Using lasers to measure magnetic fields

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A technique borrowed from astronomy employs ground-based apparatus and sodium in the upper atmosphere to determine geomagnetic fields with high precision and at relatively low cost.

Measurement of magnetic fields permits identification of features below the earth’s surface, with applications ranging from the detection of unexploded ordnance and buried hazardous waste containers to oil and mineral exploration. A high-resolution magnetic map (a collection of magnetic-field readings taken at different points in space) can pinpoint small-scale magnetic sources near the surface. However, for large or deeply buried objects, such readings are subject to systematic errors. These arise from the difficulty of accurately separating weak but large-scale magnetic field variations from the stronger but short-scale fields generated by nearby or near-surface objects.

By measuring at very high altitude, one can map magnetic fields with a deliberately lower spatial resolution and ‘see’ larger-scale and deeper objects. Such measurements can be implemented using satellites in low-earth orbit, but it is challenging to keep the stray magnetic fields produced by the satellite platform below the level required for useful measurements. Moreover, the cost of deploying spacecraft places limits on the number of available sensors.

We recently suggested an alternative magnetometry method. Although it makes use of the natural layer of atomic sodium in the mesosphere, located at around 90km, the scheme involves entirely ground-based apparatus. It takes advantage of the high-powered laser projection systems developed to create artificial laser ‘guide stars’ (LGSs) that are used in astronomical adaptive-optics imaging. The 100km-length-scale measurements permitted by this technique are applicable, for instance, to geological studies of the crust and outer mantle, determination of large-scale ocean currents relevant to climate, and calibration of magnetic maps for navigation.

Our method is based on the remote detection of a magneto-optical resonance. An atomic spin (for sodium, essentially the spin of the valence electron) precesses in a transverse magnetic field, that is, the spin axis rotates. The frequency of this precession, known as the Larmor frequency, is directly proportional to the magnitude of the field, with the proportionality given simply by fundamental constants. Therefore, determining this frequency is equivalent to measuring the magnetic field. Under normal circumstances, the spins in an atomic vapor are

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randomly oriented. But when the atoms interact with a laser beam, they can absorb angular momentum and be optically pumped into a definite state, that is, be forced to have their spins all point in the same direction. Larmor precession around a transverse field tends to ‘smear out’ the effects of optical pumping unless this pumping occurs synchronously with precession. When the frequencies match, the atomic polarization created during one cycle is in phase with that generated during previous cycles, and the atoms are efficiently polarized.

Moreover, laser-induced fluorescence intensity depends on atoms’ spin state, so that the resonant match of frequencies results in a detectable change in the fluorescence. Thus, by varying the frequency at which the pumping laser beam is modulated in the neighborhood of the Larmor frequency and monitoring the fluorescence, we can determine the magnetic field experienced by sodium atoms. In this remote-detection scheme, only these particles need to be at high altitude; both pump laser and detector remain on the ground (see Figure 1).

Recent advances in LGS technology greatly benefit this technique. Currently, most sodium LGS systems on astronomical telescopes project under 10W of average optical power per guide star on the sky. Based on Raman fiber lasers developed at the European Southern Observatory (ESO), for example, the next generation will raise this limit to 20W per guide star at a bandwidth of only a few megahertz. We have numerically optimized this laser format to achieve maximum photon return by optical pumping, and we anticipate it to yield about $12 \times 10^6$ photons/s/m$^2$ on the ground (no modulation applied).

The usefulness of the technique depends on its ability to detect small changes in the magnetic field. The attainable sensitivity, in turn, is determined by the number of sodium atoms that can be interrogated, the physics of atomic collisions in the mesosphere, and the quantity of fluorescence that can be detected. The number of usable atoms is limited by the available laser power and the requirement of sufficient intensity for optical pumping. Our numerical calculations show that collisions of sodium atoms with background atmospheric gas molecules are important. They limit to around 100$\mu$s the time during which an atomic spin can precess before decohering and, in turn, the sharpness of the magneto-optical resonance (see Figure 2). Finally, the fraction of captured fluorescence is very small at a distance of 90km, even with a large telescope. Nevertheless, we calculate an achievable sensitivity of better than 1nT (nanotesla) in a 1Hz bandwidth, suitable for the planned applications.

The numerical modeling of our high-precision technique to measure magnetic fields using ground-based lasers and mesospheric sodium shows promising results. Consequently, we

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Figure 2. Representative resonance profiles for mesospheric sodium. The resonances shown correspond to distinct absorption lines of sodium, conventionally designated by D$_2$ (upper curve, blue diamonds) and D$_1$ (lower curve, green circles). Symbols represent numerical calculations, and solid lines are Lorentzian fits to these results. The width of the resonances is determined by collisions with atmospheric molecules and by optical power broadening.

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