Quarterly Report for ERIP Grant # DE-FG49-92CE15500.

Commercialization of Atom Interferometers for Borehole Gravity Gradiometry.

Quarter 4, July - Sept. 1993.

Principal Investigator: John F. Clauser

Present Status of Tasks:

Task 1 - Solution of tomography problem (completed qtrs. 1 and 2).

Task 2 - Study influence of vibrations (completed qtr. 3).

Task 3 - List of borehole imposed constraints
(completed qtr. 3, with update this qtr.)

Task 4 - Evaluate merits of various cooling schemes (completed this qtr).

Task 5 - Specify magnet system requirements (completed qtr. 3).

Task 6 - Specify laser system (in progress).

Task 7 - a. Specify detector (in progress),
b. Specify gratings and layout (in progress),
c. Specify grating and magnet spacers (in progress),
d. Specify vacuum system (in progress).

During this 4th quarter, we report an update to Task 3, as well as completion of Task 4. Work on Tasks 6 and 7 is in progress.

Update of work on Task 3 - Compile a list of borehole imposed constraints and tradeoffs for the design of the gradiometer:

An update to the list of tool requirement requirements has been added, via a conversation with the Dr. Strack at Atlas Wireline Services. An important practical aspect of typical boreholes was overlooked in our previous study. It is the fact that, in general, most boreholes are way out in the "Boonies" and otherwise hard to get to! He thus said that as far as his company is concerned, any such tool must be no longer than 20 feet, so that it would fit on an industry-standard rough-terrain vehicle, and transportable on his company's aircraft! He was quite adamant on this point, and said that unless this requirement is met, his

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

company would never buy one.

Upon reanalysis of our instrument's current design state, we conclude that such a length limitation is not serious. As far as sensitivity is concerned, limiting the interferometer length to about 5 meters (thus allowing additional length for lasers, dewars, pumps, electronics, etc. on the ends) does not hurt the design, too much. At this short length, the device may be forced to use e-beam lithography, rather than the more conventional (and flexible) optical lithography for fabrication of the gratings. On the other hand, construction of a shorter device will be easier. In addition, the shorter device will be much stiffer and make it easier to meet the magnet flexure limits.

Work on Task # 4 - Evaluate the merits of various possible cold, slow, atomic beam production schemes as suitable for the device:

4a. Use of a Magneto-Optic Trap (MOT):

A foremost requirement for the device is that its source for ultra-cold, ultra-slow atoms must have a very high brightness. Indeed, the lion's share of our parallel work at UC Berkeley to produce a working atom interferometer has been in the area of high-brightness low-velocity atomic source development. Given recent experience at other laboratories, as well as that in our own lab, our current best choice for a source is to use a pulsed source. First we will direct a thermal lithium beam to load a magneto-optic-trap (MOT) with ultra-cold atoms. The MOT consists of the intersection of six circularly polarized laser beams inside an inverse Helmholtz field coil set. Then, upon accumulating a suitable density of atoms, we will turn off the MOT and drop the atoms, thereby providing an intense pulsed source of ultra-cold atoms. Operation of a MOT in this manner has been demonstrated at many different laboratories for a wide variety of species.

4b. Choice of Atomic Species:

Considerations regarding choice of source cannot be made fully until the atomic species has been determined. To work within the limited confines of a borehole sonde, it appears that the cooling must be done with diode lasers. Presently available diode lasers work at the resonance wavelengths of lithium, potassium, rubidium and cesium. Earlier, we favored the use of a device that uses Talbot-vonLau interferometry working with a dropped balls of ultra-cold rubidium atoms from a MOT. Our work under Tasks 5 and 7b, however, indicates that the use of a heavy atom (such as rubidium) places rather strong requirements on the magnet system. To alleviate these problems, we thus now favor the use of lithium. Lithium's low mass and long deBroglie wavelength, in turn, will require use of separated-beam rather than Talbot-vonLau interferometry.

4c. State of the Art for Lithium MOT's:

One uncertainty over the operation of a MOT-based source is whether we can operate such a source at the desired brightness using available diode laser systems. Existing theoretical analyses of a MOT's operation generally overestimate the required laser power. Thus, experimental results at present provide the best guide. MOT's for lithium have been built at U. Tokyo, Rice U., and Stanford U. The U. Tokyo configuration uses a cumbersome tapered solenoid for Zeeman slowing to feed the trap. It employs four laser frequencies at 10 and 80mw of total laser powers (typically with a 1 MHz bandwidth). That experiment reports associated atomic buildup rates of 10^7 and 10^8 atoms per sec, respectively. The Stanford experiment also uses four laser frequencies, one pair with a total of 100 mw and 100 MHz bandwidth and the other pair at 0.1mw with a 1 MHz bandwidth. However, it has no Zeeman slower magnet, but instead feeds the trap directly with a thermal lithium beam. It evidences atomic buildup rates of about 10^7 atoms per sec. The Stanford experiment appears to produce colder atoms, with about the same phase space density as the Tokyo experiment for comparable laser power. In either experiments the final density

appears to be proportional to the available laser power.

4d. Use of Lenses to Increase the Intensity:

One key to further improving source brightness was given by the PI earlier (in patents and at the '89 ONR sponsored Santa Fe conference on atom interferometry). The key is to focus atoms from the source before feeding them into the interferometer. To do so, one can use zone-plate lenses, magnetic lenses, electric lenses, light-shift graded-index laser lenses, gravitational lenses, or some combination of these. It is noteworthy that experiments at Univ. of Colo./NIST and at Eindhoven Univ. have both successfully launched rubidium atoms from a MOT through magnetic lenses, and thereby achieved extremely high source brightness, successfully focusing almost all of the trapped atoms to a small spot. However, given the solid-angle acceptance of our interferometer and the small bore of our vacuum vessel, our focusing requirements are not the same as theirs. Fortunately, given the light mass of lithium, a lens for it will be easier to build and more efficient than one for rubidium. Design considerations for our lens are discussed below.

Should the atoms move up or down? Dropping of atoms rather than launching them upwards is clearly preferred. Experiments at Stanford and NIST launched atoms upward and experienced both gravitational defocusing, as well as additional perpendicular heating by the launch process. But when a lens is used in combination with dropping rather than launching the atoms, a lens (or telescope) becomes even more effective, since gravity itself provides a natural focusing action.

4e. Computer Simulation of System Throughput:

We have performed computer simulations to estimate the net system throughput. We assume a MOT accumulating atoms into a ball about $300 - 500\mu$ in diameter, with a temperature corresponding to an average lateral velocity of about $5 - 8$ photon recoil velocities. The atoms are then dropped through a magnetic lens

(including the effect of its chromatic aberration), a collimating aperture, and four gratings corresponding to those of a separated beam interferometer 5m long. We assume a grating period of about 0.8μ , the lower limit for the best available UV lithography for grating fabrication. The lens parameters and collimation geometry are varied to maximize throughput flux, while simultaneously minimizing diffraction order overlap at the gratings (most severe at the 3rd grating). Related further simulations (in progress, as part of Task 7b) will determine whether aberrations in this geometry in the presence of the magnetic field gradients will allow high fringe visibility. Results indicate that we should be able to focus as much as 3.5% of the trapped atoms through a 5m long interferometer. Use of a two element lens (Galilean telescope with one positive and one negative lens) will yield results no better than those for use of a single element positive lens. Factoring in the expected interferometer loss rate and assuming a MOT buildup rate of about 10^7 cold atoms per sec in our device, we find that the geometry considered should produce the desired statistics (to accomplish the tomography inversion outlined wrt. Task 1) with about a 10 sec integration time.

By using a higher MOT feed density, a higher pulse repetition rate, and/or higher laser power, we may be able to increase the trap accumulation rate further. Any additional margins will then allow us considerable latitude over other competing design parameter trade-offs, and/or decrease the required integration time.

4f. Magnetic Lens Design:

To accomplish the focusing we evaluated various possible lens designs. The NIST experiment used pulsed current rings, while the Eindhoven experiment used an iron hexapole magnet. The current rings used by NIST provide rather weak focusing for a given current. Thus, given the high pulsed current requirements of the NIST design, we considered its use in our application undesirable (although probably workable). Further, given the cramped environment in our borehole sonde, and given the proximity of the

lens to both the MOT and the interferometer, both of which are highly sensitive to fringing fields from the lens, we consider the Eindhoven design also unworkable. We next evaluated the possible use of a purely electric field "Stark" lens. Unfortunately, we find that only negative "Stark" lenses can be produced. Finally, we evaluated a magnetic quadrupole lens in which the windings take the shape of the lacing on a baseball. We calculated numerically the magnetic fields for such a configuration and integrated atomic trajectories through it. We find that the "baseball" lens has highly desirable characteristics, has minimal aberration, and will focus lithium to the required focal length with only about 40 Amp-turns and a baseball winding "lobe" radius of about 1cm. The "baseball" lens is thus our current choice.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.