## CESIUM OPTICALLY PUMPED MAGNETOMETERS

### Basic Theory  of  Operation

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**Introduction:**

The following description of the theory of operation of the Cesium vapor magnetometer contains many simplifications in order to keep the discussion brief.  Some of these simplifications are expanded in later sections.

The cesium atom has only one electron in the outer-most electron shell.  If there were more electrons in the shell they would interact with each other, but in the case of the cesium atom the electron is free to change energy states in an independent fashion and we therefore consider only the single electron case.

An electron has an electrical charge and a spin, hence it will have a small magnetic moment.  This moment means that there will be some variability in the energy of the electron depending on the direction of it's spin axis relative to an ambient magnetic field vector.  If for example the electron's magnetic field is aligned with the ambient magnetic field, the energy will be lower than if it is opposed to the field.

If we could measure the differences in energy caused by changing the electron's orientation, we could determine the strength of the ambient magnetic field.  The energy difference is equal to the strength of the magnetic field times an atomic constant.

The rules of quantum physics state that the electron can only take on a limited number of orientations with respect to the ambient field vector.  In the case of cesium there are 9.  Each of these orientations will have a slightly different energy level.  This phenomenon of electron energy differentiation in the presence of an external magnetic field is called Zeeman splitting after Pieter Zeeman, a Dutch physicist awarded the Nobel Prize in 1902 for his discovery.  The differences in energy from one Zeeman level to the next are roughly equal and always proportional to the strength of the ambient field.

It is these energy differences between the Zeeman levels that are measured to determine the earth's total field strength.  Remember that the energy of a photon and its frequency are related by Planck's Constant.  This fact is exploited to allow very accurate measurements of the energy differences by measuring the Larmor frequency as described below.

The elemental cesium metal is in the form of a vapor in a chamber we call the absorption cell.  It is the non-radioactive variety in microgram amounts and does not pose a health hazard. The cell is a 1 inch by 1 inch glass cylinder that holds the vapor in a partial vacuum.   In addition, there is a source of light called the "lamp" which contains Cesium metal also, but at a slightly higher vapor pressure.  It is the light from the lamp that does the actual pumping of the cesium atoms in the absorption cell.  On the far side of the absorption cell (from the lamp) is a photocell for capturing the light that has passed through the absorption cell.

Most people are familiar with the concept of polarized light.  Normally we think of linearly polarized light where the magnetic component may be all horizontal and the electrical component all vertical.  Circularly polarized light differs in that the electric field runs like the threads of a screw.  There can be two types of circular polarization, left and right handed, depending on the direction the field rotates as it propagates.

If a photon of incident light from the lamp has exactly the right amount of energy, an electron can absorb it, moving the electron up to a higher orbit.  With circularly polarized light this works much better if the direction of spin of the electron matches the direction of polarization.  The energy required to move the electron to this higher orbit is well above the Zeeman divisions of energy caused by the differing electron orientations with respect to the ambient magnetic field as we discussed earlier.

Imagine we shine circularly polarized light (from the lamp and associated optics) through the absorption cell.  The electrons that have a spin that matches the polarized light's direction will absorb the light and be kicked up to a higher orbit.  However, when in this higher orbit they are not stable and will  immediately decay or fall back down releasing energy as light, and their spin direction becomes randomized in the process.  The light they give off when they fall is not aligned to the path of the absorbed light.  For this reason the light passing through the cell will be dimmed slightly by the electrons absorbing it.

Because the electron's spin axis is random when it falls back down, there is a chance it will be aligned so that the light cannot kick it back to the higher orbit again.  Over time all the electrons will eventually land with their spin axes in a manner that will not allow them to absorb the light.  When this happens the light passes through the absorption cell and impinges on the photocell.

Now imagine that we send some RF (radio frequency) energy into the cell at just the right frequency to match the energy differences between orientations.  Remember RF is made of photons too, except in the RF case the photons have much lower energy.  This RF will tend to kick the electrons back over to the other orientation(s) where they can again absorb the light.  The light will dim again at the photocell when the frequency of the RF "depumping coil" is correct.  This RF signal is called the "H1 drive" and the coil used to inject it into the absorption cell is the "H1 coil".  It is the frequency of this RF signal which we count to produce the accurate reading of the ambient magnetic field strength.

(If we sweep the frequency of this RF power back and forth we can find the exact point where it couples with the electrons and then follow that frequency as it changes with variations in the magnetic field.  This is the way a "swept" vapor magnetometer works.)

When the electrons are kicked from one orientation to the next they tend to do it in step with the RF signal. If a high frequency photocell is used, we see that the light not only dims during the transition but also has a slight RF modulation on it when this occurs. If this RF signal is amplified it can be used as the RF H1 depumping input to the absorption cell. By closing the loop in this way the whole system will oscillate at the frequency directly dependent upon the ambient magnetic field strength. This is the operating principle of the self-oscillating alkali vapor optically pumped magnetometer.

**The Light Source**:

The light needed to move the electrons from one orbit to the next must be of exactly the right frequency. Its wave length is 894.35 nM, which when expressed as a frequency is about $3.3 \times 10^{16}$ Hz.

We presently use a Cesium discharge lamp as the light source. The lamp makes the desired light along with a great deal of undesirable light which must be removed with a filter. The lamp is about 0.2 inches in diameter and about 0.4 inches long. The lamp is powered inductively because Cesium is so chemically reactive that it is not possible to use electrodes inside the lamp. It is surrounded by an induction coil driven with 80 MHZ. The frequency was selected for practical reasons only.

**The First Lens**:

The light rays emerging from the lamp are diverging. We need light to pass through the cell as a set of parallel rays. The first lens converts the light from the lamp to parallel rays.

**The Interference Filter**:

The discharge lamp makes a great deal of light at unwanted frequencies or lines. Some of this light, called the "D2 line", will significantly degrade the signal. Other light merely impairs performance by having unwanted light reaching the photocell detector. The interference filter removes the unwanted light from the beam prior to it entering the absorption cell.

**The Polarizer**:

Although either direction of polarized light will make a functioning magnetometer, the measured field will be different by about 5 nT depending on the direction of polarization used. Turning the sensor end-for-end reverses the direction of travel of the light and has the same effect as reversing the polarization direction. This would cause all sensors to have a 5 nT heading error. To prevent this we split the polarizer along its diameter and make one side right handed and the other left handed polarization. This prevents this heading error at the cost of a much lower signal level. Sufficient signal remains however to achieve very low noise measurements at high sample rates. See the Counting discussion in the Glossary below.

**The Cell**:

The cell is a glass chamber 1 inch in diameter and 1 inch long. It has a buffer gas and the Cesium metal in it. The amount of Cesium vapor is controlled by controlling the temperature of the cell. At about 55° C we get the desired amount of Cesium vapor. The buffer gas is used to

keep the Cesium atoms from moving too far too quickly.  Any Cesium atom that hits the wall of the cell will have its state randomized and will not add to the signal.  Any that cross from one side of the cell to the other side where the sense of polarization is reversed will actually subtract from the signal.

**The Cell Heater**:

A length of special resistance wire is doubled back on its self and tightly twisted together to form the heater.  This greatly reduces the magnetic field created when a current is passed through the heater.  This heater is wrapped around the outside of the cell.  In spite of the fact that the heater is constructed in this way it still must be driven with an AC waveform to prevent offsetting the field measurement.  The cell's temperature is monitored by a thermistor so that it can be regulated.

**The Second Lens**:

Once the light has passed through the cell the light is then focused onto a photocell by another lens.  The quality of this focus is low but so long as most of the light lands on the photocell, performance is not degraded.

**The Photocell**:

We use a special wide area photocell with a good infrared energy band response and high frequency capabilities.

**The Signal Amplifier (Larmor Amplifier)**:

The signal derived from the H1 Drive Loop is called the Larmor signal after its discoverer, Sir Joseph Larmor.  This signal is only about 0.1 mV at the photocell.  It must be amplified to a useful amplitude without introducing any phase shifts.  Any phase shift in the Larmor amplifier will cause the field measurement to be slightly offset.  One degree of phase shift causes about 1 nT of offset in the measurement.  Once the signal is amplified it is limited to make a constant amplitude signal to send to the sensor's H1 coil.

**The H1 Coil**:

The H1 coil is wound such that the magnetic lines of force from the coil are parallel to the path of the light. Only the magnetic component of the H1 drive that is at right angles to the earths magnetic field matters for the operation of the magnetometer.  This component can be thought of as two counter rotating vector fields.  Only one of these rotating vectors actually does any work.  If the coil's axis is not aligned with the path of the light, rotating the sensor around the light path would change the phase of the rotating vector.  A one degree change in phase will cause a 1 nT change in the reading.  Tight alignment is assured using a series of adjustment screws on the side of the optical sensor assemblies.  These are adjusted in a trial and error method to optimize heading errors to as low as ± 0.1 nT for the entire 360° rotation.

# Glossary of Terms
## Used in the Discussion of Cesium Magnetometers

Auto-Hemisphere Switching:
    The signal developed on the photocell is at the same frequency as the H1 drive but its phase inverts if the lines of magnetic force pass through the sensor in the other direction. Auto-hemisphere switching is the switching of the sense of the H1 drive back and forth until the correct phase for oscillation is found.

Buffer Gas:
    This is a gas added to a lamp or cell which is not directly part of the magnetic measurement process. The lamp has an inert gas added which makes the lamp easier to strike and makes it easier to keep the lamp in "White" mode. The cell has a buffer gas added to keep the cesium atoms from moving around too much. If a cesium atom can cross the width of the cell in about 1 millisecond the signal will be greatly reduced. This is for two reasons: 1) If the atom strikes the side or another cesium atom its energy state is randomized and 2) the atoms on each side of the cell are pumped to opposite states; if they move from one side to the other the state is backwards for the new side, thus reducing signal.

Cell (Absorption):
    The cell is a chamber that is cylindrical in shape. It is about 1" in diameter and 1" in length. It is in the cell that the magnetic field is actually measured. The cell contains elemental cesium that is turned into a vapor by heating.

Circular Polarization:
    Light is an electromagnetic wave. In all electromagnetic waves there is an electrostatic vector at right angles to the direction of propagation. In linearly polarized light this vector can be thought of as growing in the positive direction vertically then shrinking to zero and growing in the negative direction as the light travels along. In circularly polarized light the length of this vector is constant but it rotates like the threads on a screw as it travels along.

Counting:
    The term "counting" is often used where a frequency is being measured. In many cases it is actually the period of the frequency that is being measured and converted into a frequency by inversion. Proper counting is crucial to the operational performance of the cesium magnetometer and can provide sensitivities as low as $0.00005nt/\sqrt{Hz}$ (0.5 picoTelsa per root Hertz). Geometrics provides both rack-mounted and integrated counters (which reside inside the sensor electronics bottle.)

D1 line:
    The color of useful infrared light generated by the cesium lamp is called the D1 line. The D1 Filter is the interference filter that passes the D1 light and absorbs the undesirable light. There is a color very near the desirable line that is destructive to the signal. This is called the D2 line.

Dead Zone:

The sensor is specified as capable of making a useful signal when the lines of force of the magnetic field pass through the sensor at angles between 10° and 80° to the axis of the sensor (for the upper hemisphere, duplicated in the lower hemisphere with auto-hemispheric switching).  If the angle between the sensor and the field is outside of this range the sensor is said to be in its dead zone.  In practice, the dead zones are typically ±6° of the axis and equator of the sensor.  Normal installation orientations allow the sensor to be installed and surveys conducted in all compass headings in all areas of the northern and southern magnetic hemispheres (approximately equal to the geographic hemispheres).  At the equator, the sensor is installed in a manner that allows survey in the cardinal directions (N, E, S, W) or at 45° to these cardinal directions, but not simultaneously in all directions.  See the free program CSAZ available from Geometrics for a graphical explanation (FTP from our web site www.geometrics.com.)
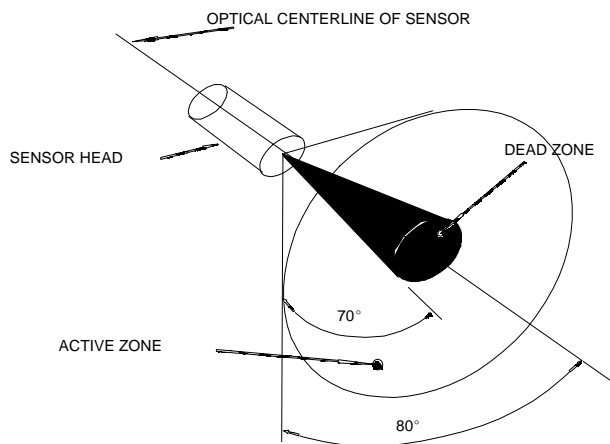
Gamma:

A gamma is defined as one  nanoTesla (nT) or 1/100,000th of a gauss.  The earths field is from 20,000 to 100,000 nT. In North America it is about 50,000 nT. The term gamma is falling out of use in favor of nanoTesla.

H1 Drive:

This is a low amplitude signal at the larmor frequency returned to the sensor to sustain oscillation.  It is referred to as an H1 drive because it generates the magnetic field H1.  The earth's field is called H0 .

H1 coil:

This is a coil in the sensor to which the "H1 drive" is applied. Inside the sensor is a G10 (fiberglass) tube that contains all of the optical assemblies such as the polarizer.  The H1 coil is wound around this tube to provide the depumping electromagnetic energy.

Head:

The terms "head" and "sensor" are commonly used to refer to the housed optical package.  This optical package is connected to the sensor/driver electronics assembly that may be in its own housing (G-822A, G-823A, G-880) or incorporated into another electronics assembly (G-858).

Heading error:

This is the error in measurement caused when the angle of the magnetic field passing through the head is changed.  There are several causes for this effect.  Magnetically dirty parts is one obvious one.  Misalignments between the light passing through the cell and the axis of the H1 coil causes a tangent curve shaped heading error when the sensor is tumbled end over end.  The cesium line (excitation light) we are using is not symmetrical.  If the sense of the circular polarized light is reversed the peak of the line is moved by about 5 nT.  If we did not use a split polarizer, flipping the sensor end-for-end would cause a 5 nT change in the reading.  The split

polarizer causes the line and its mirror image to be added making it appear symmetrical. Any error in the balance between the two sides of the polarizer will cause some heading error.

Heater:
There is a heater in the cesium sensor that heats the absorption cell to create the cesium vapor. This heater is in parallel with a heater that warms the lamp assembly. This is done to make the lamp oscillator's output requirements independent of ambient temperature. This heater is usually driven with a sine wave at about 10 KHz so there is no DC field generated and no harmonics in the band of larmor frequencies.

Lamp oscillator:
The discharge lamp inside the sensor is illuminated by applying RF to a coil around it. The circuit that does this is called the lamp oscillator. The coil around the lamp is part of a tuned circuit that determines the running frequency of the oscillator. There is a capacitor in the lamp holder assembly that along with the inductance of the coil is responsible for the operating frequency. The frequency is about 80 to 90 MHZ. There must be a separate lamp oscillator for each sensor because the operation frequency must be the one determined by the components of the sensor being operated.

Larmor:
This is the signal developed that has a frequency proportional to the absolute value of the field at the sensor. The constant of proportionality is 3.498572 Hz/nT. The amplitude of this signal is measured only to determine if there is a valid Larmor signal being counted. The frequency ranges from about 70 to 350 Khz over the range of 20K to 90K nT. Sir Joseph Larmor was an Irish physicist (1857-1942, knighted 1909 for his work in mathematics) who first explained the splitting of spectral lines in a magnetic field.

Larmor amplifier:
The larmor signal is developed as a small AC voltage on the photocell in the sensor. The amplifier which amplifies this has a gain of about 25,000 to make a 2 volt sine wave signal. Great care must be exercised in the design of this part of the circuit because a 1° change in the phase shift of the Larmor amplifier will cause a 1 nT change in the measurement.

Line:
When an electron changes from one energy state (orbit) to another it must gain or lose the difference in energy between those two states. This is often done by absorbing or emitting light. When the spectrum of light from a discharge lamp is observed these energy differences appear as bright or dark lines in the spectra. The term line is now generally used for any difference between energy levels even when spectra are not being discussed. The "line" we use in the cesium magnetometer is actually a closely spaced group of lines that blend together.

Optical package:
This is also called the physics package and usually refers to the internal parts of the sensor including the lamp, cell, photocell and lenses, etc.

Purple mode:
Sometimes called "red mode". The discharge in a lamp can appear in two modes. This mode happens at comparatively low power. This mode is undesirable because it tends to flicker and

does not efficiently produce the color light needed.  When a lamp is hot it takes more RF power to take it from the purple to the white mode.

Sensor driver:
> This is all of the circuitry needed with a sensor to take DC in and produce a Larmor out.

Split polarizer:
> The polarizer used in the sensor is circular with a split running down the center (diameter) of this circle.  One side of the polarizer generates right handed circular polarized light.  The other side makes left handed polarized light.  This is done to reduce heading error at the expense of signal strength.

White mode:
> The discharge in the lamp can appear in one of two modes.  The white mode happens when there is comparatively a large amount of R.F. power applied to a cool lamp.  This mode is the desirable mode because it is stable and creates the needed light.  See purple mode.

Zeeman splitting:
> Electrons have a charge and rotation (spin and orbit) and hence a small magnetic moment.  Because of this they can be at slightly different energy levels depending on their orientation in a magnetic field.  This splitting of energy levels is the basis of the cesium, potassium and helium magnetometers.  Pieter Zeeman was a Dutch physicist (1865 -1943) who received the Nobel Prize in 1902 for his discovery.