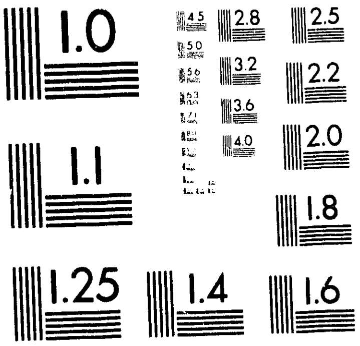
1.0
4.5
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5.6
2.8
3.2
3.6
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1.6

1 of 1

DOE/CE/15500--T3

Quarterly Report for ERIP Grant # DE-FG49-92CE15500.
Commercialization of Atom Interferometers for Borehole Gravity Gradiometry.
Quarter 3, April - June 1993.
Principal Investigator: John F. Clauser

Present Status of Tasks:

Task 1 - completed qtrs. 1 and 2 (solution of tomography problem).
Task 2 - completed qtr. 3 (study influence of vibrations).
Task 3 - completed qtr. 3 (list of borehole imposed constraints).
Task 4 - in progress (evaluate merits of various cooling schemes).
Task 5 - completed qtr. 3 (specify magnet system requirements).
Task 6 - in progress (specify laser system).
Task 7 - in progress (specify detector, gratings, spacers, vacuum system).

Tasks 2, 3, and 5 were completed this quarter. The results are as follows:

Task # 2:

Study the influence of vibrations of the logging tool itself.

To perform this task exactly would require a rather difficult integration of the Kirchoff diffraction integral with time retarded boundary conditions. To do so is a formidable job. On the other hand, by noting that the displacement of the fringes at the gratings and focal plane of a single cell of the diamond shaped figure-eight trajectory geometry can be predicted classically.The task is then greatly simplified and readily accomplished, producing essentially equivalent results. Indeed, we long ago used the quantum-classical correspondence to show that in a vertical gravitational field, the longitudinal positions of the gratings must be shifted to allow equal propagation times rather than equal propagation distances among the five planes of the figure-eight pattern.

Being able to calculate the fringe displacement for a single cell, we can link together the two cells of the figure-eight and produce our result. The first cell is modeled as an isotropic point source (corresponding to the first grating), a pinhole aperture (corresponding to the second grating) and an image plane (corresponding to the gravitationally shifted mid-plane of the now longitudinally asymmetric figure-eight). The lateral position of the atoms passing the image plane is calculated by assuming that atoms follow a ballistic trajectory in a constant gravitational field. (We here ignore any gravity gradient, since its perturbation will be additive.) The second cell treated similarly, and is linked by using the target point on the image plane of the of the first cell as its source location. To access the effects of vibration, all planes are translationally accelerated, and/or rotated as a rigid body, and the target positions recalculated as a function of time.

The results of our calculations are basically what was anticipated intuitively, although the quantitative results are reassuring. If the interferometer's reference frame departs from an inertial one (except for the constant gravitational field), so that the integrated motion of one of either of its ends moves more than a grating slit period during the transit time of an atom, then the integrated motion will appear as a displacement and hence a spurious fringe shift. For rotations the integrated fringe shift is typically twice that experienced by each end, while for translations, it is four times that at each end.

In addition when the motion is periodic, then nulls in the response to vibration occur at zero frequency and all harmonics of the inverse transit time. The reason for the presence of the nulls is readily visualized. When an atom is between the interferometer grating planes, then the gratings may move with impunity as long as they return to their original positions exactly as the atom passes each subsequent grating.

How do these results impact on the usage of the device in a borehole? The answer lies on what is the vibrational environment within a borehole. Our best estimates of its magnitude are obtained from conversations with Andrew Black of EDCON, and the Final report from CER corporation on contract with the Gas Research institute to study borehole gravity gradiometry and conversations with Leo vanderHarst of CER. EDCON's experience is especially valuable in that they are the only company to offer gravity based well logging on a commercial basis. Both information sources indicate that the environment varies, both in time and in location.

Seismic activity is one important source of vibrations. Its magnitude varies typically from 5 to 20μGal. For our device, this magnitude in turn translates to about 2.5 - 10 E effective gradient noise. At noisy times, EDCON is forced to wait for quiet periods. EDCON has not done a careful spectral analysis of the noise, but the CER report indicates that it may be effectively averaged over in a period of about a minute, which they contend represents an acceptably short pause duration for start-stop logging operation.

EDCON also indicates that noise transmitted down the logging cable represents a serious source of vibrations. During data taking, EDCON stops the tool's transit, clamps it to the wall, slacks the cable, and waits for fluid swirling to damp before proceeding to acquire data.

In addition EDCON has found that mechanical navigational gyros also can represent a source of vibrational noise. The use of ring-laser gyros is thus preferred. Fortunately, highly rugged military grade ring-laser gyros are now available off-the-shelf. Alternatively, if mechanical gyros are employed, they should be chosen so that all of the harmonics of their periodic motion fall on the nulls of our response curve. Moreover, since their noise will occur at high frequency, a quite simple vibrational isolation of mechanical gyros may suffice.

Finally, GRI had hoped that gravitational logging can be done with the associated logging tool in motion. To evaluate this suggestion, CER conducted tests in which an accelerometer was placed in a logging tool and the tool then run through a typical transit. At high logging speeds the tool bounced off the walls and created large shocks. At low speeds the tool was basically quiet. However, in our view their sensitivity was far too poor to determine whether it was quiet enough to sustain gravity data taking. We suspect that it was not! Our suspicion is that GRI's hope is probably in vain, unless advanced significant control techniques are employed, and that EDCON's procedure is preferred in the absence of such control.

The above noise sources will plague virtually any gravity sensor. We note that our ultimate sensitivity and dynamic range is notably higher than EDCON's. Also, our tool and responds to different vibrational modes, although the distinction is probably of little consequence. Eventually, to obtain our ultimate sensitivity we may probably require some effort spent at vibrationally isolating our logging tool. On the other hand, we feel that this effort is best left for second generation devices.

Our conclusion is based on the following observations:

(1) The noise environment is insufficiently severe as to cause loss of fringe count in our device, which will be typically about 40 E per fringe.

(2) Depending on the spectrum (which is now unknown) the averaging process may be quite effective.

(3) Quite useful tomographic data can be obtained, albeit with shorter range, even at the seismic-noise degraded sensitivity level.

(4) The start-stop-average mode of operation used by EDCON is consistent with an appropriate use for our device, and will probably far more effective than it is with EDCON's device, since transients associated with the start and stop will not ruin our calibration.

(5) Experience gained by field testing will be essential in designing an appropriate vibration isolation system.

(6) We have enough problems to solve at present and why add one

more.

Task # 3:

Compile a list of borehole imposed constraints and tradeoffs for the design of a gradiometer.

Work on Task 3 is now complete. In combination with information compiled in other tasks the relevant constraints are presented in the pertinent format of a list of design target specifications for the device, which are consistent with the constraints. Although the design parameters are, at present, not firm, we believe the following set of target specifications for our design to be realistic and achievable. In principle, our sensitivity and stability can be extended further. In practice, however, the performance undoubtedly will be limited by local seismic noise, and the required integration time will be set by the seismic environment, rather than by our instrumentation. This being so, second generation devices will incorporate onboard vibration isolation techniques.

Tool outside diameter: 3 5/8".
Tool length: 35′.
Max pressure: 20,000psi.
Max temperature: 200°C.
Gradient components measured: $\Gamma_{xz} = \frac{\partial g_x}{\partial z}$, and $\Gamma_{yz} = \frac{\partial g_y}{\partial z}$,
    (where z represents the wellbore axis).
    (Γ_{xz} and Γ_{yz} measured simultaneously).
Gradient sensitivity: ≈ 0.2 - 0.5 E
    (in absence of seismic disturbances).
Longitudinal gradient baseline: ≈ 5m (average over 10m)
Equivalent gravity sensitivity: ≈ 0.4 - 1. μGal
In-situ calibration: via laser metrology
Integration time per sample: < 1 minute,(may be as low as 1-10 sec)
Shock tolerance: > 10 - 20 G.
Maximum tilt from vertical: 20° (may be higher).
Typical sample interval: 2m

In addition, to the above requirements, the tool should employ the following:

Depth sensing accuracy requirements: modest. (e.g. that obtained from parallel neutron, casing collar tally, and/or pressure logs).

Tool inclination measurement: by off-the-shelf military-grade ring-laser gyros will correct for cross-talk introduced by static vertical (free-air) gradient components of the tensor.

Telemetry system: should use off-the-shelf logging industry digital components and standards. Standard logging cables (standards set by Gearhart) are either 7 or 17 conductors, 7/16"OD, 20 Gauge wire, about 1KV insulation, and have a resistivity of about 14.5 Ω per 1000′.

Eric Rantalla of Mineral Logging Systems (Ft. Worth) indicates that his company can fabricate the pressure vessel and provide the most of the associated well-logging industry hardware, and telemetry. Discussions are in progress with Dr. Andrew Black of EDCON, Inc. (Denver). He has indicated EDCON's possible willingness to collaborate in the actual downhole testing, and marketing, and further, to provide us with his valuable experience. EDCON already has accumulated a broad customer base for its gravity well-logging services. Many conversations with Dr. Don Eckhardt of the Air Force Geophysical Lab. (Hanscom AFB), Dr. Leo vanderHarst of CER corporation (Las Vegas) and Dr. Larry Beyer of USGS (Palo Alto) have already provided valuable borehole gravity instrumentation information. These men are considered valuable sources for additional information.

Task 5:

Formulate the requirements for a magnet system and determine the feasibility for use of a combination of permanent magnets and electromagnets to produce the necessary fields.

In our original device concept, a magnetic field gradient is employed to levitate the atoms under the constant force of gravity so as to cancel the majority of its perturbing force. There are two possibilities for doing this. One is to cancel only the perpendicular force components, while the other is to cancel all of the components. Now, in order to get a sensitivity to gravity gradients, it is necessary for an same atom to be influenced by the gravitational field both at the top and bottom of the device, which must have some separation, i.e. a length of a least a few meters. To get high sensitivity, it is necessary for the atom's interaction with gravity to last for at least a second or more, which happens naturally for a free-fall of a few meters. if the atoms are unsupported vertically (i.e. the vertical component of gravity is not canceled). Assuming that the sonde will not be exactly vertical, then the resulting gravitational force component perpendicular to the device axis must be canceled so that the slowly falling atoms will not run into the side of the vacuum pipe during their fall.

To cancel the transverse force we planned to apply a transverse magnetic field gradient to the atoms, which when acting on the atoms' intrinsic magnetic moments will supply the required force. To cancel the vertical force and increase the devices sensitivity, it is possible, although more difficult to apply an additional axial field gradient to levitate the atoms vertically. So doing, atoms can drift vertically at any desired constant velocity, whereupon their transit time can be lengthened. Since the application of this vertical component adds additional complexity and new problems it is preferably left out.

As a result of our work on this Task, we make the following observations:

(1) Maxwell's equations pose an additional requirement that the sum of the magnetic field gradients in the three transverse directions (i.e. the trace of the gradient tensor) must vanish. This constraint, when applied to the transverse field gradients

causes additional forces radial defocusing. Although benign by itself, if the magnet windings are not exactly straight, <u>and</u> the tool is simultaneously inclined from vertical, then it can cause a serious crosstalk between other large components of the gravity gradient tensor, and/or in combination with constant gravity can create unacceptably large fake gradient components.

(2) The spurious effects of (1) are minimized when a light atom (such as lithium) is used, rather than a heavy atom (such as cesium or rubidium). Use of lithium, in turn, requires a separated beam geometry rather than a generalized Talbot-vonLau geometry. On the other hand, in a device of the envisioned size, the collimation requirements for a separated beam interferometer are acceptable. (More detailed analysis of this problem will be considered during the work on Tasks 4, 6, and 7.) Additionally, the use of lithium, in view of its lower vapor pressure at borehole temperatures, is actually preferred from the point of view that it reduces the problem of scattering of the beam by background vapor. Its use then makes the vacuum system requirements less demanding.

(3) Addition of a transverse electric field gradients will cancel the spurious forces created by the effects of (1), and allow moderate departures from tool straightness.

(4) The required transverse fields can be created by first housing the device in a cylindrical magnetic shield (necessary in any case to prevent spurious effects from the earth's magnetic field, and/or from magnetized well casing), and then applying magnet windings axially and adding a second magnetic shield to act as a return field yoke.

(5) The magnet windings and shield must be kept accurately straight, no matter what the inclination of the tool is. A means for doing this is to float the vacuum pipe (and associated shields and windings) in light oil inside the pressure vessel. If the density of the oil is carefully chosen, then the tube will be neutrally buoyant and experience no bending stress when the tool

is inclined. In addition, a careful choice of the positions for supports between the pressure vessel and the vacuum pipe will minimize any bending stress not canceled by the flotation. A low thermal expansion coefficient material should be chosen for the vacuum vessel, and temperature gradients across the device should be monitored.

(6) Device sensitivity is sufficient without the use of axial field gradients, if the device is 5 to 10m long and the atoms start from rest and are then dropped through the tube. (The final length choice will depend upon the atomic flux estimates obtained during Tasks 4,6, and 7.) Hence, permanent magnets are not required.

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