**MINIATURE DUAL-MODE ABSOLUTE SCALAR MAGNETOMETER BASED ON THE RUBIDIUM ISOTOPE $^{87}$Rb.** H. Korth[1], K. Strohbehn[1], J. Kitching[2], [1]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA. [2]National Institute of Standards and Technology, Boulder, Colorado, USA.

**Introduction:** The magnetic field is a fundamental physical quantity, and its precise measurement plays a central role in addressing the scientific objectives of many planetary, solar, and interplanetary science missions. Magnetic fields in space have been measured by fluxgate magnetometers, proton-precession magnetometers, and optically-pumped magnetometers. The measurement technique in the latter two categories is based on absolute frequency standards and does not require calibration. As such, the instruments provide an ideal in-flight calibration source for fluxgate magnetometers on missions that necessitate ultra-precise measurements or which are of extended duration. However, a major disadvantage of atomic magnetometers, i.e., proton-precession and optically-pumped instruments, is their significant mass and high power requirements, which effectively prevent their routine use in space. Hence, to allow for more widespread use of atomic magnetometers in space, mass, size, and power consumption of these instruments must be substantially reduced.

In response to an on-going paradigm shift in space research, we have developed a low-resource, miniaturized, absolute scalar magnetometer based on the rubidium isotope $^{87}$Rb. Our instrument takes advantage of recent breakthroughs in micro-fabricated atomic devices, which have demonstrated reductions of power requirements and mass by one to two orders of magnitude over conventional instruments. The resulting instrument has a total mass of 210 g and uses <1 W of power, while maintaining sensitivity, 15 pT/√Hz at 1 Hz, comparable to present state-of-the-art absolute magnetometers.

**Hardware Description:** Most atomic optically-pumped magnetometers are based on the Larmor precession of electron or nuclear spins in a magnetic field [1]. A cell containing a suitable gas is illuminated with light with a wavelength that correspond to resonance with an optical (electronic) transition in the atoms. Under these conditions, atoms are optically pumped into a non-thermal population distribution and the gas cell becomes largely transparent to the optical beam. If the cell is then subjected to a radio frequency (rf) signal at the Larmor precession frequency, an oscillating population distribution is excited within the atoms, which causes a time-dependent modulation of the optical absorption. By detecting the phase shift ($M_x$ mode) or the amplitude ($M_z$ mode) in the resonance of the atomic response, the Larmor frequency can be

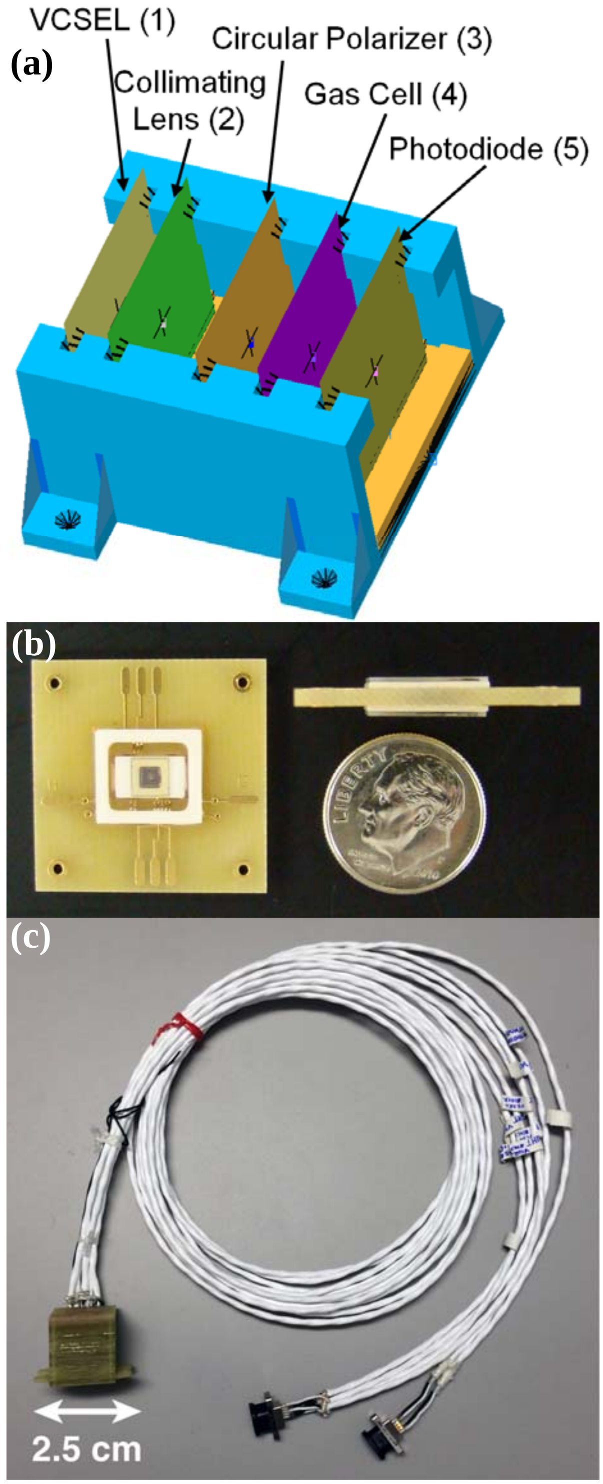


Figure 1: Atomic magnetometer (a) configuration, (b) vapor cell assembly, and (c) sensor.

determined and from that the magnetic field can be deduced. Our sensor technology is based on the isotope $^{87}$Rb selectively uses $M_x$- or $M_z$-mode magnetic field detection.

Our device [2] employs a low-power semiconductor laser and a miniature rubidium vapor cell of millimeter dimensions produced using modern micro-fabrication processes [3]. In recent years, MEMS vapor cells have been employed in chip-scale sensitive magnetometers [4]. The combination of MEMS vapor cell and a semiconductor diode laser has allowed a substantial reduction in mass, size, and power dissipation of atomic magnetometers with only modest decrease in performance. The MEMS vapor cell has been integrated into a magnetic field sensor configured as shown in Figure 1a. The micro-fabricated rubidium vapor cell (4) is illuminated by light emitted from a vertical-cavity surface-emitting laser (VCSEL) (1). The laser light passes through an optics package, where the laser light is collimated (2) and circularly polarized (3). The resonant response of the atoms is detected using a discrete photodiode (5). The assembled prototype sensor, shown in Figure 1c, measures 35 × 25 × 25 mm$^3$ and has a mass of 40 g without harness; future reductions in size and mass are anticipated.

An additional key aspect in the miniaturization of the device is the monolithic integration of the vapor cell with heaters and Helmholtz coils using silicon-on-sapphire (SOS-CMOS) technology. The latter are glued to the two faces of the vapor cell perpendicular to the optical axis. The SOS-CMOS technology was chosen because the sapphire substrate is intrinsically transparent to the light emitted at the wavelength of the laser. The SOS-CMOS chips heat the vapor cell to its operating temperature of about 100°C using 0.5 W of power generated by a 10 mA current from a 50 V power supply. Even though the heater current is low, extreme care must be taken in the implementation of the heater because the flow of current generates a contamination magnetic field in close vicinity of the detection volume. To minimize interference with the measurement of the ambient field, the integrated conductor widths and spacing are on micrometer scales, and near-perfect magnetic compensation was achieved using two sets of dual square loops arranged in neighboring conducting layers of the chip. The contamination due to the heater was measured to be less than 10 nT, and comparison with numerical calculations shows that the finite residual field is largely due to limitations in the accuracy of the alignment of the two SOS-CMOS dies. The second function of the SOS-CMOS die is to generate the rf magnetic field necessary to establish the atomic resonance via a single-turn circular coil. To maximize the uniformity of this field across the detection volume, the coils of both SOS-CMOS dies are sized to yield the Helmholtz arrangement, where the coil radius matches their separation prescribed by the thickness of the vapor cell. Finally, the SOS-CMOS die includes circuits to support temperature measurements and signal conditioning. The system reported in this paper does not use the latter electronic circuits to stay compatible with external instrumentation. The assembled vapor cell including transparent SOS-CMOS dies is shown in Figure 1b.

The sensor is controlled by a dedicated electronics and software in an FPGA, which generates the signals to excite the rubidium atoms within the vapor cell and measures and processes the resonant response at a rate of 10 samples per second. The prototype electronics are implemented on two 10×10 cm$^2$ printed circuit boards and has a mass of 170 g.

**Performance:** The sensor response to different step-like changes in the magnetic field magnitude between 0.5 nT to 2 nT is illustrated in Figure 2. The sensor has a sensitivity is 15 pT/√Hz at 1 Hz or about 0.1 nT rms. The prototype instrument demonstrates that absolute magnetometers can be miniaturized to serve future planetary missions even under severe resource constraints.

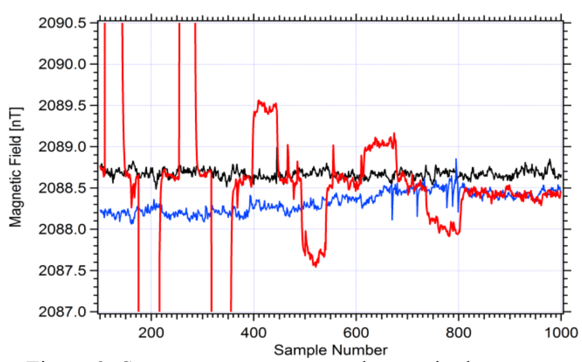


Figure 2: Sensor response to step changes in the magnetic field (red) vs. ambient field (black, blue).

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