

NONVOLATILE SOLID STATE DATA RECORDER FOR SPACE APPLICATIONS

Russell E. Averill, LT, USN

Naval Postgraduate School
Space Systems Academic Group
Monterey, California

Abstract: Solid state data recorders provide numerous advantages over reel-to-reel tape recorders. Having no moving parts, they offer great reliability and do not produce troublesome reaction torques as compared to mechanical recorders. The Naval Postgraduate School has designed and built a solid state magnetic bubble memory data recorder for use on board a satellite. This recorder is based on a modular concept. The basic configuration consists of a back plane, power supply card, a controller card, a recorder interface card, a system interface card, and a selectable number of memory cards, containing four Mbytes each.

INTRODUCTION

Existing non-real time telemetry systems use analog tape recorders as their data storage device. They are usually comprised of several separate low capacity tape recorders for redundancy or record data on the large capacity payload tape recorders. The problems associated with these types of recorders include high cost, low reliability, and large size. A small and reliable solid state data recorder would be a desirable alternative.

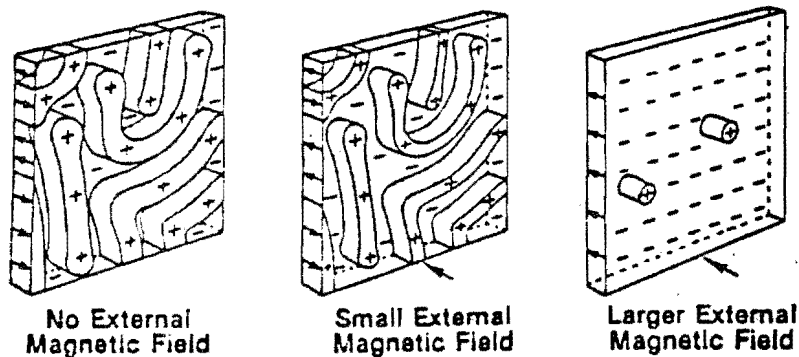
Significant advances in magnetic bubble memory technology have demonstrated its feasibility for use in data storage systems. Recently, a number of systems have been developed for the military using bubble memory devices. These current applications have successfully demonstrated the use of bubble memories in a harsh environment. However, the use of bubble memories in space applications has been limited.

The Naval Postgraduate School (NPS), through thesis research over several years, has studied hardware configurations for possible solid state data recorders. Magnetic bubble memory for use as the storage medium was found to be the most attractive solution. The advantages of bubble memories include nonvolatility, high density, survivability, and no moving parts. As a result a twelve Mbyte solid state data recorder (SSDR) using magnetic bubble memory was built to support a Get Away Special experiment to measure the acoustic environment of the space shuttle cargo bay during lift off. It provides a memory medium capable of recording data during the extreme environment of a shuttle launch. Due to the experience gained in the development of this recorder and the subsequent knowledge obtained from companies performing bubble memory research, it was possible to investigate the feasibility of a small, space-qualified telemetry recorder using bubble memory. The telemetry recorder incorporates several innovative designs for reducing the number of components, thus dramatically decreasing size and weight. To illustrate this

point, the same capacity 12 Mbyte recorder used for the NPS shuttle acoustic experiment with this design could be reduced to roughly one half the weight and one sixth the size.

MAGNETIC BUBBLE MEMORY

The concept of the magnetic bubble memory was first reported by Dr. Bobeck of Bell Laboratories Incorporated, in 1967. He found that when an external field of proper intensity was applied to a thin film of magnetic material formed on a substrate, cylindrical magnetic domains (called bubbles) could be created. Figure 1 shows the formation of these bubbles from the serpentine magnetic domains to the cylindrical bubbles, when a large external magnetic field of the correct intensity is applied. If the external magnetic field is increased further, all magnetic bubbles will collapse, because of the magnetization in the bias magnetic field direction. For a magnetic bubble memory the existence of a bubble corresponds to a 1 and the absence to a 0. Since the external magnetic field is formed by a permanent magnet, a magnetic bubble will be permanent, making the information non-volatile.

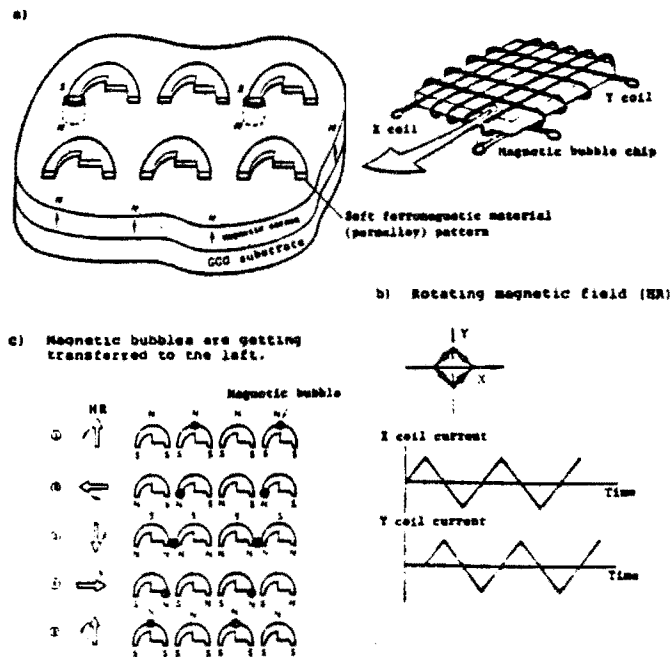


Source: [Ref. 1:p 1]
Figure 1 Magnetic Bubble Formation

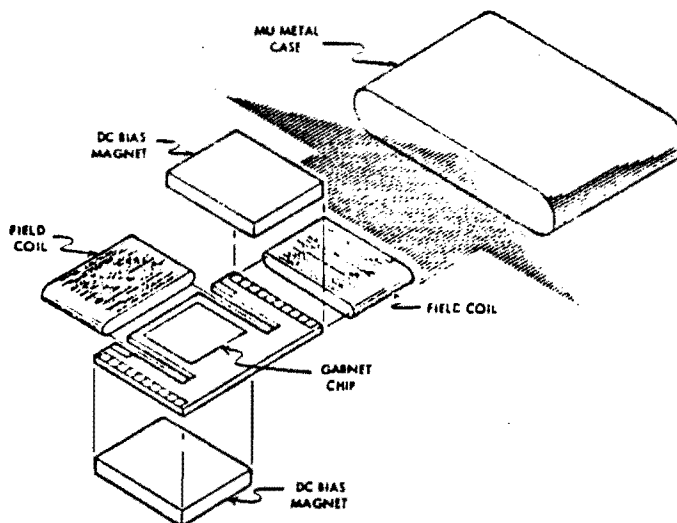
To organize the magnetic bubbles formed, a chevron like pattern is deposited on the film. To move the bubbles through the chevron pattern a rotating magnetic field is applied by means of two orthogonal coils. A 360 degree rotation of this field will move a bubble exactly one chevron. The bubble motion can be performed with several types of propagation patterns. Bubble propagation using the common chevron scheme is illustrated in Figure 2. When the rotating magnetic field is stopped by removing the current through the coils, the bubbles stop in their last magnetized position until the rotating field is energized again.

An entire bubble memory module, as shown in Figure 3, consists of a memory chip mounted on a substrate to facilitate electrical, mechanical and cooling interfaces. The substrate is surrounded by two orthogonal coils and then placed between two permanent magnets. To prevent external magnetic interference, the whole package is shielded by a MU metal case. The storage capacity of the bubble module has increased from an initial 64 Kbits to today's 4 Mbits. Modules of 16 Mbits and greater are promised for the future.

The bubble memory module requires support components to read and write data to memory. These parts provide the rotating magnetic field to move the bubbles, amplification of the low level bubble signals and the necessary control.



Source: [Ref. 2:p 5]
 Figure 2 Bubble Propagation



Source: [Ref 1:p 1]
 Figure 3 Bubble Memory Module

ANALOG DATA RECORDERS

Space rated analog tape recorders are comprised of complex electromechanical devices to store information on magnetic areas of tape. The operation of the recorder moves the tape past playback or record heads to sense the magnetic information or induce it. Two serious deficiencies of this type of recording system are (1) that they have moving parts and (2) that they are serial access devices. Access time for certain data can be high if it is stored at one end of the tape. By contrast, most solid state memory systems can retrieve data randomly with short access time.

The problem associated with moving parts can be summarized as follows:

Because of the electromechanical nature of tape recorders, their reliability when compared to other components on spacecrafts does not compare favorably. The major areas contributing to recorder failure are the head/tape interface, negator spring fatigue, drive belt failure, tape jam and electronics failures. [Ref. 3: p. 2-4]

The failure of a recording system after extended operation due to wear, can degrade or limit a spacecraft's mission. This is illustrated with the French imaging satellite SPOT, where one of its two tape records has failed [Ref. 4:p. 14]. The following summarizes these and other drawbacks of analog tape recorders:

- Moving parts
 - (1) Generated waste heat
 - (2) Creates torque
- Microgravity - Drive and suspension systems "G" susceptible
- Air required between medium and head
- Null packets (A string of zeroes) placed in the data at slow tape speeds to reduce the on/off cycling of the tape heads
- Ground station reversal of data is required (Head cycling is minimized by not rewinding the tape for playback)
- Fragility of the recording medium

A solid state recorder could improve the performance of many data storage systems in all these areas. Current technology of solid state memories limits their use for recording systems onboard satellites requiring large storage capacity, such as imaging satellites. Yet, low capacity tape recorders have extremely low reliability at a high cost. To achieve an 80% probability of success, the Odetics and RCA telemetry recorders require four separate recorders to be flown [Ref 3: p. 2-27]. The low storage capacity requirement for telemetry systems permits the use of solid state memories.

SOLID STATE MEMORY DEVICES

Solid state memory can be separated into two basic groups of semiconductor and magnetic devices. Semiconductor examples include ROM, PROM, EPROM, E²ROM, RAM, and CCD, while examples of magnetic devices include tape, disk, core and MBM. The semiconductor group uses voltage, charge or current levels to represent data. The magnetic group uses variation in magnetic flux.

The individual features of each memory should be considered in choosing an appropriate device; using one in space adds even more constraints to the selection process. Some required features are radiation hardness, temperature range, versatility, non-volatility, reliability, small size, low power consumption and low cost.

The PROM (programmable ROM) and EPROM (erasable programmable ROM) must be programmed by the user outside the circuit, thus they lack versatility. ROM and E²ROM are electronically erasable, but lack the density. These devices, including RAMs and charge-coupled device (CCD), have been used, but rely on batteries for data retention which limits their usefulness to short missions. Core memory is non-volatile and reliable, but size and power constraints limit its use in space applications. Magnetic disks and drums have problems similar to those discussed for tape recorders. This leaves MBM to be considered.

The advantages and disadvantages of magnetic bubble memories are summarized in Table 1. These disadvantages were overcome for the NPS telemetry recorder as follows:

- **Data transfer rate:** Telemetry recording systems have low data transfer rates which results in low power consumption for a bubble memory system.
- **Multiple support chips:** Low data transfer rates of telemetry systems allow a design to use only one set of support chips, incorporating a switching network to address the bubble modules. This limits the recorder to a maximum transfer rate of one bubble memory module or 256 Kbits per second with Hitachi components.
- **Rad soft support chips:** Using component and selective shielding, radiation levels can be reduced for the critical components to allow survival for several years in a low Earth orbit.

Table 1
MBM ATTRIBUTES

| <u>Advantages</u> | <u>Disadvantages</u> |
|---|---|
| Reliable Rugged/Robust Non-volatile No moving parts Random access High density | High power for high transfer rates Multiple support chips required Support chips rad soft |

NPS RECORDER

Concept

The initial concept of the recorder design was to make it as small and as simple as practical. The memory needed to be modular in design to allow for future flexibility in total memory capacity. Also, redundancy was desired for reduction in cost, size and weight. This combination would produce the most basic recorder for testing and "proof of concept."

Since the bubble memory controller can address a maximum of 64 bubble modules, multiplexing bubble memories with one set of support peripheral chips limits access to this

number. With this configuration, the NPS recorder data transfer rate is only limited by the specification of the Hitachi bubble memory chip (256 Kbits per second).

The new Hitachi components are desirable for several reasons. The bubble module and peripheral circuits are all hermetically sealed, a definite advantage for a space environment. They are smaller in size than their predecessors and are capable of increased frequency operation permitting a data transfer rate of 512 Kbits per second.

To obtain a modular design, the total recorder function is divided into several subfunctions implemented on different circuit boards, as shown in Figure 4. One board contains the power supply, one the bubble control circuit, one the memory, and two the interface. The satellite interface card can be tailored for the specific mission, while the recorder consisting of the remaining four cards can be made generic.

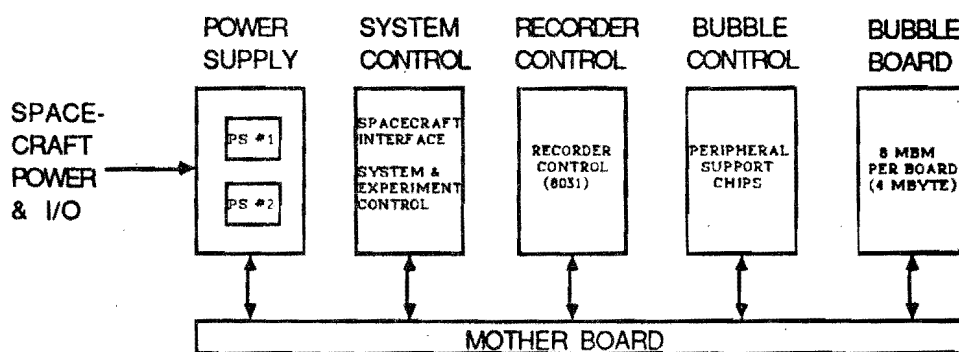


Figure 4 NPS Telemetry Recorder System

Due to component dimensions and memory capacity per circuit board, the memory board dictates the size of all the circuit cards. The area required for eight four Mbit bubble modules and the minimum number of support components determines the smallest card size possible. Utilizing only one coil driver for two bubble modules was considered in order to reduce the number of components on the memory board.

Hitachi's new picture frame coil (PFC) bubble device requires an external coil in series with the coil driver. The external coil has an inductance roughly equivalent to that of the PFC bubble itself. Therefore, the possibility exists of removing the external coil and using one coil driver for two PFC bubbles in series. This would eliminate the cost and space of eight components for the memory board.

An analysis of the coil driver circuits was performed using the SPICE program available on the NPS IBM 3033 computer. Comparison of the current waveforms from the coil driver with an external coil and the PFC in series and then with two PFCs in series is summarized in Table 2. As seen in Figure 5, the peak current of two PFCs in series was within one percent of the PFC module external coil peak current values given by Hitachi.

Table 2
COIL DRIVER PFC CIRCUIT

| | Hitachi Values PFC, External Coil | Spice Values PFC, External Coil | Spice Values Two PFCs |
|-------------------------|--------------------------------------|------------------------------------|--------------------------|
| Peak Coil Current mA | 1270 | 1338 | 1258 |

Based on SPICE analysis, reducing the number of coil drivers seems feasible. However, the risk involved in experimenting with the entire memory board was considered too great. A more reasonable approach was taken testing the operation of one coil driver with only two BMUs on the memory board. This allowed testing and operating the recorder with six functional BMUs if the coil driver experiment failed.

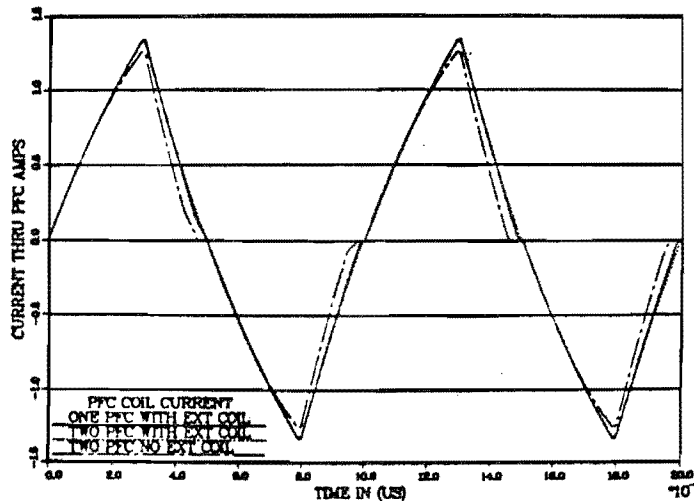


Figure 5 SPICE Current Waveforms For Coil Driver Circuits

The coil driver experiment was incorporated into the memory board using bubble number seven and eight. After operation of the NPS recorder, initial results of the coil driver experiment proved successful, with the actual current waveform shown in Figure 6.

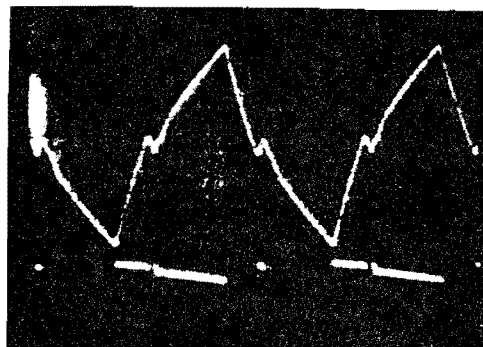


Figure 6 Actual Current Waveforms For Coil Driver Circuits

The ultimate goals for the recorder design are that it (1) will be able to emulate an analog (reel-to-reel) recorder, (2) will use readily available parts compatible with radiation hard parts, and (3) will be as compact as possible. The use of component chips compatible with radiation hard chips becoming available in the future is especially important to allow improvements without redesign of the basic recorder.

Environmental Criteria

The environment in which the bubble memory recorder will be expected to operate is dependent upon the particular mission of the spacecraft. The ability of bubble memories to operate over a temperature of -40°C to 85°C permits a wide range of operation. Magnetic bubbles are capable of withstanding high doses of radiation on the order of 1×10^6 Rads without failing. The peripheral components are affected by total radiation as low as 1×10^3 Rads. Finally, bubble memories are capable of operation in a total vacuum, and do not require an artificial atmosphere as analog recorders do.

Radiation levels in low earth orbit vary depending upon the orbit chosen and are usually not a problem. However, a satellite in polar orbit, such as the Defense Meteorological Satellite Program (DMSP), has experienced total dose radiation levels of 1×10^5 Rads over four years [Ref.3]. This radiation dose will fluctuate over a period of solar maximum to solar minimum.

Solutions to reducing radiation dose can be found in several ways. The primary method is accomplished by use of passive shielding. This involves placing metal around radiation soft components. Next, a low duty cycle of the system can greatly increase a device's ability to withstand radiation. In the standby mode the NPS recorder does not energize the support components susceptible to low radiation dose failure. Finally, the recorder housing was designed and built to reduce radiation levels by an order of magnitude.

The recorder housing was designed with a 250 mil wall thickness to shield the bubbles against increased radiation doses in polar low earth orbits. Aluminum was selected due to weight considerations and the lack of secondary emission due to incident radiation.

Since some non-space-rated components were used in the recorder circuit, the recorder was hermetically sealed to prevent contamination of the spacecraft from outgassing.

Final Design and Fabrication

With these basic guide lines for the recorder formulated, SEAKR Engineering Incorporation was contracted to finalize the design and build the memory card, controller card, recorder interface, and mother board of the NPS recorder. NPS designed and built a system interface and recorder housing. The system software development, environmental testing, and power supply card design are being carried out by the Naval Postgraduate School. The power supply card will consist of two separate power supplies for redundancy. The system interface card transfers signals to and from the satellite, controls all sensors and all data to and from the recorder. It will have the ability to bypass the microprocessor on the recorder interface card and access the bubble memory controller. The present system interface utilizes an IBM personal computer for recorder control.

Testing

Power consumption of the recorder was the first parameter to be measured using laboratory power supplies. Power was calculated in the standby and running (read/write) mode. A power box was used between the power supplies and the recorder to allow for power conditioning and for turning on all three voltages (+5, +12, and +30 volts) simultaneously from a single switch. The power consumed by this equipment was subtracted from the total standby and running power to reflect true recorder power values.

Table 3 summarizes the power consumption measured during operation of the recorder. Original design predictions were for approximately 12 watts running mode and 3 watts in standby mode. The 11.23 watts measured while running the recorder is 6% less than expected, while the 4.93 watts in standby mode is 64% greater.

Table 3
TELEMETRY RECORDER POWER CONSUMPTION DATA

| | <u>Test Equipment</u> | | <u>Recorder Standby</u> | | <u>Recorder Running</u> | |
|------------------|-----------------------|----------------|-------------------------|----------------|-------------------------|----------------|
| | Current mA | Power watts | Current mA | Power watts | Current mA | Power watts |
| 4.9 volts | 50 | 0.595 | 450 | 2.2 | 490 | 2.40 |
| 11.9 volts | 50 | 0.245 | 300 | 3.57 | 690 | 8.21 |
| 29.1 volts | ≈0 | ≈0 | ≈0 | ≈0 | 50 | 1.45 |
| Total Power | | 0.84 | | 5.77 | | 12.07 |
| Minus Test Equip | | | | <u>4.93</u> | | <u>11.23</u> |

Operation of the single coil driver for bubble modules number seven and eight caused a power increase of 0.72 watts. Depending on the success of the coil driver experiment to properly operate both bubble modules with the temperature range required, the trade off of this small power increase for reduction of components would be acceptable.

The time required to transfer all data between the recorder and IBM personal computer was 155 seconds for both the read and write operation. This gives an average data transfer rate of 291 Kbits/second. This is better than the 256 Kbit/second expected while operating the BMUs at 100 KHz frequency.

The NPS satellite telemetry recorder weighs 11.1 pounds. The circuit boards contributed a total weight of 3.5 pounds. Individually the boards weigh 16 ounces for the memory board, 13 ounces for the controller board, 11 ounces for the recorder interface board, 5 ounces for the mother board, and 11 ounces for the system interface card. The housing, designed and built as discussed earlier, weighs 7.6 pounds. Adding 2.5 pounds to allow for a power supply card, changes to the interface card, and sensors would give an estimated recording system weight for launch of 13.6 pounds.

The currents from specific coil drivers during recorder operation were found to have irregularities. A current probe was used to display the current waveforms for each bubble's X and Y coil on an oscilloscope. The current waveforms for the odd bubbles (1, 3, 5 and 7, right side of the board) had small spikes when in transition from positive to negative or negative to positive current flow, while the even bubbles displayed the spike with the Y coil. Mutual inductance with the external coil and board circuit traces are considered to be the probable cause. Preliminary experimentation with MU metal shielding has not reduced the effects. Operation of the recorder at room temperature has not been affected by these irregularities in the coil driver waveform. Further testing through the operating temperature range of the bubble modules is required to investigate this problem further.

Specifications

The NPS recorder specifications are summarized in Table 4.

Table 4
EXPERIMENT DATA MATRIX

| | |
|----------------------------|---|
| EXPERIMENT: | MAGNETIC BUBBLE MEMORY |
| RECORDER | |
| EQUIPMENT COMPONENT: | ONE |
| FOOTPRINT DIMENSIONS (IN): | 8.5 x 8.4 |
| HEIGHT (IN): | 4.5 |
| COMPONENT WEIGHT: | 13.6 LBS |
| POWER (WATTS) | |
| PEAK: | 14 |
| STEADY STATE: | 11.5 |
| STANDBY: | 5 |
| DUTY CYCLE: | N/A |
| TURN ON SURGE: | .5 A OVER NOMINAL |
| TURN ON CONSTRAINTS: | N/A |
| VOLTAGES | |
| OVER: | +5 VOLTS |
| UNDER: | -5 VOLTS |
| REVERSE: | NO |
| SERIAL: | UNKNOWN |
| COMMANDS | |
| DISCRETE: | N/A |
| SERL MAG: | N/A |
| TELEMETRY | |
| ANALOG: | N/A |
| DISCRETE: | N/A |
| PARALLEL: | N/A |
| SERIAL: | 2 LINES, 1 DATA, 1 ACKNOWLEDGE, 1 KBIT/DAY |
| FIELD OF VIEW: | N/A |
| ALIGNMENT KNOWLEDGE: | N/A |
| SPIN RATE: | N/A |
| INTERFACE | |
| CONDUCTION REQ: | 12 WATTS |
| THERMAL: | -20°, +60°C |
| EMC: | N/A |
| PURGE: | N/A |
| CONTAMINATION: | N/A |

CONCLUSION

The use of bubble memories in space applications is an attractive alternative to analog recording systems. Bubble memories can solve many of the problems associated with analog recorder systems which require high redundancy, null packets, and have moving parts. Bubble memory recorders are already being tested in space by other countries.

A bubble memory recorder, similar in size to the NPS recorder, was built by Hitachi and launched on Japan's ASTRO-C satellite. Two follow-on recorders are scheduled for launch on Japan's EXOS-D and ERS-1 satellites. SAGEM of France currently has three satellite programs using magnetic bubble memories. The recorder (EBS 2801) system will be used on SIGMA, EURECA 1, and SPOT 4 satellites. The memory capacity of the recorder ranges from 4 to 32 Mbytes and has been space qualified by France and European agencies.

The NPS recorder meets the requirements for moderate data rate systems with its memory capacity expandable to 32 Mbytes and no increase in power consumption. The recorder is ready to fly as an experiment on a satellite sponsored by the Space Test Program (STP) Office. An improved bubble memory recorder design is being planned for use on the NPS ORION satellite.

REFERENCES

1. Fundakowski, Sally W., "Bubbles Bursting With Military Potential", Defense Electronics, July 1984.
2. Fujitsu Bubble Memory Technical Information, BP-0000-02, Fujitsu Limited, March 1985.
3. Space Division (YD), USAF, Telemetry Storage Techniques Study, CDRL Item 087A2, January 1987.
4. "Tape Recorder Fails On SPOT Satellite," Aviation Week and Space Technology, V. 125, 29 September 1987.