A Fully Integrated Micro-Magnetometer/Microspacecraft for Multipoint Measurements: The Free-Flyer Magnetometer

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Abstract

In the decades since the advent of in situ plasma measurements on board spacecraft, the instrumentation has grown bigger, heavier, and more complex as our understanding of space plasmas improves, and our appetite for more information increases. The result is that current state-of-the art instruments may be up to several kg in mass. However, we can no longer afford either these larger instruments or the spacecraft which carry them. There has thus been a recent interest in the miniaturization of both spacecraft and the instrument payload. Traditionally, the design of a spacecraft and its payload proceed along relatively independent paths, with little attempt at producing an optimized "whole". The need for optimization becomes more critical as the spacecraft becomes smaller, since interactions between subsystems become more severe. However, to achieve such optimization, the spacecraft + instruments must be treated as a complete system. This paper describes the results and status of an ongoing design study to understand the problems and trade space of fully integrating an instrument into a micro-spacecraft. The example chosen for the study is a miniature ("chip" sized) magnetometer, under development at the Jet Propulsion Laboratory, using the electron tunneling effect in silicon. The micro-spacecraft is then built around the very specific needs of the sensor. The fully integrated electronics include circuits for the sensor, signal processing, and telemetry. As an application, a set of these autonomous, expendable "Free-flyer Magnetometers" would be ejected from a parent spacecraft to measure both temporal and spatial structure of the magnetic field in selected

regions of the magnetosphere during the approximately 1 hour life of the free-flyer's battery power.

1. Introduction

The Free-Flyer Magnetometer (FFM) program at the Jet Propulsion Laboratory has pursued dual goals: 1) develop a process for the design and fabrication of a highly integrated, as nearly monolithic as possible, highly miniaturized, autonomous spacecraft which 2) can provide scientifically meaningful measurements. In addition, an eventual goal of the FFM program is to show that most of the free-flyer itself can be mass produced in the manner of integrated circuit chips, greatly reducing their cost.

Attempts at miniaturizing most space instruments (whether counting photons or ions) eventually run into an entrance aperture problem; no matter how small the other components can be made, a useful signal to noise ratio requires the front end of the instrument to be much larger. However, magnetic field sensors are unique in that regard since they have no "aperture", although in a sense, they are measuring the magnetic flux. Hence we have chosen magnetic field measurements as the basis of the micro-spacecraft. To allow the possibility of a monolithic structure, we have been developing a silicon-based sensor using the electron tunneling effect [*Miller et al.*, 1996]. We have also investigated other sensor possibilities, but the tunneling sensor appears to satisfy overall requirements best. Details of this sensor are given below.

The scientific application of the FFM is to provide the capability of multipoint vector measurements of the magnetic field in regions of the magnetosphere. This capability would allow determination of source currents, and the separation of spatial and temporal effects. These have both long been goals in the magnetospheric community and are goals of the Cluster as well as Grand Tour Cluster Missions. (See for example, "Cluster: mission, payload and supporting activities", ESA SP-1159, European Space Agency, March 1993.) Whereas these two missions employ relatively small numbers of spacecraft, the FFM can provide dozens of measurement points at a reasonable cost. We are currently targeted to be able to cover volumes of the order of a few tens of km, and hence the interest would be in small scale structures such as in boundary regions in the magnetosphere.

The overall concept of the free-flyer magnetometer is as follows. A host spacecraft contains an ejector mechanism which, on command, selects a free-flyer (FF) from a storage magazine and ejects it with a relative speed of a few m/s. The FF sensor measures the magnetic field and telemeters the data back to the host for storage, processing, and later transmission to the ground. The measurements continue for as long as the FF's battery lasts. A sufficient number of FFs are carried on the host to allow multiple ejection events. These events can be initiated either by on board stored, time-tagged command, by real time ground command, or autonomously when, for example, measurements on the host meet some predetermined criteria for an ejection condition.

This paper is a report of work in progress. We describe the overall concept of the FFM study, give a summary of results of work to date, and discuss briefly some of the open issues yet to be tackled.

2. Free-Flyer Magnetometer Architecture

The free-flyer magnetometer system can conveniently be divided into three functionally separate systems: 1) the free-flyer itself, 2) the host flight system, and 3) the host spacecraft system. Their relationship and component parts are shown schematically in the block diagram of Fig. 1. Although separate "boxes" are drawn to emphasize functionality, many of the electronic components shown in fact can be physically combined into a single component. This is in keeping with our goal of producing a highly integrated system.

Except for the magnetometer sensor, most of the components are in the conceptual design stage. In order to bound the design, we have assumed a FF ejection speed of 3-5 m/s from the host spacecraft, a measurement duration of 1 hr for each FF, and a maximum range of 10-20 km from the host spacecraft. We also took the host spacecraft to be in a high inclination orbit for magnetic field measurements in the polar cusp region.

2.1. The Free-Flyer

The free-flyer consists of a set of sensors to provide three-axis measurements, sensor drive electronics, logic and data storage electronics, a telemetry transmitter and antenna, and a battery and power processing electronics. The heart of the free-flyer is the sensor, which is described in detail below. Here we mention that the baseline is an electron tunneling effect sensor. Since this sensor is fabricated in silicon, it allows the possibility of combining it with much of the FF electronics into a monolithic structure. This is one of the goals of the program, as mentioned above.

The FF is disk-shaped and spun up by the ejector to maintain its inertial orientation. The ejection process also turns the circuitry on. A photograph of a model of a concept of an FF is shown in Fig. 2. The required power level (~few hundred mW) is kept low by sharing power alternately between the measurement electronics and the transmitter. That is, the process consists of the sequence: measurement, store, transmit. Transmission is via a patch antenna on the base of the FF. The carrier of each FF is coded to distinguish the signal of one from another. Preliminary studies have shown that thermal control of the FFs can be accommodated by using appropriate coatings.

The measurement duration (and therefore spatial range), size and weight of the FF, and the battery size are interrelated. We have not done any detailed trade studies, but obviously, increasing the measurement time in order to increase the range, for measurements in the magnetosheath, for example, would require more stored energy, and hence a larger FF.

2.2. The Host Flight System

The host flight system consists of those elements which directly interface with the free-flyers: the ejector and FF storage, the FF signal receiver and antenna, and a data processing subsystem. A CAD drawing of an ejector/magazine concept is shown in Fig. 3. In this concept, an FF disk is first positioned into the spring loaded ejection tube. On firing, the disk is spun up as it is ejected. Analysis indicates that less than a few hundred RPM is sufficient to provide the needed inertial stability. The length of the tube is the order of half a meter. The total mass of ejector plus storage magazine is estimated to be the order of several kg.

2.3. The Host Spacecraft System

The host spacecraft system consists of the components necessary to "service" the flight system just described. This includes power, command, and data busses. To allow for missions of opportunity, in which the flight system is a piggyback payload on a spacecraft not specifically designed for it, these interfaces should be kept simple. The flight system must therefore be designed to accommodate standard interfaces, or be easily configured to do so.

3. The Tunneling Sensor Magnetometer

The tunneling sensor represents a very new approach for magnetic field measurements. This "chip-size", all silicon device is based on the quantum mechanical electron-tunneling effect which has been used in scanning-tunneling microscopy since 1982 [*Binnig and Roher*, 1982]. The magnetometer sensor exploits the tunneling effect in an arrangement that nulls the deflection of a thin, flexible silicon membrane caused by the Lorentz force resulting from the ambient field to be measured, and a current carrying element on the membrane. The tunneling effect itself can be described with reference to Fig. 4. The tunneling tip is typically submicron in radius, with a gap ~10 Å to the surface. The tunneling current between the tip and the surface depends exponentially on that distance. This current therefore provides a sensitive measure of the gap distance. By use of a flexible membrane for the surface, this current then becomes a sensitive measure of the membrane displacement, and therefore the force which produced the displacement. Further, electrically rebalancing this force provides a nulling method of force measurement [*Kenny et al.*, 1994]. A schematic view in cross section of such a device, with the drive electronics, is shown in Fig. 5. The gap distance is controlled by the membrane to tip voltage, and this voltage thus provides the rebalance error signal which is the measure of the force on the membrane.

In operation as a magnetic field sensor, it is the Lorentz force resulting from the ambient field and a current carrying element on the membrane which is measured [*Miller et al.*, 1996]. The feedback signal is thus a measure of the applied field. Figure 6 shows schematically a configuration in which the current element is actually a loop of several turns, in order to increase the sensitivity. To provide good DC response the current element is AC driven.

The device is fabricated by microelectromechanical systems ("MEMS") technology, and is currently under development by the JPL Microdevices Laboratory [*Kenny et al.,* 1994]. Based on working prototypes, we estimate the capability of <4 nT/√Hz sensitivity, linear response, wide bandwidth, wide dynamic range (>100 dB) and excellent stability. Power consumption for a 3-axis system is projected to be < 300 mW.

4. Current Status

As indicated in the introduction, this is a report on work in progress. There is much yet to be done. Current efforts proceed along three lines: 1) the sensor, 2) system issues, and 3) mission analysis. Some aspects of the tunneling sensor work were summarized above. At present, performance is a few orders of magnitude away from the goal of ~1 nT/√Hz, but projections indicate the goal is attainable with further development within a year.

Regarding the system, as shown by Fig. 1, the basic building blocks are understood, but the critical issues of how to integrate these has received only little study. One key issue, for example, involves the magnetic cleanliness of the FF: how do you design such a compact system while avoiding contamination of the measurement by nearby circuitry? Another important issue involves how accurately the position of each FF can be determined. Since determining currents involves calculating finite differences between FFs, the position accuracy directly establishes the accuracy of the current determination. Our present concept is that over the life of the order of an hour, the position can be determined accurately enough from orbit mechanics if the ejection speed and direction are known accurately enough. One way of determining the speed is with a type of "radar gun" on the host. An alternative method that has been suggested is to use the measurement of the field itself to determine the position, for regions where Earth's field is modeled well enough.

The mission analysis performed to date has been directed toward understanding some of the characteristics of how the FFs disperse relative to the host. The result of one such study is shown in Fig. 7, for the trajectories of 8 FFs ejected in 45° intervals at 2m/s relative to the host at an altitude of 6600 km. The ordinate is along the radial direction, while the abscissa is horizontal and in the plane of an 80° orbit. The points are plotted at 30 min. intervals. For this example, the FFs therefore cover a region of about 5 to 10 km around the host in an hour after ejection. Similar calculations for any arbitrary host orbit and ejection velocity are straightforward.

5. Acknowledgments

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6. References

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Kenny, T. W., et al., Widebandwidth electromechanical actuators for tunneling displacement transducers, *J. Microelectromech. Sys., 3,* 97-104, 1994.

Miller, L. M., et al., A miniature, high performance magnetometer based on electron tunneling", *J. of Microelectromech. Sys.*, in press, 1996.

Ratcliffe, J. A., "An Introduction to the Ionosphere and Magnetosphere", Cambridge University Press, Cambridge, 1972, p. 71.

7. Figure Captions

1. System Block Diagram of Free-flyer Magnetometer system.

2. Photograph of free-flyer mockup.

3. CAD drawing of free-flyer ejector concept.

4. Schematic diagram illustrating the principle of the electron tunneling effect. The tunneling current I is exponentially dependent on the gap distance Z, with $\alpha = 1.025\ eV^{-1/2}Å^{-1}$, and Φ is the potential barrier hight in eV between the tip and the conductive surface.

5. Schematic diagram illustrating a method for using the tunneling effect in a force rebalance sensor. The voltage between the tunneling tip and the flexible membrane is used in a feedback circuit to readjust the gap in the presence of an external force on the membrane.

6. Schematic diagram illustrating the tunneling effect force rebalance sensor used as a magnetic field sensor. In this case, it is the Lorentz force resulting from the external field to be measured and the current along the flexible element which is sensed. The device will thus measure the component of the field normal to the plane of the diagram.

7. Dispersal pattern of eight free-flyers ejected 2 m/s in 45° intervals for a release altitude of 6600 km. Positions are shown at 30 min. intervals in the plane of the 80° inclination orbit of the host.

Functional Block Diagram of FFM Flight System & Host Spacecraft

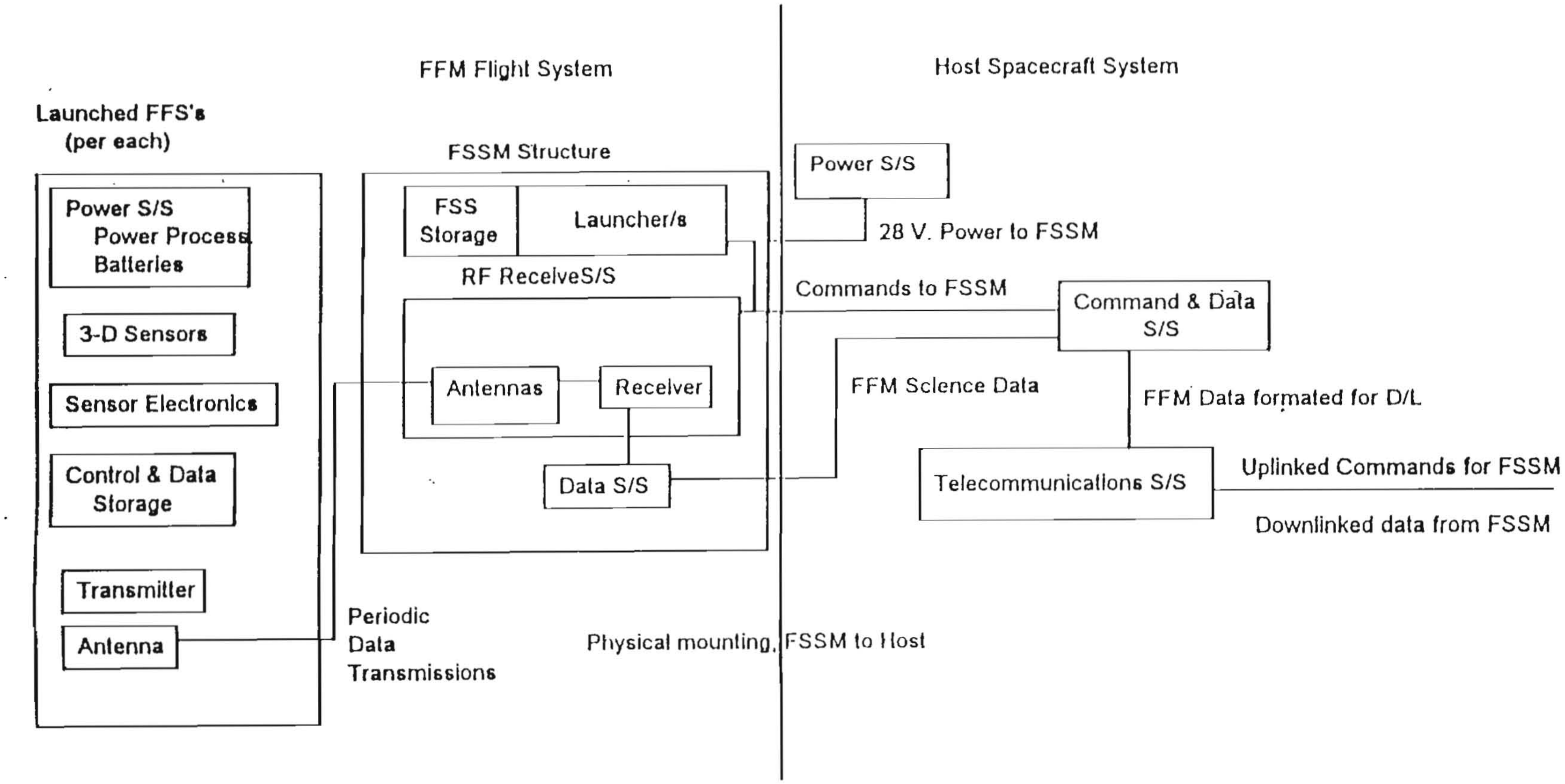


Figure 1

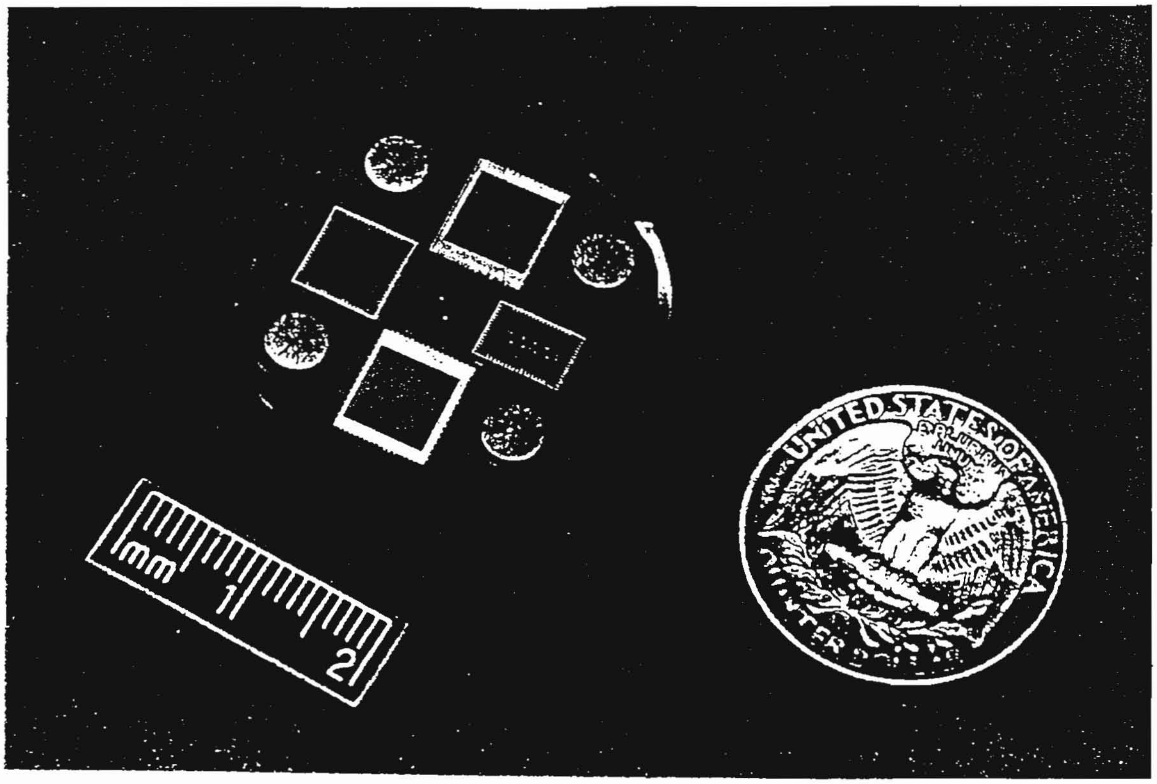


Figure 2

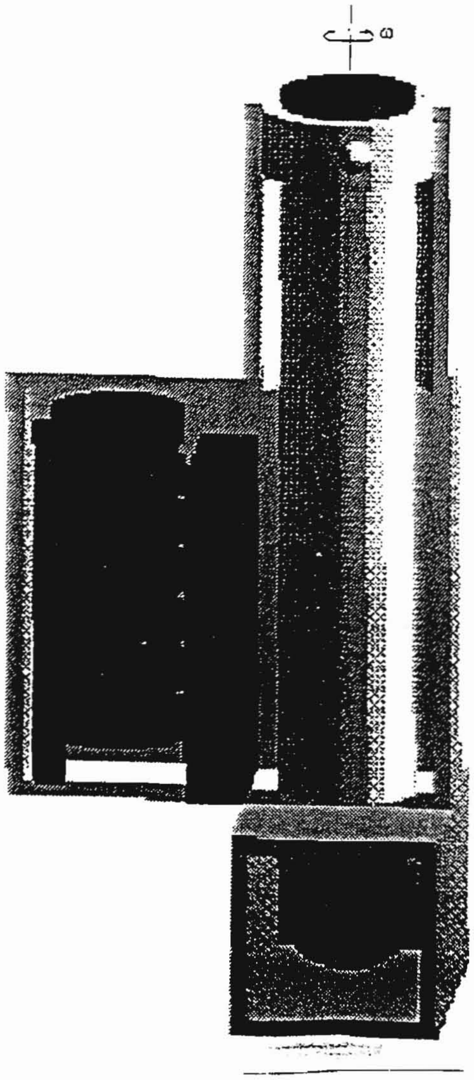
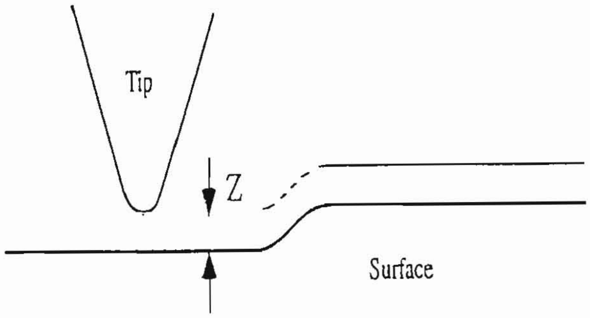


Figure 3



$$I_{tunneling} = I_0 \exp(-\alpha Z \sqrt{\Phi})$$

Figure 4

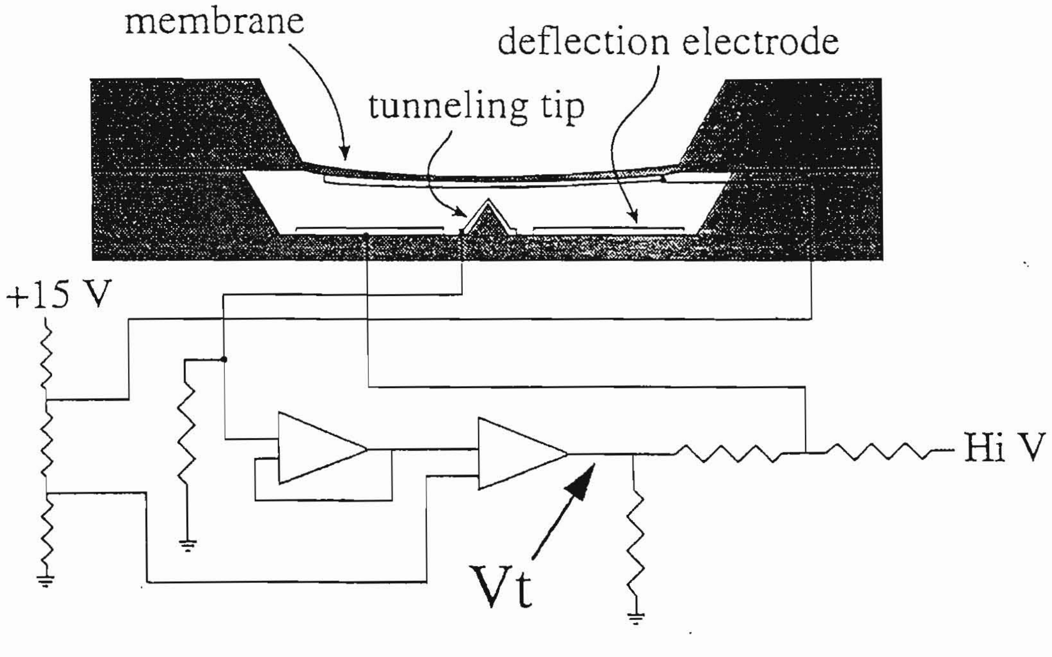


Figure 5

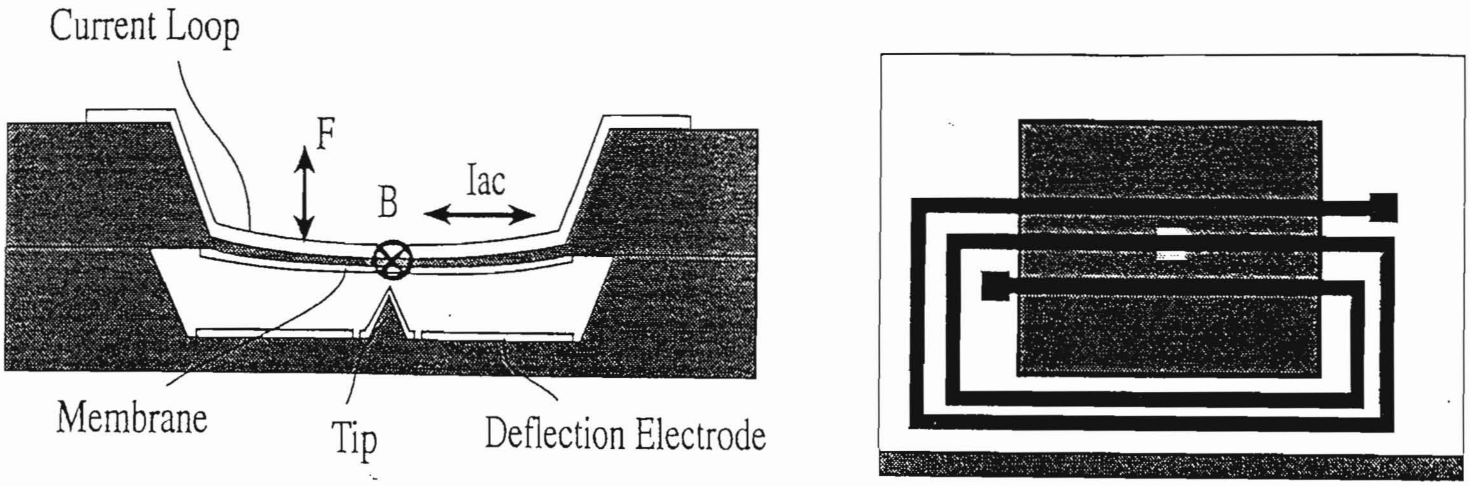


Figure 6

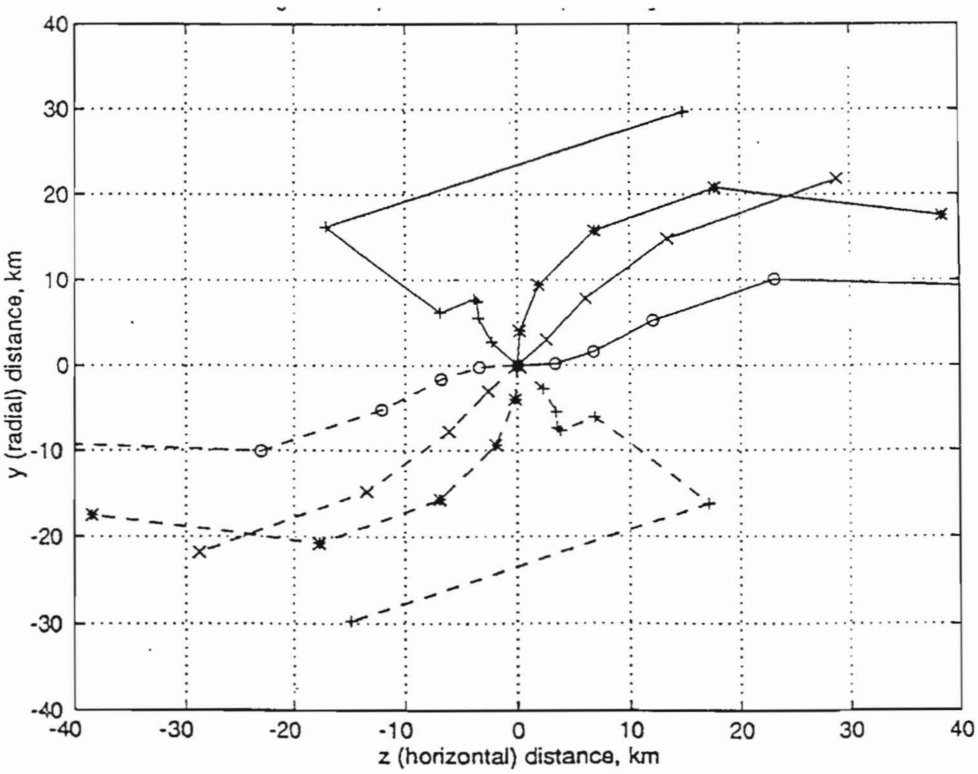


Figure 7