Multiprobe in-situ measurement of magnetic field in a minefield via a distributed network of miniaturized low-power integrated sensor system for detection of magnetic field anomalies

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ABSTRACT

Based on technologies developed for the Jet Propulsion Laboratory (JPL) Free-Flying-Magnetometer (FFM) concept,[1] we propose to modify the present design of FFMs for detection of mines and arsenals with large magnetic signature. The result will be an integrated miniature sensor system capable of identifying local magnetic field anomaly caused by a magnetic dipole moment. Proposed integrated sensor system is in line with the JPL technology road-map for development of autonomous, intelligent, networked, integrated systems with a broad range of applications. In addition, advanced sensitive magnetic sensors (e.g; silicon micromachined magnetometer, laser pumped helium magnetometer) are being developed for future NASA space plasma probes.

It is envisioned that a fleet of these Integrated Sensor Systems (ISS) units will be dispersed on a mine-field via an aerial vehicle (a low-flying airplane or a helicopter). The number of such sensor systems in each fleet and the corresponding in-situ probe-grid cell size is based on the strength of magnetic anomaly of the target and ISS measurement resolution of magnetic field vector. After a specified time, ISS units will transmit the measured magnetic field and attitude data to an air-borne platform for further data processing. The cycle of data acquistion and transmission will be continued until batteries run out. Data analysis will allow a local deformation of the Earth's magnetic field vector by a magnetic dipole moment to be detected.

Each ISS unit consists of miniaturized sensitive 3-axis magnetometer, high resolution analog-to-digital converter (ADC), Field Programmable Gate Array (FPGA)-based data subsystem, Li-batteries and power regulation circuitry, memory, S-band transmitter, single-patch antenna, and a sun angle sensor. ISS unit is packaged with non-magnetic components and the electronic design implements low-magnetic signature circuits. Care is undertaken to guarantee no corruption of magnetometer sensitivity as a result of its close proximity with the electronics and packaging materials. Accurate calibration of the magnetometer response in advance will allow removing the effects of unwanted disturbances. Improvements of the magnetometer performance in the areas of the orthogonality, drift, and temperature coefficient of offset and scale factor are required.

Keywords: Free-Flying-Magnetometer, integrated sensor system, multi-probe measurement system, mine-detection, flux-gate magnetometer, sun-angle sensor

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1. ISS DEVELOPMENT TASK PLAN

The Integrated Sensor System (ISS) Development task is an offshoot of the JPL FFM Technology Development task. The ISS task plans are to modify the existing FFM design, to add required subsystems and build an advanced miniature integrated sensor system for detection of magnetic field anomalies due to hidden mines or arsenals, and to provide full system design and support infrastructure for ISS field demonstration.

2. ISS DEVELOPMENT TASK

Integrated Sensor System development work break-down is as shown in Fig.1. The ISS subsystems (bottom row of boxes in Fig. 1) either have already been developed or they are under developments. The ISS support activity (middle row of boxes in Fig. 1) are still in the preliminary design phase.

3. ISS MINE DETECTION UNIT

Block Diagram of ISS mine detection unit system is shown in Fig. 2 with mechanical structure in Fig. 3. Details of subsystem design and test are discussed in this paper.

The central part of this unit is a FPGA-based digital electronics interfacing with sensors (magnetic, temperature, sun- angle), memories [Electrically Eraseable Programmable Read Only Memory (EEPROM), and Static Random Access Memory (SRAM)], IR umbilical command communication, clock [Temperature Compensated Crystal Oscillator (TCXO)], and output subsystems (RF communication subsystem). Upon the receipt of "Power" , and "Measure" commands via umbilical interface, the FPGA will be turned on. It will go through some initiation routines; it loads the program codes from the EEPROM, and turns on the magnetometer and sun angle sensors. The data as it gathers will be stored in SRAM. At the end of each 7 minutes, the data will be fetched from the SRAM, fomatted to Non-Return-to-Zero (NRZ-M) and Viterbi encoded (K=7,1/2), and is dumped to the S-band transmitter. All the electronics on-board this unit runs from a single clock, so no low-frequency signal will be generated (due to frequency beatings between multiple clocks) which may our sensitive magnetometer.

The half hemispherical base of the ISS mine detection unit is designed to lower its center of gravity and to stabilize its upright stand when dropped on a field.

3-1. ISS MAGNETOMETER

A miniaturized 3-axis high-field magnetometer developed for the FFM task is suited for the proposed mine detection unit. The magnetometer consists of one toroidal core (with coil windings for X and Y axes) and one race-track shaped core placed in the middle of the toroidal one (with single coil winding along the Z-axis). The cores are made out of $Ni_{0.83}V_{0.06}Fe_{0.11}$ compound with superior noise properties. The overall dimensions of the sensor core box is 13 x 13 x 16 mm. Magnetometer cores are driven to saturation by a 50 KHz signal. Second harmonic response is synchronously detected and amplified. An active filter (single pole with 3-dB cut-off at 100 Hz) is emloyed at the output. Drive electronics for the cores and the read-out electronics are implemented on two PCBs (Figure 4). Commercial-off-the-shelf electronic components are used.

Applied Physics Systems (Mountain View, CA) under a contract from JPL has developed a prototype miniaturized sensitive 3-axis flux-gate magnetometer with the following characteristics:

- Maximum signal:	+/- 60,000 nT
- Orthogonality range:	1 - 3 degree (+-0.5 degree error)
- Sensitivity:	2.0 V / 60000 nT
- Magnetic noise level:	<0.06nT rms/sqrt(Hz) at 1 Hz, 1/f below 1 Hz
- Frequency response:	DC to 100 Hz (3 dB)
- Linearity:	<0.1% FS

- Temperature coefficient:	strong temperature dependences (to be modified with proper thermal packaging) (to be compensated by a calibration matrix)
- Drift :	< 20 nT / 20 min. < 2 nT/1 min. < ~0.3 nT/1 sec.
- Power consumption:	+3V @ 60 mA -3V @ 60 mA
- Size (cylindrical):	38 mm diameter x 17 mm long
- Packaging: thermal design: mechanical design:	extended ground plane PCBs (to be potted for large thermal mass) provide coordinate references
- Temp. charcaterization:	-40° C, -5° C, 5° C, 27° C, 40° C

Table 1

In order to achieve large dynamic range, the amplifiers must run close to voltage supply rails causing a larger nonlinearity at fields >50000 nT. Outputs of magnetometer are directly connected to channels 1-3 of the ADC (1 nT corresponds to 33 mV). Temperature dependence of drift and scale factor is of concern. Proper thermal design and packging can alleviate this problem.

The biggest challenge of the FFM project is integration of live electronics in close vicinity of a sensitive magnetometer. Our goal is to limit total interference of the electronics and packaging materials on the magnetometer to <1 nT in the frequency range of interest (10 mHz-100 Hz).

3-2. ISS DATA SUBSYSTEM

Data subsystem design encompasses analog and digital electronics interfacing sensor subsystem. It includes power regulation and management, Analog to Digital Converter (ADC), FPGA-based control and data flow management. ADC is a high resolution 22-bit 4-channel Σ-Δ converter with noise specified at 11 μVrms. ADC chip (Analog Devices AD7716) has an internal digital filter. The output rate is chosen to be 279 words/sec. As only one out of every two data points is taken, the Nyquist frequency is 279/2/2= 69.75 Hz. The digital filter settle time is 10.8 msec. Channel 4 will measure output of four photodetectors inside the sun angle sensor periodically (each photodetector sampled every 8 measurement cycles). FPGA is a 13000 gate count chip in a plastic package (Xilinx, XC4013). The data from photodetectors occupy two subframes in the data package (16-bit word). Each frame has a total of 64 words. It starts with two synchronization words (total overhead 3%). It has a frame ID and an ISS unit ID (to identify data). The units are also distinguishable by their transmission frequencies. The data from ADC channels 1-3 are saved in 17-bit value (16 consecutive measurements of 3-axis data is stored in 51 words). It is expected that the magnetometer readings become contaminated when the transmitter is on. A 4 Mbit SRAM is used to store data before transmission (this can constitute ~7 minutes uninterrupted data acquisition). Data transmission takes about ~34 sec which is preceded by 15 sec of carrier-only broadcast. These time intervals are chosen to allow the receiver to lock to the transmitter frequency. The SRAM size can be increased to acomodate a more convenient mission scenario. It is envisioned that an aerial vehicle can receive data from a fleet of ISSs dispersed on a mine-field while flying over.

Data subsystem includes power management circuitry which turns different subsystems on/off in order to save power. Before ISS units are dispersed in a field, they will be kept in an incubator powered from an external power source via inserted-pin electrodes. This will allow unit's electronics to warm-up and stabilize. As the units are removed from the incubator, they will run on their own batteries.

3-3. ISS TRANSMITTER AND ANTENNA

A prototype transmitter has been built and tested, its block diagram is shown in Fig. 5 which consits of a Voltage-Controlled Oscillator (VCO) (Vari-L VCO-2250T) phase locked to a TCXO (Cardinal Components CTCX-A4B4-16). Temperature dependence of the TCXO in the range of -10° C to $+40^\circ$ C is shown in Fig. 6 indicating +-1 ppm total variation.

Phase lock chip is from National (LMX2330A). The synthesized frequency is in the range allocated to space-Earth communications (2200-2300 MHz). The output of the synthesizer is fed to a phase-modulator chip (RF MicroDevices RF2422). The result is a Bi-Phase Shift Key (BPSK) carrier signal which is then amplified to the appropriate level and fed to a single-patch antenna. A single-patch antenna on a 2 mm thick substrate (TMM6.060 Rogers Corp.) is designed and built by MicroPulse, Inc for the FFM project. A strip-line hybrid is used for the antenna feed. It is implemented on FR-4 substrates. Two probes connect the hybrid feed to the appropriate locations on the patch (Fig. 7). The performance data of the antenna is shown in Table 2.

- Center frequency:	2250 MHz
- Polarization:	RHCP
- VSWR (>1.5:1) BW:	80 MHz
- CP BW:	80 MHz
- Axial Ratio:	< 4 dB across the full 60° half solid angle beamwidth
- Substrate thickness:	2 mm thick high-ε microwave substrate on top of a 1.5 mm thick PCB
- Diameter of antenna disk:	77 mm
- Antenna gain at nadir:	> 2 dB CP gain
- Antenna Pattern:	better than -3 dB gain (with respect to nadir) at 30° from the nadir better than -8 dB (with respect to nadir) at 60° from the nadir
- Feed:	single point feed at the edge of the antenna

Table 2

A typical antenna pattern is shown in Fig. 8. The antenna CP gain drops from 5 dB at nadir to -1 dB at 60° off, and to -2 dB at 90° off. Axial ratio represents antenna cross-polarization levels of -21 dB at nadir, -11 dB at 60° off and -7 dB at 90° off.

A similar single patch antenna with a smaller ground plane has to be designed for the ISS mine-detection unit as we plan to place the antenna on top of the Sun-angle sensor housing.

3-4. ISS BATTERY

High-capacity $LiSOCl_2$ batteries support nearly one hour life span for a FFM unit. Dimensions of the LTC-312 battery is 2 x 17 x 37 mm. A full load test (based on the FFM mission) is depicted in Fig. 9. The wide solid line is the voltage of a single battery under load and the narrow solid line is the current. Typical load is 4.7 minutes long @ 40 mA, and 15.6 minutes @ 100 mA (middle of the graph). Prior to a typical mission there are loads corresponding to functional tests and work-in of the battery. Batteries soaked at -20° C under 0.1 A load provide the minimum voltages needed for the low-drop-out 5V regulators to function. Total of 3 pairs of batteries are needed to supply voltages for all ISS subsystems. The flux-gate magnetometer requires +/-3 V as input (+/- 60 mA current) and provides +/- 2.0 V full scale signal at X,Y,Z output ports. The transmitter requires +5V. The data subsystem interfaces with magnetometer and transmitter and it provides power management for the entire ISS mine detection unit. The data subsytem circuit will use 5V supply voltage.

The shelf life of Lithium batteries is good due to build-up of a passivation layer on the Li electrode which prevents depletion of the charged capacity (~3% depletion/year). At the same time, this passivation layer requires a "work-in" of the battery before the mission.

3-5. ISS SUN ANGLE SENSOR

The sun angle sensor (Institut fuer Aerospace-Technologie) is a wide angle sensor designed for application on small satellites. It is designed as a low-cost high precision sensor for 3-axis stabilized platforms. Wide angle sensor housing is in shape of a pyramid with a spherical field of view up to 300° (+-150° angle to pointing axis) with a resolution of ~2 degrees over full FOV. The position signal is derived out of the difference current of the four solar cells each.

4. CONCLUSION

We have described the results of our preliminary work in developing subsystems for a future minaturized integrated sensor system intended for deployment in a mine-field for multipoint investigation of the magnetic field and detection of magnetic anomaly.

Future plans will include further miniaturization of the ISS units via fabrication of a monolithic magnetometer, and low-magnetic signature ASIC design.

5. ACKNOWLEDGEMENTS

6. REFERENCES

1. R. Goldstein, M. Boehm, E. Cutting, E. Fossum, H. Javadi, L.M. Miller, B. Pain, J.E. Randolph, P.R. Turner, "A Fully Integrated Micro-Magnetometer / Microspacecraft for Multipoint Measurements: The Free-Flyer Magnetometer", *American Geophysical Union Monograph : Measurement Techniques for Space Plasmas*, (1997).
- H. Javadi, B. Blaes, M. Boehm, C. Cruzan, J. Gibbs, W. Goodman, U. Lieneweg, K. Lynch, P. Narvaez, D. Perrone, B. Snare, M. Sue, L. Turoski, K. Leschly, and R. Goldstein, "Jet Propulsion Laboratory Free-Flying Magnetometers for Distributed *In-Situ* Multiprobe Measurement of Current Density Filamentation in the Northern Auroral Zone: Enstrophy Mission", *Digest of the American Geophysical Union 1997 Fall Meeting, Special Session on Science Closure and Enabling Technologies for Magnetospheric Constellation Missions.* (1997).
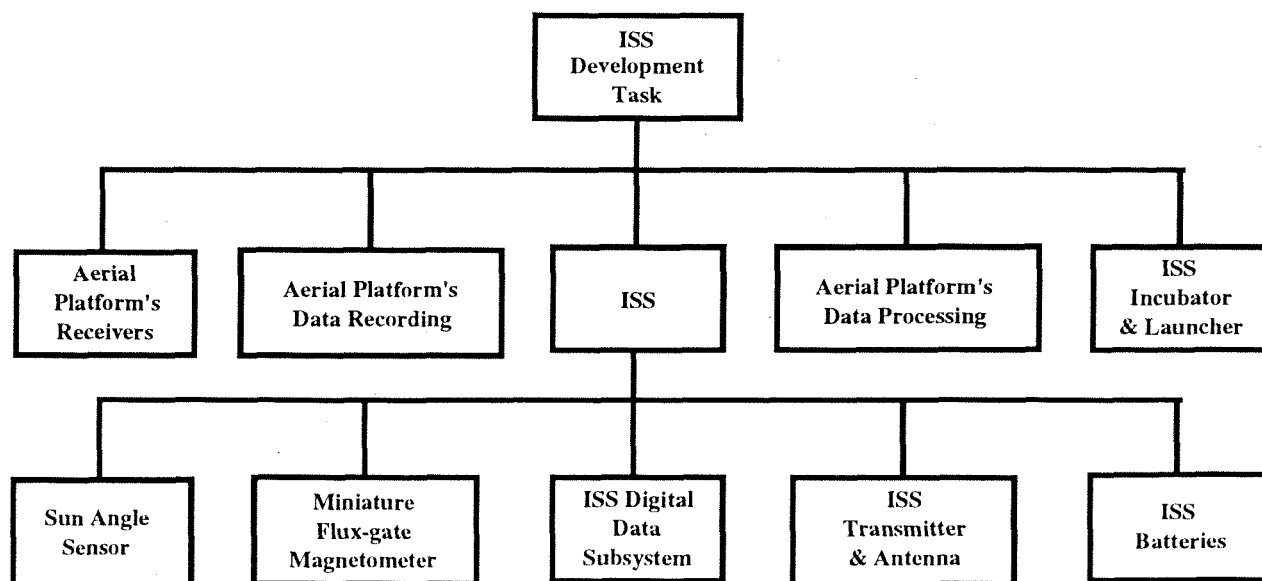

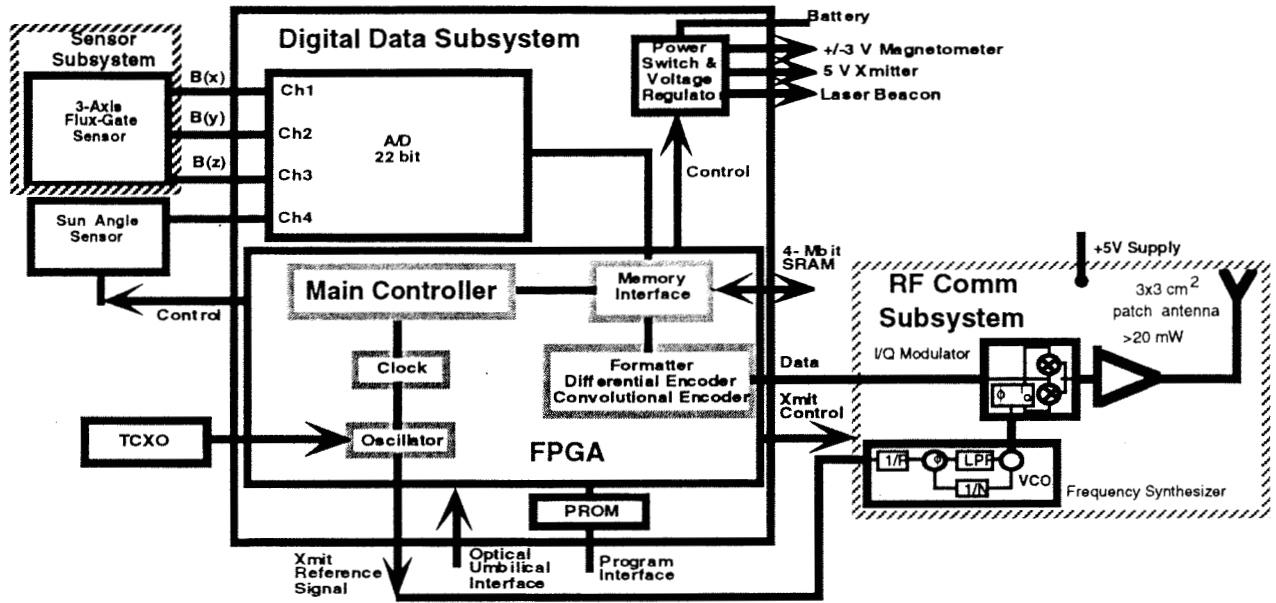**Figure 1-** Work breakdown for the proposed Integrated Sensor System (ISS).

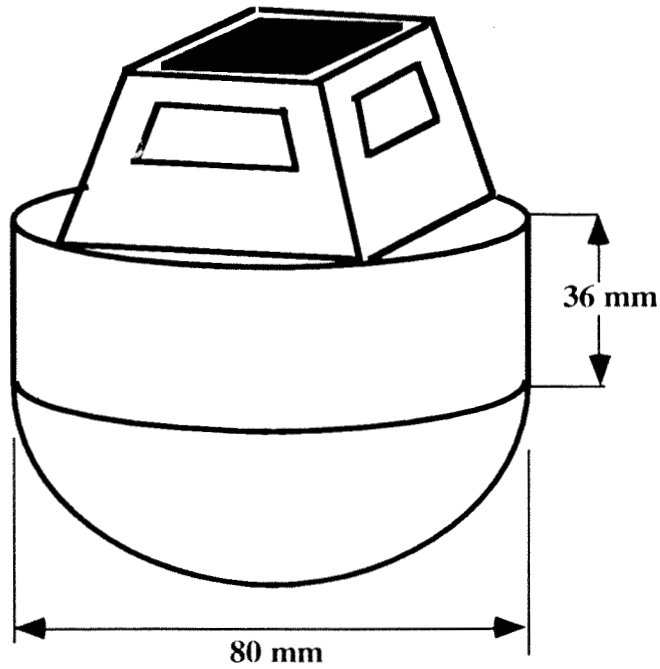**Figure 2-** The block diagram of the proposed ISS mine-detection unit.

Figure 3- A mechanical drawing for the proposed ISS mine-detection unit.
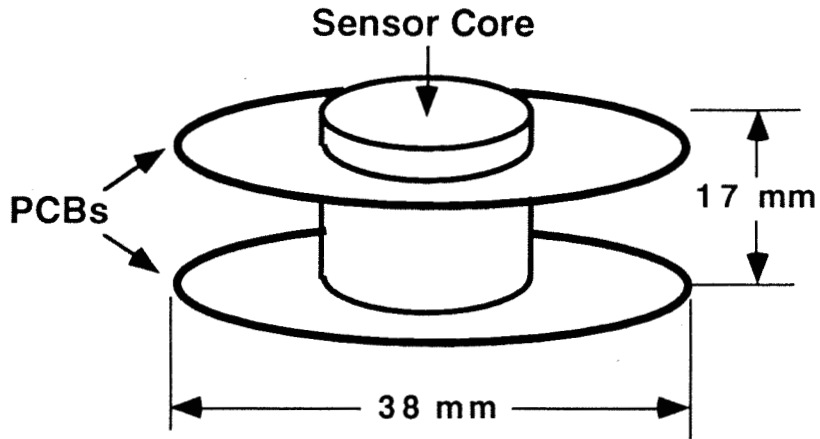
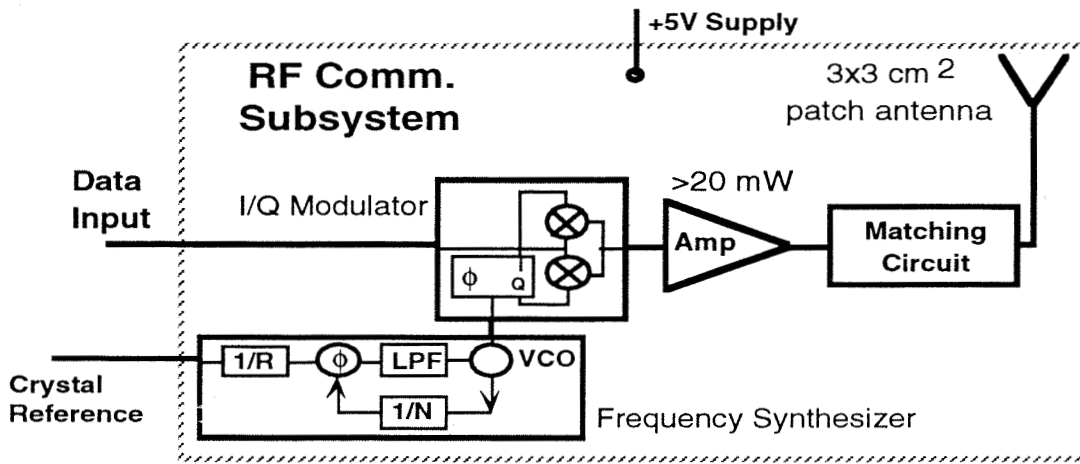**Figure 4-** Sketch of the ISS miniature flux-gate magnetometer (Applied Physics System)

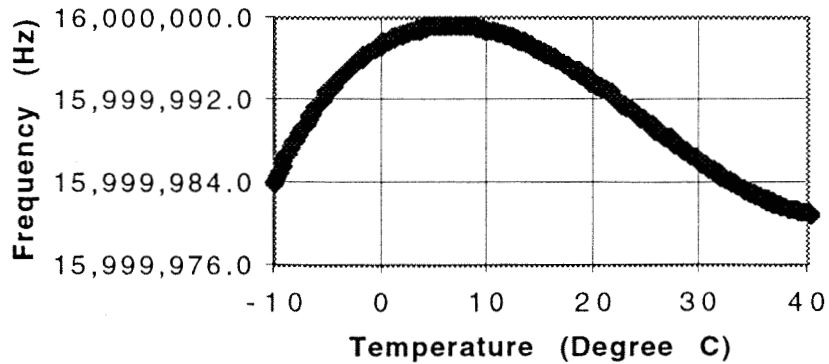**Figure 5-** Block diagram of the ISS S-band transmitter with the connected antenna.

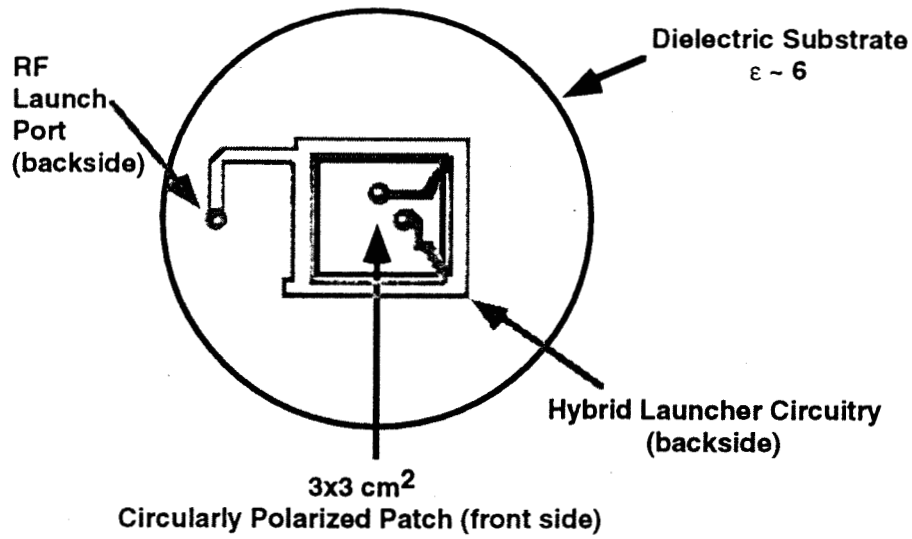**Figure 6-** Temperature dependence of the ISS 16 MHz TCXO

Figure 7- Schematic of the FFM single patch antenna, its hybrid launcher, and feed points
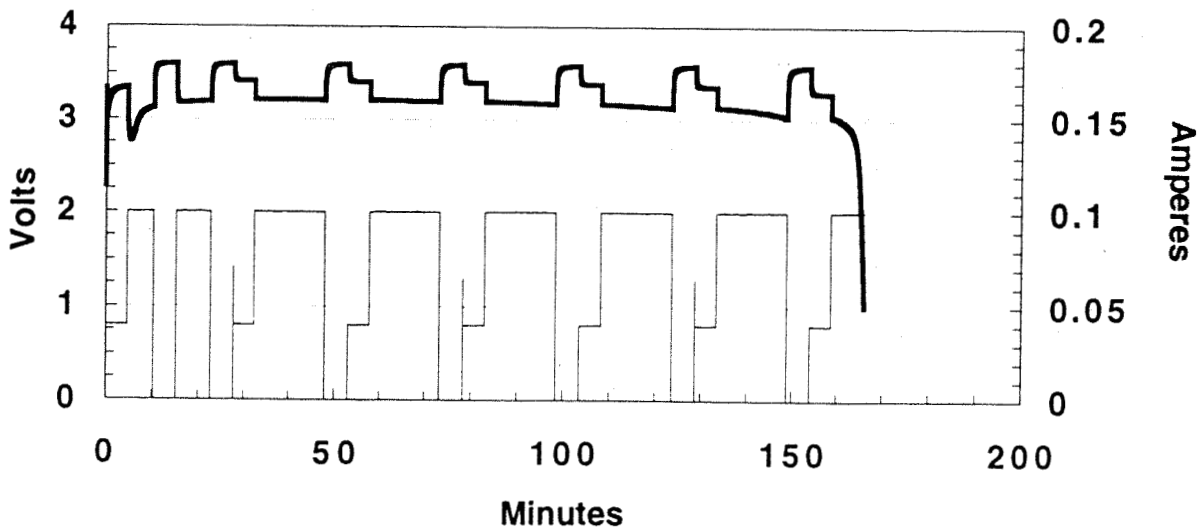

Figure 9- Capacity measurement of a single LTC-312 battery vs time. The wide solid line is the battery voltage and the narrow sold line is the load current. The load is based on a FFM mission.
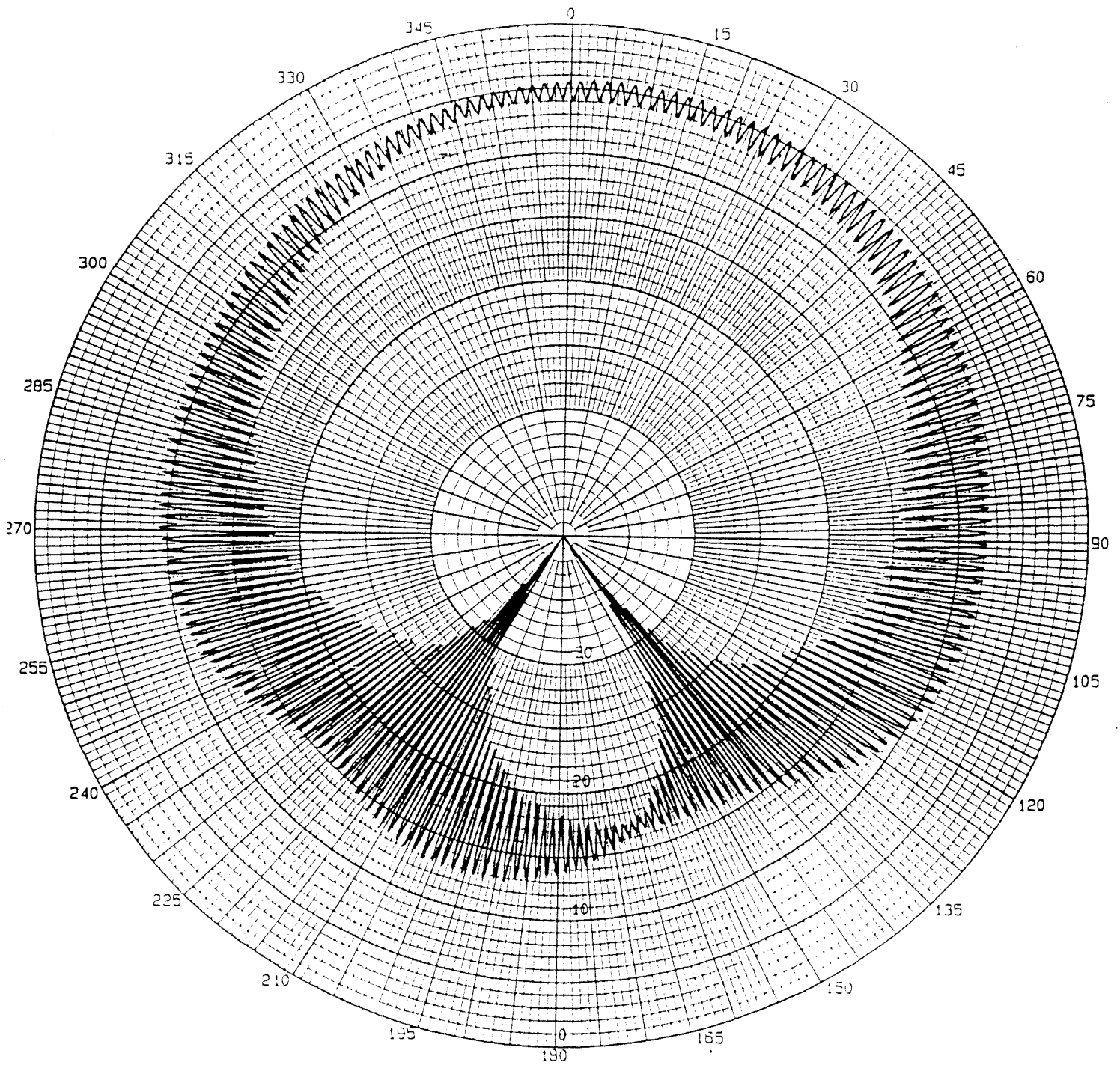
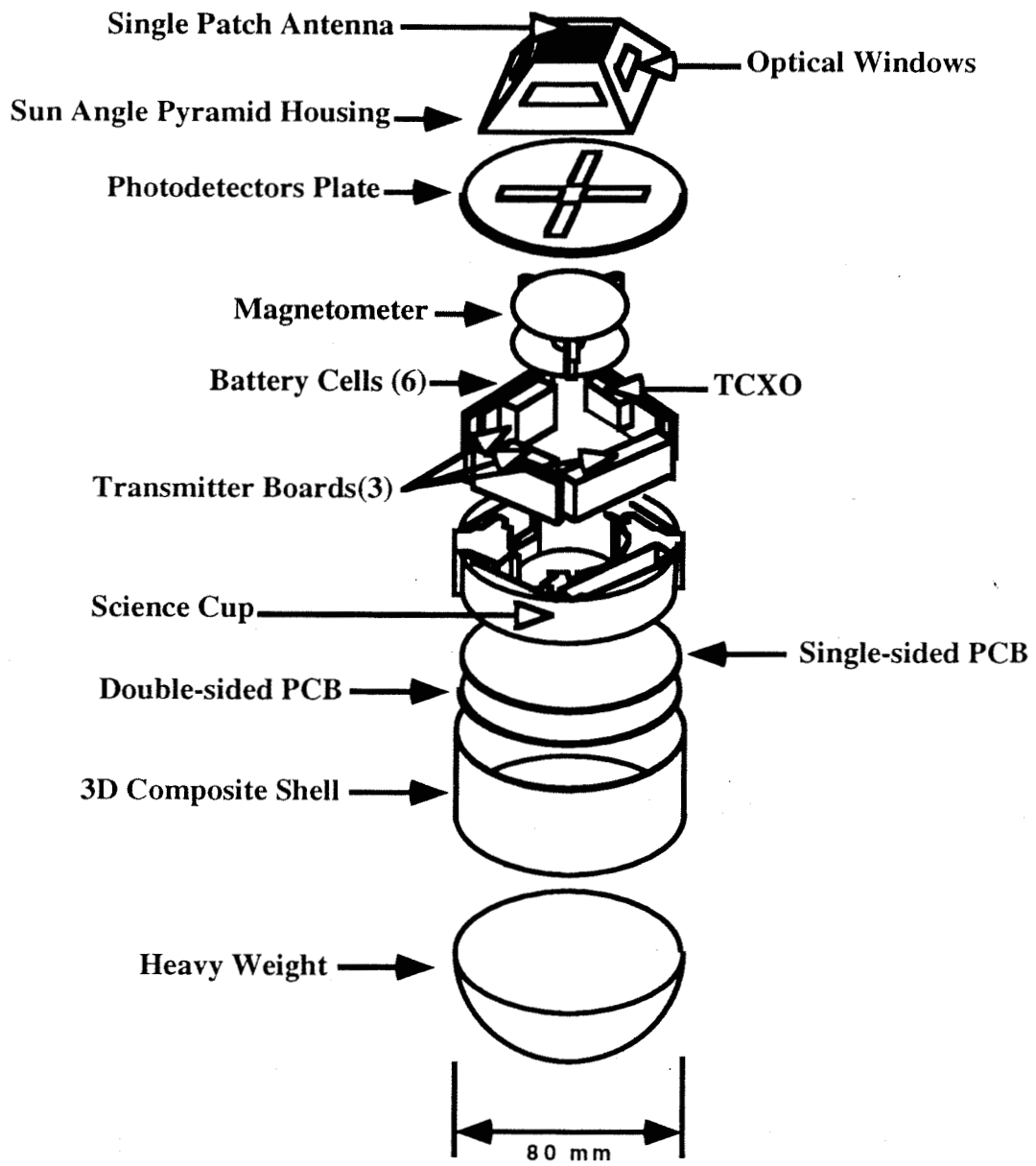**Figure 8-** A typical FFM unit antenna radiation pattern

Single Patch Antenna — Optical Windows

Sun Angle Pyramid Housing —

Photodetectors Plate —

Magnetometer —

Battery Cells (6) — TCXO

Transmitter Boards(3)

Science Cup — Single-sided PCB

Double-sided PCB —

3D Composite Shell —

Heavy Weight —

80 mm

Figure 10- Exploded view of the ISS mine detection unit.