Miniature Magnetic Field Sensors Based on Xylophone Resonators

L. J. Zanetti*, T. A. Potemra**, D. A. Oursler, D. A. Lohr, B. J. Anderson, R. B. Givens, D. K. Wickenden, R. Osiander, T. J. Kistenmacher and R. E. Jenkins

The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland

Abstract. Miniature magnetometers based on classical xylophone resonators have been designed, fabricated and tested and a breadboard version is being prepared for a rocket flight in 1999. The device consists of a conducting bar driven by a current at resonance, which will deflect in the presence of a magnetic field due to the Lorentz force; the deflection is detected optically. Laboratory models with the resonator bar smaller than 1 cm have been tested and MEMS (Micro-Electro-Mechanical-Systems) scale devices have been fabricated. Standard MEMS techniques can be used to provide three-axis systems and one- or two-dimensional arrays for magnetic imaging; the ultimate goal for non-array systems is to provide an entire magnetometer on a chip.

1. Introduction

There is a continuing need for the development of miniature magnetometers for meeting a variety of applications. Such applications include the measurement of background and disturbance magnetic fields, the curl of geomagnetic fields (using suitable arrays of sensors) and the fields generated by satellites themselves. The trend is constantly toward smaller size, lower power consumption, and lower cost for similar performance. There is a further need to continue to advance the technology of magnetic field measurements, both in order to reduce the cost-to-performance ratio of deployed systems and in order to support the development of new spacecraft concepts. The latter issues range from attitude determination and boomless magnetic field measuring satellites, to swarms of free floating magnetometers or constellations of spacecraft for mapping of large scale temporal and spatial changes in the fields of space. This report is a product of a special session at the 1997 Fall American Geophysical Union Meeting which concentrated on suitable instrumentation for small spacecraft destined for constellation configurations within Earth's magnetosphere and beyond. This paper is an expansion of the Potemra et al. (1997) presentation on miniature magnetometers. The described miniature xylophone magnetometer is also part of the New Millennium Program at the Jet Propulsion Laboratory and is being put forward by the In-Situ Instrument section of the Integrated Product Development Team for flight validation, presently on the suggested manifest for the EO3 (Earth Orbiter 3) opportunity.

The measurement of the DC magnetic fields from Earth's surface (B~35,000nT) to the interplanetary medium (B~1nT) has been traditionally performed by fluxgate sensors (Acuña, 1974, 1992, and references therein) and pumped-vapor sensors (Smith et al., 1991, and references therein). While efforts to miniaturize these sensors are ongoing, there are physical limitations beyond which construction difficulties and sensitivity losses prohibit further size and mass reduction. These efforts are justifiably intensive: Not only is there a constant need for measurements of natural magnetic fields from planetary to solar to interplanetary and interstellar, but there is also a need for measurements of artificial fields. For example, fields on spacecraft from dynamic currents and extraneous moments can introduce background noise and interfere with the intended primary measurement as is, for example, the case for the body-mounted magnetometer aboard the Near Earth Asteroid Rendezvous (NEAR) spacecraft (Lohr et al., 1997). Strategically located microsensors could be used collectively to self correct such interference fields mitigating extensive noise compensation efforts. This problem will be much more pervasive as spacecraft become smaller, since assuming a proportional reduction boom length the sensors will be much closer to the disturbing spacecraft circuits and their stray fields. This will be compounded by constellation type mission objectives of comparative measurements which will need extensive intercalibration.

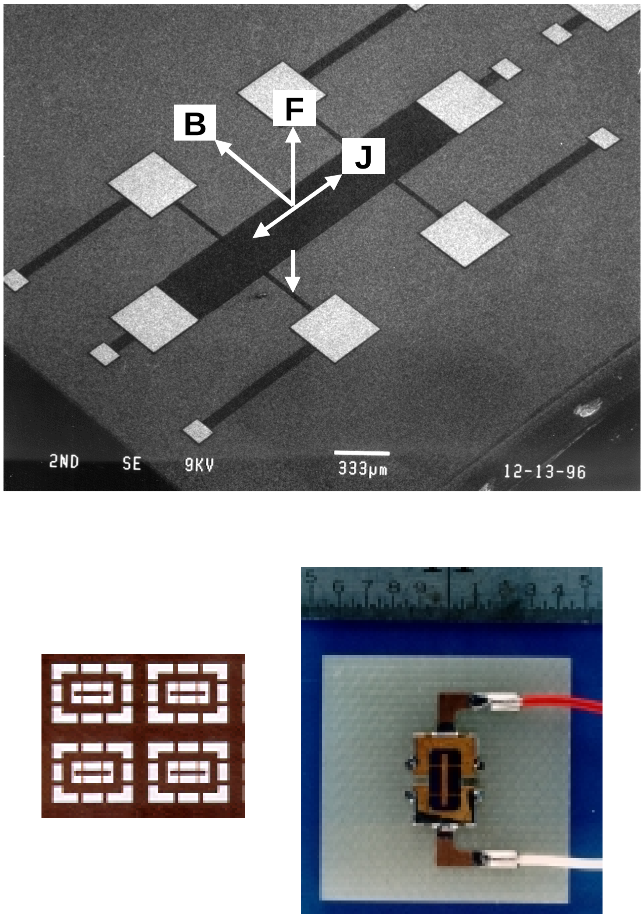

Figure 1. a) MEMS-based Xylophone Magnetometer. b) Chem-Milled Xylophone Bar for the APEX flight.

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*presently at NASA Headquarters, Washington DC

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Science Closure and Enabling Technologies for Constellation Class Missions, edited by V. Angelopoulos and P. V. Panetta, pp. 149-151 , UC Berkeley, Calif., 1998.

2. Xylophone Magnetometer

The reduction in mass and volume of the electronics can be achieved with standard custom chip and bare-die advanced packaging technologies and poses no limiting factors. Rather, the focus of this instrument development has been directed at a fundamentally different approach to sensing the magnetic field. A very promising design for a Lorentz-force magnetometer based on a resonating xylophone bar has been developed and, because of its construction simplicity, offers the possibility of fabrication and mass production by microelectronic manufacturing techniques (MEMS, for example). In addition, because of the small size of these xylophone magnetometers (sensor-head prototypes at the millimeter scale size), these sensors can also be employed in scanning or array configurations for measurement of magnetic field gradients or for magnetic imaging applications. Details of this breakthrough sensor technology have been presented in Givens et al. (1996) and Wickenden et al. (1998) and patents are pending.

Figure 1a shows a MEMS fabricated xylophone bar and mounting pad and serves as a means for outlining the basic principle of operation. An AC drive current **J** (with a frequency equal to that of the mechanical frequency of the xylophone bar [Young, 1989]) is first directed along the long-axis of the xylophone bar. When a magnetic field **B** (or field component) is subsequently projected along the short in-plane axis, the resulting Lorentz force **(J** x **B)** normal to the bar causes deflection by an amount proportional to the magnitude of the magnetic field. Importantly, because the measurement of the magnetic field is made under resonant mechanical conditions, there is a Q (mechanical quality) factor magnification of the xylophone bar response. The result is a novel, miniature magnetometer design of high sensitivity (<1 nT) and wide dynamic range (~Tesla).

At the present time, engineering prototype xylophone bars are simply and effectively fabricated from nonmagnetic CuBe foils by chemical milling. Typically, these xylophone bars are 5 mm **x** 0.5 mm **x** 250 μm, with Q values of approximately 7000. An example of a sheet fragment from a fabrication run and a xylophone sensor bar mounted on a modified PC board is illustrated in Figure 1b. Deflection of the xylophone bar is generally determined by optical methods, with the output beam of a laser diode reflected from one of the free ends of the xylophone bar into a position-sensitive detector. Consistent implementation by MEMS techniques in polysilicon and the full integration of sensor and microelectronics is in progress; high sensitivity capacitive and piezoelectric pickup schemes are under active development as well.

The engineering prototype for the drive electronics for the xylophone magnetometer is schematically shown in Figure 2. The electronics driver supplies oscillating current to the xylophone beam at it's resonant frequency. There is zero phase detection to detect the resonance peak and to provide automatic tracking of the resonant frequency to maintain the proper Q. The beam is illuminated with a miniature laser and the deflection amplitude of the reflected light beam is sychronously detected with a position sensitive detector; this amplitude is a measure of the magnetic field. Ranging is done with a calibration coil which imposes a background field to maintain proper dynamic range and which can also inject fields when resonance is lost, possibly due to zero field. The amplitude of the drive current is also adjustable within this feedback loop.

Presently a 5 mm CuBe single axis xylophone beam (Fig. 1b) with optical pickup and conventional drive and detection breadboard electronics is being readied for an upcoming rocket opportunity (APEX launch, 1999) to prove the concept in flight. Laboratory measurements of this system place the sensitivity level at about 1 nT, although the effects of changing temperature and pressure and flight dynamics need to be assessed. Although this APEX opportunity is being pursued with traditional electronics, parts and enclosures because of cost and schedule constraints, there is no technical roadblock to producing this instrument in chip or multi-chip form. Subsequent internal research and development of this ongoing effort is directed at a modest expansion to a three-dimensional sensor head. After this point in the three-dimen-

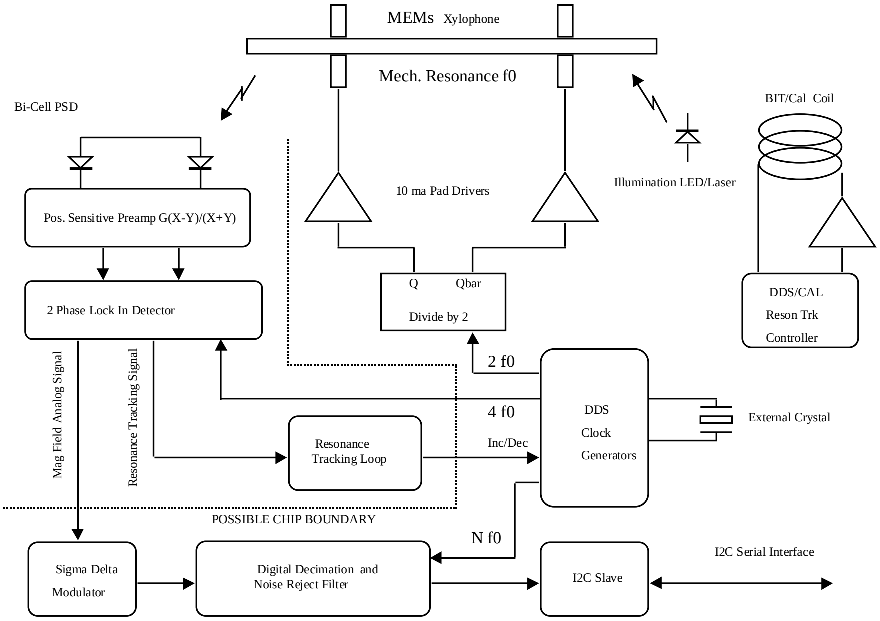

Figure 2. Block diagram of drive electronics for the Xylophone Magnetometer.

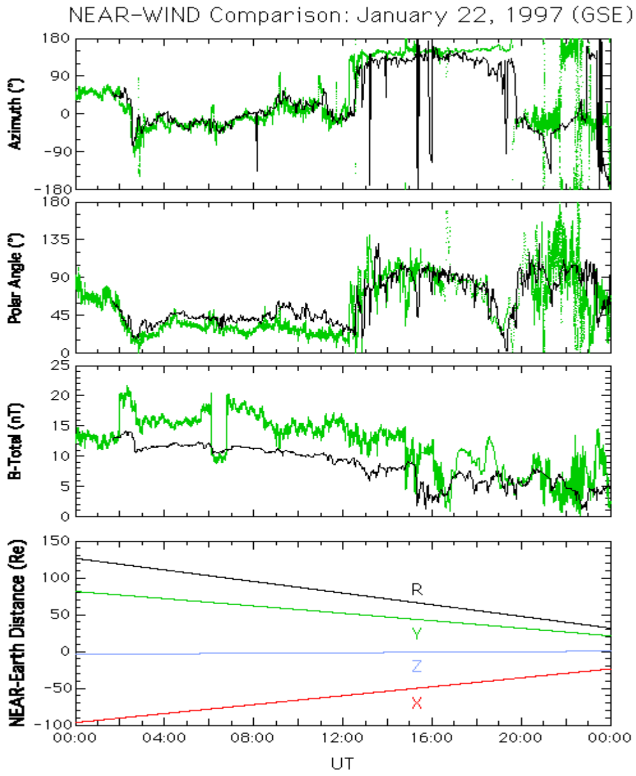

Figure 3. Magnetic field measurements (polar angles, magnitude in GSE) taken by NEAR during the January, 1997 Earth flyby compared to those taken by WIND; differences with higher values recorded when NEAR (green) was inside the magneto-

sional development, and after APEX flight results and design iteration, this design-in-chip version would be suitable for future multi-point space measurements.

The chief problem with smaller spacecraft and lower available resonances is the contamination of magnetic field measurements due to close proximity to remnant and current driven fields. Figure 3 shows that noise mitigation can produce accurate measurements in the presence of extensive dynamic noise, albeit substantial software and manual correction work is needed. Figure 3 shows data from the NEAR magnetometer taken near the Earth and compared with the WIND magnetic field measurements, both near the Earth's magnetopause. Favorable comparisons note the success of the noise mitigation techniques on NEAR, with remaining differences between NEAR and WIND being due only to location differences relative to the magnetopause. A moderate number of spot measurements on the spacecraft structure together with on-board noise rejection would produce a robust and flexible system of high accuracy magnetic field measurements for the newest constellation designs of miniature spacecraft performing multi-point observations.

In summary, breakthrough sensing technology, such as the described resonant xylophone bar magnetometer, will lead to production level devices at far reduced cost and resource demands. Depending on requirements, such devices may well satisfy needs and reduce costs while enabling mission and measurement complexity of future constellation configurations. Standard MEMS techniques can be used to provide three-axis systems and one- or two-dimensional arrays for magnetic imaging; the ultimate goal of single sensor systems is to provide an entire magnetometer on a chip.

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