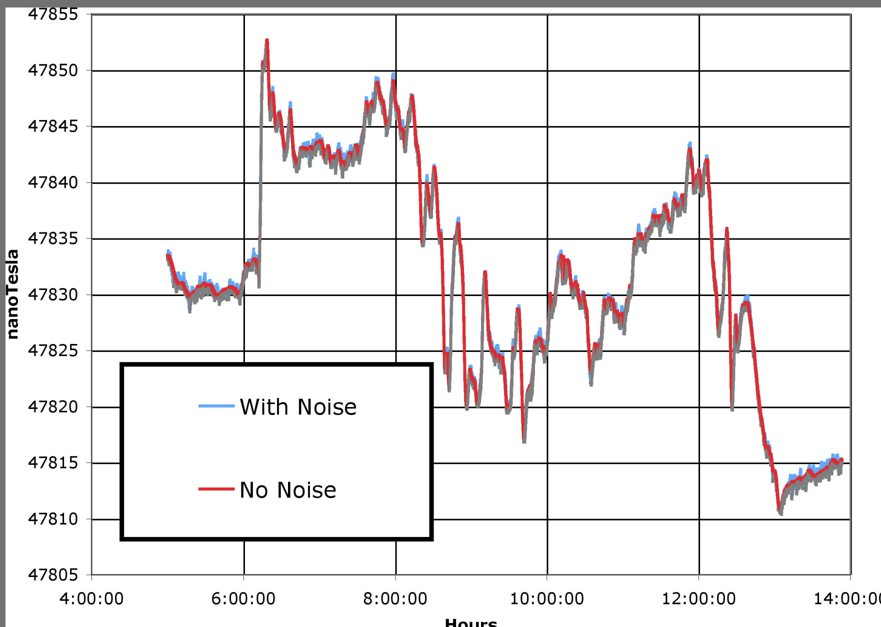
Reference Magnetometer: USGS “Observatory”

~0.1 nanoTesla noise, 1 sample per second

FASOR tronics

The USGS data, Tucson observatory, is posted on the net.
http://magweb.cr.usgs.gov/data/magnetometer/TUC/OneSecond/

Expected Signal on Magnetic Storm Day

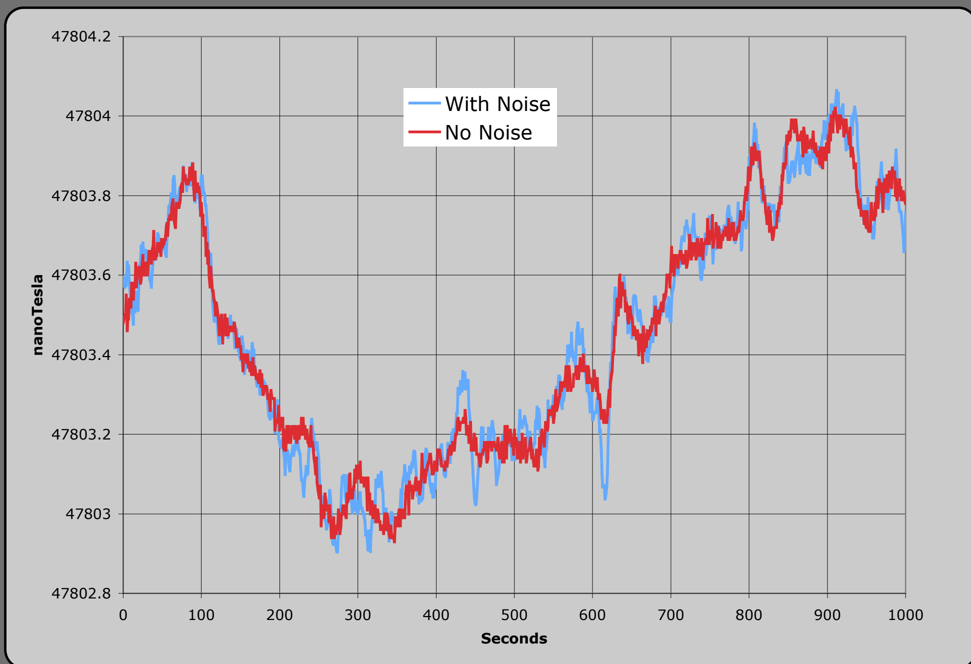


Data from USGS, Jan 22, 2012

Added noise of 4 nT √Hz does not cover signal

Even with our non-optimized laser, we should easily be able to see a magnetic storm. Shifts of many nanoTesla, over hours, should be readily observed, if the laser is reliable.

Expected Signal on Typical Quiet Day



Data from USGS, April 14, 2012

Added noise of 0.2 nT √Hz does not cover signal for >30 sec

FASOR tronics

An optimized laser should be able to see the change which typically occurs in 30 seconds, on a magnetically quiet day.