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PRELIMINARY REPORT: DESIGN AND TEST RESULTS OF KSR-3 ROCKET MAGNETOMETERS

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ABSTRACT

The solar wind contributes to the formation of unique space environment called the Earth's magnetosphere by various interactions with the Earth's magnetic field. Thus the solar-terrestrial environment affects the Earth's magnetic field, which can be observed with an instrument for the magnetic field measurement, the magnetometer usually mounted on the rocket and the satellite and based on the ground observatory. The magnetometer is a useful instrument for the spacecraft attitude control as well as the Earth's magnetic field measurements for a scientific purpose. In this paper, we present the preliminary design and test results of the two onboard magnetometers of KARI's (Korea Aerospace Research Institute) sounding rocket, KSR-3, which will be launched four times during the period of 2001-02. The KSR-3 magnetometers consist of the fluxgate magnetometer, MAG/AIM (Attitude Information Magnetometer) for acquiring the rocket flight attitude information, and of the search-coil magnetometer, MAG/SIM (Scientific Investigation Magnetometer) for the observation of the Earth's magnetic field fluctuations. With the MAG/AIM, the 3-axis attitude information can be acquired by the comparison of the resulting dc magnetic vector field with the IGRF (International Geomagnetic Reference Field). The Earth's magnetic field fluctuations ranging from 10 to 1,000 Hz can also be observed with the MAG/SIM measurement.

Key words: magnetometer, attitude, IGRF

1. INTRODUCTION

The development of the magnetometer really began with the use of fluxgate magnetometer for the submarine detection during the World War II and since then, many kinds of magnetometers have been developed. Especially, the induction magnetometers such as the fluxgate and search-coil magnetometer, which use the Faraday's Law of induction, are relatively simple, lightweight, reliable and rugged, and therefore, their applications range from space research to submarine detection (Son

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1997). Since the late 1950s, the magnetometer has generally been regarded as the one of the important space payloads and a very useful and simple instrument, which can be used for spacecraft's attitude control and produce the valuable information for the solar-terrestrial environments. The scalar magnetometer can measure the magnitude of the magnetic field, and the magnitude and direction of the magnetic field can be measured simultaneously with the vector magnetometer. This paper presents the preliminary design and test results of the vector magnetometers which will acquire the 3-axis attitude information of the rocket and also observe the Earth's magnetic field fluctuations at the high altitude of the Korean peninsula.

2. THE SYSTEM SCHEME OF KSR-3 MAG/AIM & SIM

The KSR-3 magnetometers consist of the fluxgate magnetometer, MAG/AIM (Attitude Information Magnetometer) for acquiring the rocket flight attitude information and of the search-coil magnetometer, MAG/SIM (Scientific Investigation Magnetometer) for the observation of the Earth's magnetic field fluctuations. With MAG/AIM, the 3-axis attitude information can be acquired by the comparison of the resulting dc magnetic vector field with the IGRF (International Geomagnetic Reference Field). The Earth's magnetic field fluctuations ranging from 10 to 1000 Hz can also be observed with the MAG/SIM measurement. The whole system scheme of the MAG/AIM & SIM is shown in Figure 1. For the power supply, the rechargeable 12V batteries are used. The fluxgate sensor and the search-coil are to be installed on the 1st stage of the KSR-3 science payload mount along with other kind of sensors, and the electronics, on the below stage.

3. THE MAGNETOMETER FOR ROCKET FLIGHT ATTITUDE INFORMATION (MAG/AIM)

3.1 Scheme

After launching the rocket, the trajectory and the attitude of the rocket can be measured by the onboard instruments such as INS (Inertial Navigation System). But actually, due to the various factors which the rocket may undergo through the flight, the expected results may not be acquired. In order to get the information for the rocket flight trajectory and attitude and to control them, the INS, sun-sensor, star-sensor and magnetometer are used for complement and redundancy, for the spacecraft might go through the unpredictable space environment or the trouble of the rocket system. In general, these attitude determination and control can be performed with feedback system, that is, attitude sensors send attitude data to an onboard computer which determines the attitude and then activates the control hardware (Wertz 1978). In KSR-3, however, only INS has feedback system. The main objective of MAG/AIM is to acquire the 3-axis attitude information of the rocket by the comparison of the resulting dc magnetic vector field with the IGRF after the mission. Figure 2 shows the diagram of this method. The data from this rocket magnetometer can be used basically for acquiring the attitude information and for the scientific purpose as well.

3.2 Principle of Operation

The ferromagnetic core (or cores) of the sensor is driven cyclically to saturation by means of a periodic driving current of suitable wave shape in the driving coil. In the absence of a external field, the voltage induced in the sensing coil is symmetrical, that is, contains only odd harmonics of

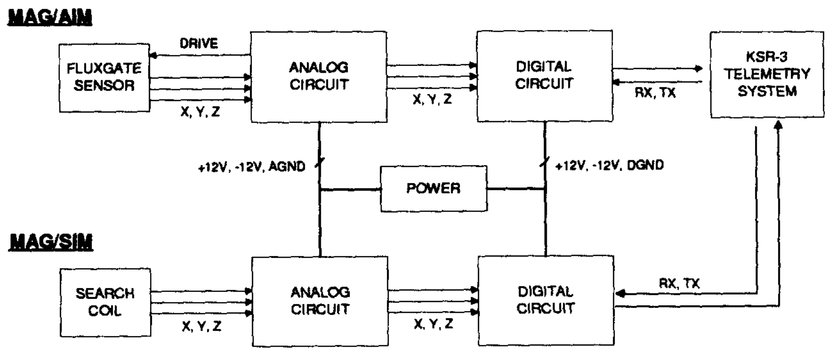

Figure 1. The system scheme of KSR-3 MAG/AIM & SIM.

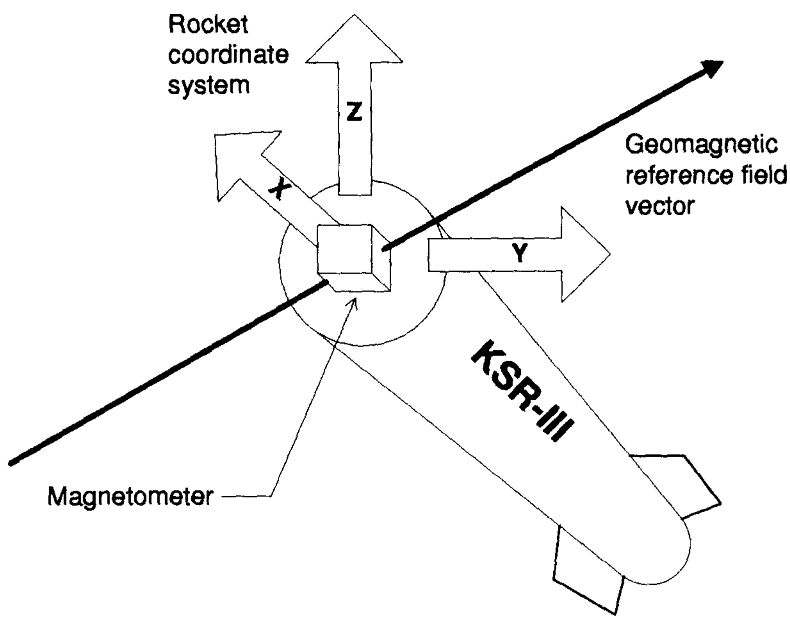

Figure 2. The measurement of the rocket flight attitude using magnetometer and geomagnetic reference field.

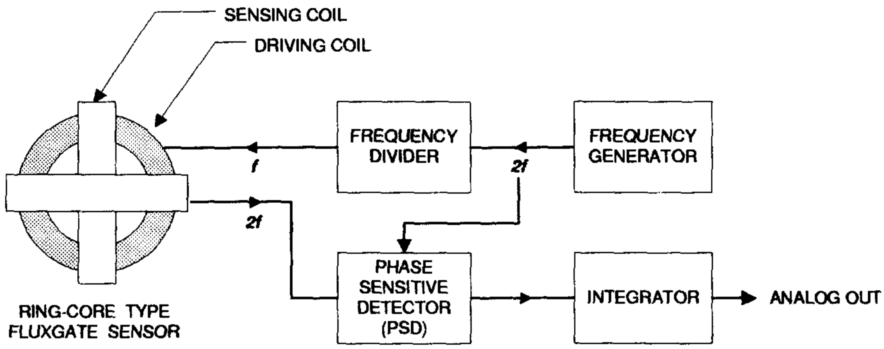

Figure 3. MAG/AIM sensor and circuit diagram.

the fundamental of the driving current. In the presence of a field, the sensing coil voltage becomes asymmetrical. This asymmetry is sensitively related to the external field and can be detected by phase sensitive detector (PSD) (Gordon & Brown 1972). Ripka (1992) presented the basic analytical description by starting from the Faraday's Law of induction:

$$V_i = NA\frac{dB}{dt} = NA\mu_o H_{ex}\frac{(1-D)}{[1+D(\mu-2)]^2} \tag{1}$$

where V_i is the voltage induced in the measuring coil having N turns, B is the magnetic flux density in the coil as we neglect the air flux, A is the core cross-sectional area, H_{ex} is the measured magnetic field outside the sensor core, D is the effective demagnetizing factor, and μ (t) is the sensor core relative permeability. This fluxgate equation shows the time dependence of the core permeability is caused by the excitation field. The size of the core affects the sensor sensitivity. Although the problem is complex due to the demagnetization effect and non-linearity, the sensitivity generally increases with the sensor diameter. With a given diameter, there is always an optimum of the other dimensions for maximum performance. Consequently, the size of the sensor and numbers of turns basically depends on the demagnetization factor and the permeability of the core material (Ripka 1992). In MAG/AIM, 20 mm diameter ring-core sensor is used, which is adequate to space applications.

3.3 Fluxgate sensor and Electronics

The MAG/AIM sensor and circuit diagram is shown in Figure 3. The two windings of sensing coil wound on the ring-core type driving coil are at right angles to each other in order to measure the 2-axis component of magnetic field. For the 3-axis measurement, one more sensor like this, which forms an angle of 90° with each other, should be arranged as shown in Figure 4 (Hwang et al.1997). The sensor is excited by the frequency generator working at the frequency f (in case of MAG/AIM, 20 kHz). The sensing coil detects a time-varying voltage that is related to the input through the hysteresis curve of the core material, and the amplitude and phase of all even harmonics are proportional to the magnitude and direction of the field along the sensing coil axis. These changes of the amplitude and phase are detected by PSD. The generator circuits also produce the $2f$ square

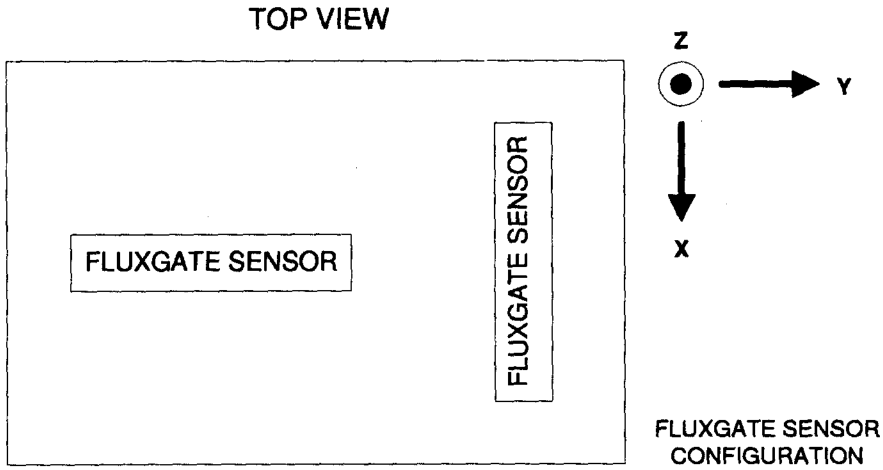

Figure 4. Top view of fluxgate sensor configuration.

wave signal as a reference for PSD. MAG/AIM is so designed as to reach the 0.1 nT resolution in the range of ±60,000 nT, which would be proper specification for aspect magnetometer onboard at the sounding rockets and satellites in the Earth's magnetic field range. For the improvement of the sensitivity of the fluxgate sensor, the modifications of the electronics relating to driving signal and PSD have been made (Figure 5). The permeability of the core and the strength and the frequency of the driving current (upper signal, top in Figure 5) are chosen so that the core is driven into saturation on each half cycle of excitation (lower signal, top in Figure 5).

3.4 The Acquisition of Rocket Attitude Information

The measurement of rocket attitude can be performed by using the reference vector field, IGRF and calculating the difference between the rocket-resulting data and the reference field, that is, the 3-axis vector components relative to the reference axes can be obtained through the process of the Euler transformation. IGRF is a theoretical model of the Earth's magnetic field and defined as follows:

$$V(r,\theta,\phi) = a\sum_{n=1}^{k}(\frac{a}{r})^{n+1}\sum_{m=0}^{n}(g_n^m \cos m\phi + h_n^m \sin m\phi)P_n^m(\theta) \qquad (2)$$

where a is the equatorial radius of the Earth, g_n^m and h_n^m are called Gaussian coefficient, r, Θ, and ϕ are the geocentric distance, coelevation, and east longitude from Greenwich, and $P_n^m(\Theta)$ are associated Legendre functions. Therefore, if the latitude, longitude, and altitude at the arbitrary region of interest are given, the vector components and magnitude of the Earth' magnetic field are calculated. To perform this, the latitude, longitude, and altitude at which the rocket flies are needed, and they may be obtained through the measurements by the tracking radar or GPS. But the intense variations of the Earth's magnetic field due to some reasons such as the solar activities and the

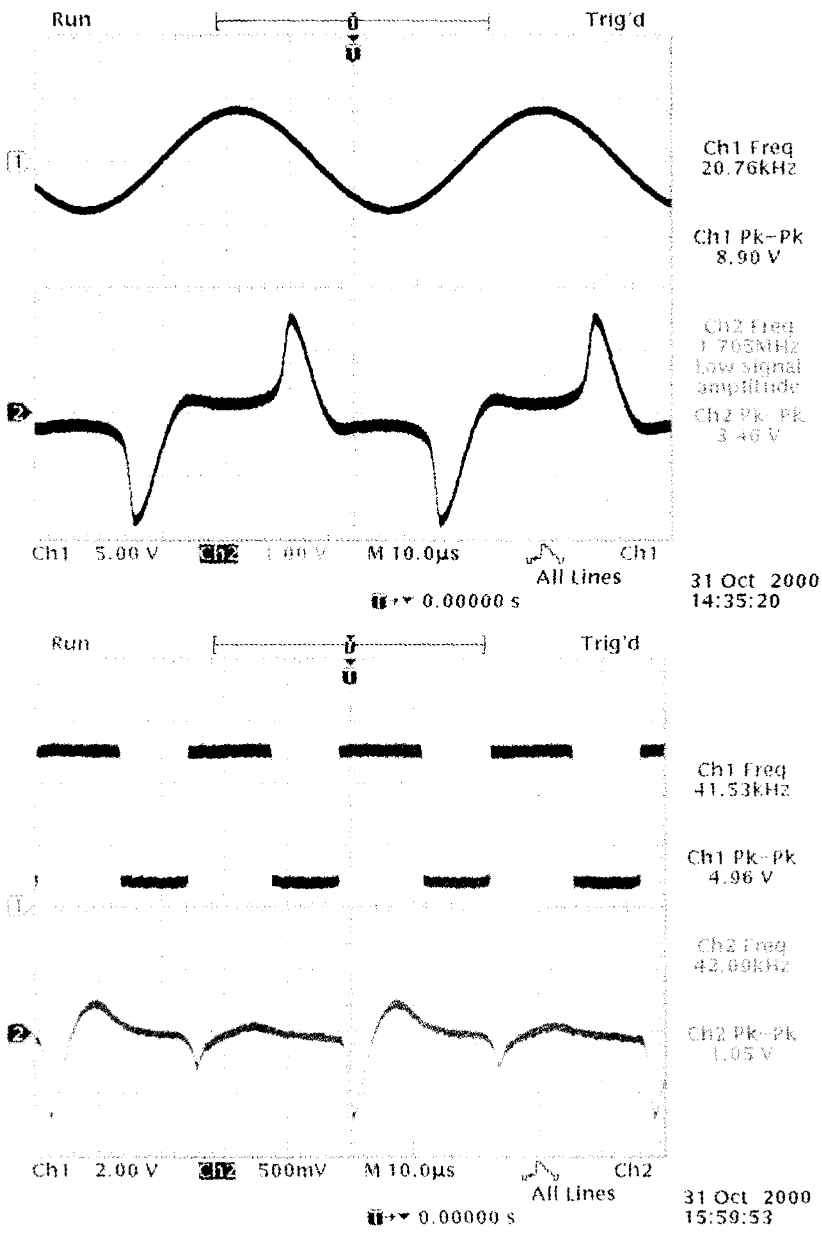

Figure 5. 20 kHz sine wave driving signal applied to driving coil (upper signal, top), induced voltage (lower signal, top), 2f reference signal of PSD (upper signal, bottom) and resulting second-harmonic signal from the sensing coil (lower signal, bottom).

Table 1. Angular errors (deg) using truncations of IGRF (1965) (Wertz 1978).

Altitude	Degree 1 (dipole)	2 (quadrupole)	3	4	5	6	7
Surface (R=1 Earth radius)							
Maximum (nT)	32	21	8	5	2	1	0.4
RMS (nT)	10	7	4	2	1	0.4	0.2
300km above surface							
Maximum (nT)	29	19	7	4	2	0.8	0.3
RMS (nT)	10	7	3	1.3	0.8	0.3	0.1

Table 2. Field truncation errors (nT) using IGRF (1965) (Wertz 1978).

Altitude	Degree 1 (dipole)	2 (quadrupole)	3	4	5	6	7
Surface (R=1 Earth radius)							
Maximum (nT)	20255	13905	8125	3452	1819	858	268
RMS (nT)	10231	6942	3685	1640	855	364	129
300km above surface							
Maximum (nT)	16367	10844	6110	2440	1244	564	169
RMS (nT)	8281	5431	2764	1171	587	240	81

rocket dynamics - vibration, spin, coning motion, etc. may be regarded as the error sources. For the reduction of errors resulting from the rocket dynamics, enough data sampling rate is basically needed. Another error source is in the field model itself. If IGRF is modeled to higher degree (n in eq. (2)) and order (m in eq. (2)), it remarkably shows the reducing error. An estimate of the error resulting from the truncation can be obtained by comparing the full field model with its truncated forms, as shown in Table 1 and Table 2. Studies on more accurate modeling using IGRF and reliable measurement with MAG/AIM are left for later discussion.

4. THE MAGNETOMETER FOR THE EARTH'S MAGNETIC FLUCTUATION MEASUREMENT (MAG/SIM)

4.1 Scheme

MAG/SIM will give the valuable information for the ionospheric structure by comparing the measurements of the local magnetic fluctuations at the altitude of 100 $\sim$ 200 km with the satellite's magnetometer data. This instrument can measure the magnetic fluctuations between 10 Hz $\sim$

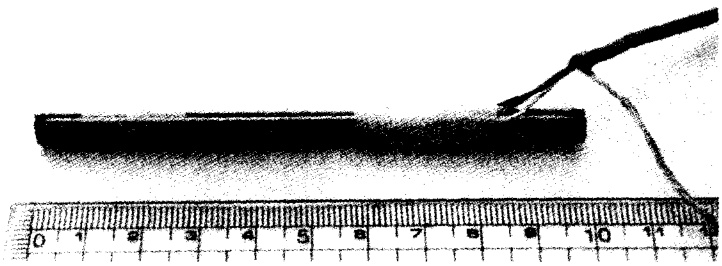

Figure 6. One set of the sandwich-shaped search-coil which consists of two coils.

1,000 Hz in the space around the Earth, which is particularly interesting because it includes some of the characteristic frequencies associated with the ionospheric and magnetospheric plasma. These characteristic frequencies determine the properties of the mode in which electromagnetic waves can propagate (Frandsen et al. 1969).

4.2 Principle of Operation

Its operation is based upon the Faraday's law of induction. The voltage V induced in the coil is equal to time rate of change of magnetic flux:

$$V = -\frac{d}{dt}(A\mathbf{n} \cdot \mathbf{B}) \tag{3}$$

where A is the effective coil area, $\mathbf{n}$ is a unit vector in the direction of the coil axis, and $\mathbf{B}$ is the ambient magnetic field (Frandsen et al. 1969). With search-coil magnetometers, the dynamic range of the coil output voltage may become very large if both the magnetic field amplitude and the frequency vary greatly. In order to get a field proportional output or registrations of the true shape of magnetic waveforms, the time integral of the output voltage must be formed (Boll & Overshott 1989). The dynamic range of MAG/SIM may also become very large according to the change of external field, but the 16-bit data process limits the range to approximately $\pm$3,000 nT in the resolution of 0.1 nT.

4.3 Sensor and Electronics

For space applications, where space and weight limitation are severe, it is desirable to increase the flux density through the coil by using highly permeable magnetic cores. Because the effective permeability of the core depends upon the ratio of its length to diameter, the simplest design becomes a long thin core with a helical coil winding. For the search-coil sensor core material, the permalloy, ferrite, and amorphous ribbon, which have high permeability, are generally used. In MAG/SIM, the amorphous ribbon has been chosen, which has relatively low coercivity and low demagnetizing factor. If the sensor core is miniaturized, the demagnetizing factor decreases accordingly.

The search coil for MAG/SIM consists of 4 layers of 0.1 mm diameter enameled copper wire wound on the laminated core of high permeability amorphous ribbon, which is 5 mm wide, 100 mm

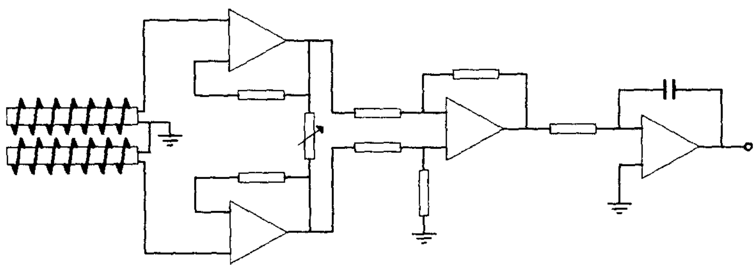

Figure 7. The diagram of MAG/SIM electronic circuit.

long, and 2 mm thick. By putting these two search-coils together, the one set of complete search-coil for 1-axis measurement is constructed. This type of sandwich-shaped search-coil can reduce the noise from the sensor itself and improve the sensitivity by the instrumentation amplifier connected to the sensor. Figure 6 shows the photographs of the EM (Engineering Model) of MAG/SIM search-coil. Figure 7 shows the circuit diagram of MAG/SIM, which has a very simple electronics (instrumentation amplifier and integrator) and low power consumption of $\sim$ mW.

MAG/SIM is designed to observe the Earth's magnetic field fluctuations ranging from 10 to 1,000 Hz and this frequency domain can be set up by the design of the sensor and electronics, that is, the adjustment of the RC value in the integrator can set up the measured minimum frequency, and the material and skin depth of the sensor shielding case, the maximum frequency. For the shielding case that can cuts off the frequency, non-magnetic material such as aluminum or copper should be used. The skin depth (δ) is defined as follows:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}(m) \tag{4}$$

where f is frequency, μ is the permeability in a free space ($= 4\pi \times 10^{-7}$H/m), and σ is the conductivity of the material. In case of aluminum, the skin depth is about 2.67 mm at 1 kHz because the conductivity of aluminum is 3.54×10^7S/m. That is, in the piece of aluminum of this thickness, the amplitude of the traveling plane wave is attenuated as much as $e^{-1}(0.368)$. By adjusting the gain of the amplifier to become 1 μT/V, the ratio between the reference field applied to the sensor and the converted voltage output from the circuit, the resolution of 0.1 nT and dynamic range of $\pm$3,000 nT have been achieved.

5. DIGITAL PROCESS

The six signals from the analog circuit of MAG/AIM and MAG/SIM, which have the three signals, X, Y, and Z, respectively, are fed to the 16-bit analog to digital converter through the MUX for the selection of such signals as shown in Figure 8. For the proper resolution of the system, the data process should be performed with at least 16 bits. Since the telemetry system of KSR-3 consists of 8-bit channel of 800 samples/sec and only one channel is assigned to MAG/AIM & SIM, the 16-bit signals from ADC should be divided into two 8-bit signals and fed to the telemetry system by the microprocessor. Consequently, an 8-bit channel of 800 samples/sec becomes 16-bit channel

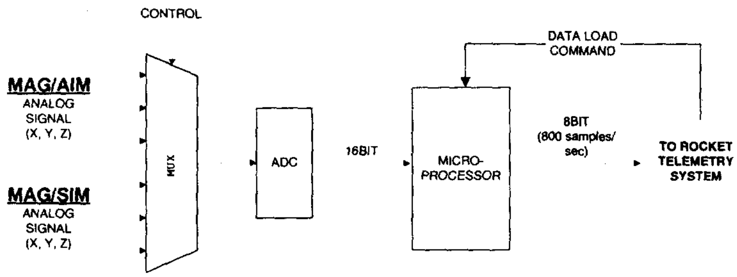

Figure 8. The diagram of digital process of MAG/AIM & SIM.

of 400 samples/sec. This means that each axis of MAG/AIM is to be measured with the sampling rate of 100 samples/sec and that of MAG/SIM, of ~33 samples/sec if the measurement of the two magnetometers are done in the ratio of 3 to 1. Because of the limitation of the telemetry channel assigned to KSR-3 MAG, MAG/SIM data showing the magnetic field fluctuations ranging from 10 to 1,000 Hz will be transformed into frequency spectrum with ~33 samples/sec, while MAG/AIM will transmit the data in the time domain with 300 samples/sec. The DSP (Digital Signal Processor) for this transformation is to be developed. The microprocessor can control the proportion of MAG/AIM and MAG/SIM signals, which is fed to the 8-bit channel of the rocket telemetry system, and will transmit the data only with the data load command from the telemetry system.

6. THE ARRANGEMENT OF SENSORS ON THE KSR-3 SCIENCE PAYLOAD MOUNT

Each sensor will measure the 3-axis components of the magnetic field, X, Y, and Z, and the coordinate system is identical with that of KSR-3 as shown in Figure 11. That is, X is defined as the roll axis of the rocket, Y as the axis perpendicular to the surface where the nose fairing is done, and Z as its right hand system. +Y-direction points toward the opposite side of the launch platform. Though there are no particular requirements for the attitude control of the spacecrafts when the sensors are installed on the payload mount, the rocket dynamics and electromagnetic interferences from the electronic circuits and other payloads should be considered. The sensor of the MAG/AIM is in a plastic case, which will measure the 3-axis components together, while MAG/SIM keeps three sensors that will measure the 3-axis components, X, Y, and Z separately to the edge of the mount.

7. VIBRATION TEST

For the verification of payload's durability in the space environment, the vibration test, one of the rocket environmental tests in component level, was taken on Jan. 11~12 and Aug. 23~24. The tests were made with the acceleration of ~14 Grms over the frequency range of 20~2,000 Hz in random vibration, and ~2 G over 5~200 Hz range in sine vibration. Each test was performed in X, Y, and Z-direction, respectively. The durability for the vibration was verified by mechanical damages, electrical contacts, and reliability of the electronic circuits being checked. In particular, the stability of the driving signal during the vibration is an important criterion for MAG/AIM as

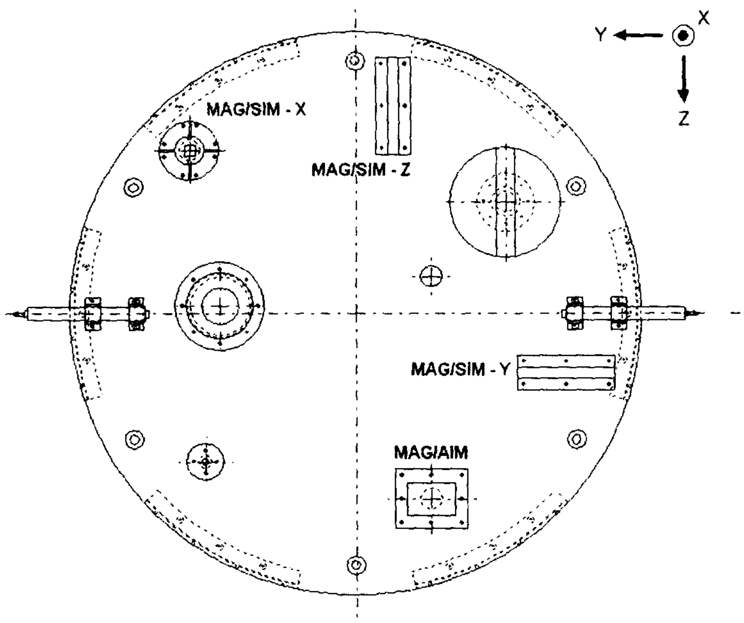

Figure 9. The arrangement of sensors on the KSR-3 science payload mount.

shown in Figure 5, and in MAG/SIM, it was checked whether the sensor could detect the frequency of the shaker, which originates the regularly varying magnetic field. After the tests, it was found that there were no problems in keeping on a normal condition.

8. CONCLUSION

In this paper, we discuss the preliminary design and test results of the two magnetometers onboard the KARI's sounding rocket, KSR-3. In addition, the durability in the space environment has been verified through the vibration tests done in twice. Though MAG/AIM is for the measurement of dc magnetic field and MAG/SIM is for the magnetic field fluctuation observation, these two magnetometers are expected to be used complementarily through the modifications (e.g. frequency range adjustment) and data analysis. The acquisition of rocket attitude information, the main objective of MAG/AIM, may not be achieved properly if there are unpredictable magnetic disturbances such as magnetic storm. Therefore, to produce the data efficiently, the simultaneous measurements by other payloads or proper data analysis algorithms are needed. This fluxgate magnetometer for the attitude information should be able to cover the whole range of the Earth's magnetic field with the proper resolution, and to sample the data sufficiently to reduce the errors due to the external electromagnetic noise and rocket dynamics. Through the improvement of the sensitivity of the fluxgate sensor, the modifications of the electronics relating to driving signal and PSD have been performed. Since the main objective of MAG/SIM is to measure the ac Earth's magnetic field, the frequency range setup based on the scientific objectives has to be considered properly. To get more scientific data with MAG/SIM, the boom deployment and the study on the electromagnetic interference should be taken into consideration as well as the proper data analysis algorithm for the error reduction, in the same way as MAG/AIM. The magnetic field measurements using Korea's first rocket magnetometers will be very meaningful space experiments, which would play a crucial role in the study of the Earth's magnetosphere where the satellites generally cannot cover.

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