Low-Frequency Magnetic Fields Near the ASRG Engineering Unit

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Summary

Reconnaissance measurements of magnetic fields from DC to 800 Hz were performed at the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU) test facility at NASA Glenn Research Center. The purpose was to determine actual limits to the ASRG EU magnetic fields, because (1) the military standard specified for conformance is much higher than acceptable for geophysical and space-physics measurements and is indeterminate below 30 Hz, and (2) the measurements cited from development test results are ambiguous. Although the broadband signature of the ASRG EU could not be separated from the lab background, the upper limit to magnetic emissions at 1-m distance is ~60 dBpT/√Hz (1 nT/√Hz) at 1 Hz and follows a spectrum no worse than 1/f. This is still large, however, compared to many natural magnetic fields. The piston frequency of the ASRG EU at 102.9 Hz was readily distinguished; although its peak value at 1-m distance is ~90 dBpT/√Hz, it can be easily filtered out due to its narrowband nature. The DC magnetic signature was not separable due to a large magnet in a nearby vacuum pump. Detailed, broadband characterization of the ASRG EU in a magnetically controlled environment is recommended for any Discovery mission in Phase A making electromagnetic measurements.

1. Introduction

The ASRG Functional Description, document number 16 in the Discovery library (hereafter denoted DDOC-16, gives the following electromagnetic (EM) specifications for the ASRG:

4.4 Electromagnetic Compatibility and Interference

The ASRG is compliant with MIL-STD-461F for space power applications.

4.4.1 Magnetic Field Emissions

ASRG magnetic field emissions are not controlled by requirements. The values described in this section are characteristics derived from development test results.

4.4.1.1 DC Magnetic Field Emissions

The total ASRG dipolar magnetic field vector will not exceed 90 nT, when measured at 1 m from the geometric center of the ASRG when operating at maximum BOM power, at 28 volts output.

4.4.1.2 AC Magnetic Field Emissions

With the ASRG operating at nominal condition, the H-field emissions will not exceed 120 dBpT when measured at 1 m from the geometric center of the ASRG.

Because MIL-STD-461F was developed to control electrical-equipment interference, its acceptable levels of electromagnetic emissions are high compared to ambient fields that would be measured in geophysical or space-physics research. DDOC-16 does not specify whether the Army (RE101-1) or Navy (RE101-2) standard is used for magnetic emissions. The Navy standard is more conservative, up to 44 dB lower than the Army. Furthermore, the 120 dBpT (1000 nT) limit to AC magnetic field emission at 1 m in DDOC-16 does not specify a frequency band.

Conventional EM measurements report spectral density, i.e., power/Hz or amplitude/√Hz. MIL-STD-461F is converted to spectral density and a measurement distance of 1 m as follows: Emission tests in MIL-STD-461F (§4.3.10.3) are made in 10-Hz bandwidths from 30 Hz to 1 kHz. Therefore the specified limits must have 10 dB subtracted to convert to 1-Hz bandwidth. Note that the specification does not go below 30 Hz. Measurements of radiated magnetic field emissions (RE101, §5.16) are made at a distance of 7 cm from the equipment under test (EUT), with the pickup loop rotated until the maximum signal is obtained. Assuming the target behaves as a dipole, signals at the 1-m distance specified in DDOC-16 would be 37 dB lower than given by MIL-STD-461F (this accounts for the 17-cm difference between the DDOC-16 distance being measured from the geometric center of the ASRG whereas MIL-STD-461F measures from the face of the EUT, i.e., 24 cm from the geometric center). In total, the dBpT given in RE101-1 and RE101-2 should be reduced by 47 B to convert to dBpT/√Hz at 1 m for a dipole-like EUT. The conversion of the Army specification is plotted in Figs. 1 and 2. Above 1 kHz the MIL-STD-specified bandwidth increases but these frequencies were not tested here.

Given that the Army standard exceeds 1000 nT/√Hz at 30 Hz and the DDOC-16 AC limit of 1000 nT does not specify a bandwidth—and that both of these figures are large compared to natural AC fields typically in the pT/√Hz to nT/√Hz range—it is evident that better characterization of the ASRG EU magnetic emissions are required for any missions measuring natural EM fields. The 90-nT limit in DDOC-16 for DC magnetic field at 1 m is straightforward as it involves no time variation, although the meaning of "dipolar" magnetic field in this context is unclear.

2. Methods

Time series of the ambient magnetic fields were recorded by search coils and by a fluxgate magnetometer. Joint search-coil and fluxgate measurements are often used to span frequencies << 1 Hz to tens of kHz. The fluxgate was the Bartington Mag-03 IE with a noise floor < 5 pT/√Hz at 1 Hz. The fluxgate noise floor is approximately constant from 1 Hz to 4 kHz; it increases as 1/√f at low frequencies and is cut off by the fluxgate drive at high frequency. The 18" search coils were custom research units fabricated by Quasar Federal Systems (QFS), Inc. of San Diego, CA. They use feedback to obtain a nearly flat noise floor <20 fT/√Hz from 100 Hz to 30 kHz, which increases as 1/f above and below. Because the performance crossover between the two sensor systems is near 1 Hz, the search coils are more sensitive over most of the frequency band investigated here, but only the fluxgates can record DC. Analog outputs were digitized by high-speed, 24-bit National Instruments ADCs, although only a modest sample rate of 1667 samples/sec was used for this study. A Labview program on a laptop PC controlled the data acquisition and spectral analysis was performed in Matlab.

All measurements were made at 107 cm above ground level, using stacked boxes to provide a reference plane 13 cm below the ASRG EU vertical geometric center. The sensors and support electronics shared this surface. The Lexan-enclosed ASRG EU test facility is part of a much larger, crowded work and laboratory space, restricting the positions at which measurements could be made. The five distances measured were therefore at different azimuths from the ASRG EU. The "x" component was always directed towards the ASRG EU and is therefore approximately the radial component; conversely "y" is the horizontal transverse component. Because only two search coils were available, repeat measurements were used to acquire the z-component.

The DC component (temporal average) was subtracted from all signals prior to spectral processing. Two-pole Butterworth filters removed 60-Hz energy and all its harmonics. The time series were Fourier transformed following application of a Hanning window and adjusted to amplitude density per root hertz. These spectra were divided by the complex (amplitude and phase) frequency-dependent gain functions to compensate for sensor response.

3. Results

3.1 Broadband Spectra

The full spectra of representative measurements at each of the stations are given in Figure 1 (search coils) and Figure 2 (fluxgate). These plots show the resultant horizontal component derived from the two horizontal components (the rationale for this is discussed further in §3.2 below). The main features are (1) a nearly uniformly "red" background, with a frequency dependence just under 1/f, (2) an apparent flattening below ~1 Hz, and (3) several high-amplitude narrowband features. Among the last, the ASRG EU piston frequency near 100 Hz is the largest, but several other strong unidentified signals are present, particularly at 11 and 30 Hz.

Apart from the narrowband piston signal, it is hard to distinguish unique emissions from the unit. The strongest overall signal is from 1-m distance, but amplitudes at other distances do not fall off monotonically. This is likely dominated by emissions from other equipment. The net measurement at 1 m may still be useful, however, as an interim upper limit on the AC emissions from the ASRG EU, approximately 1 nT/√Hz at 1 Hz and with a spectral slope no larger than 1/f.

The broadband emissions at the ASRG EU facility are far less (~80 dB) than the Army MIL-STD-461F, and still ~40 dB below the corresponding Navy specification. However, the broadband amplitudes are about an order of magnitude higher than observed with the same instruments in other indoor tests, and 2−3 orders of magnitude higher than natural magnetic fields on Earth at 1−100 Hz. The apparent flattening of the measured spectra below 1 Hz suggests that terrestrial geomagnetic signals <0.1 Hz, for example, could be detected, but longer time series with the fluxgate would be necessary to confirm this.

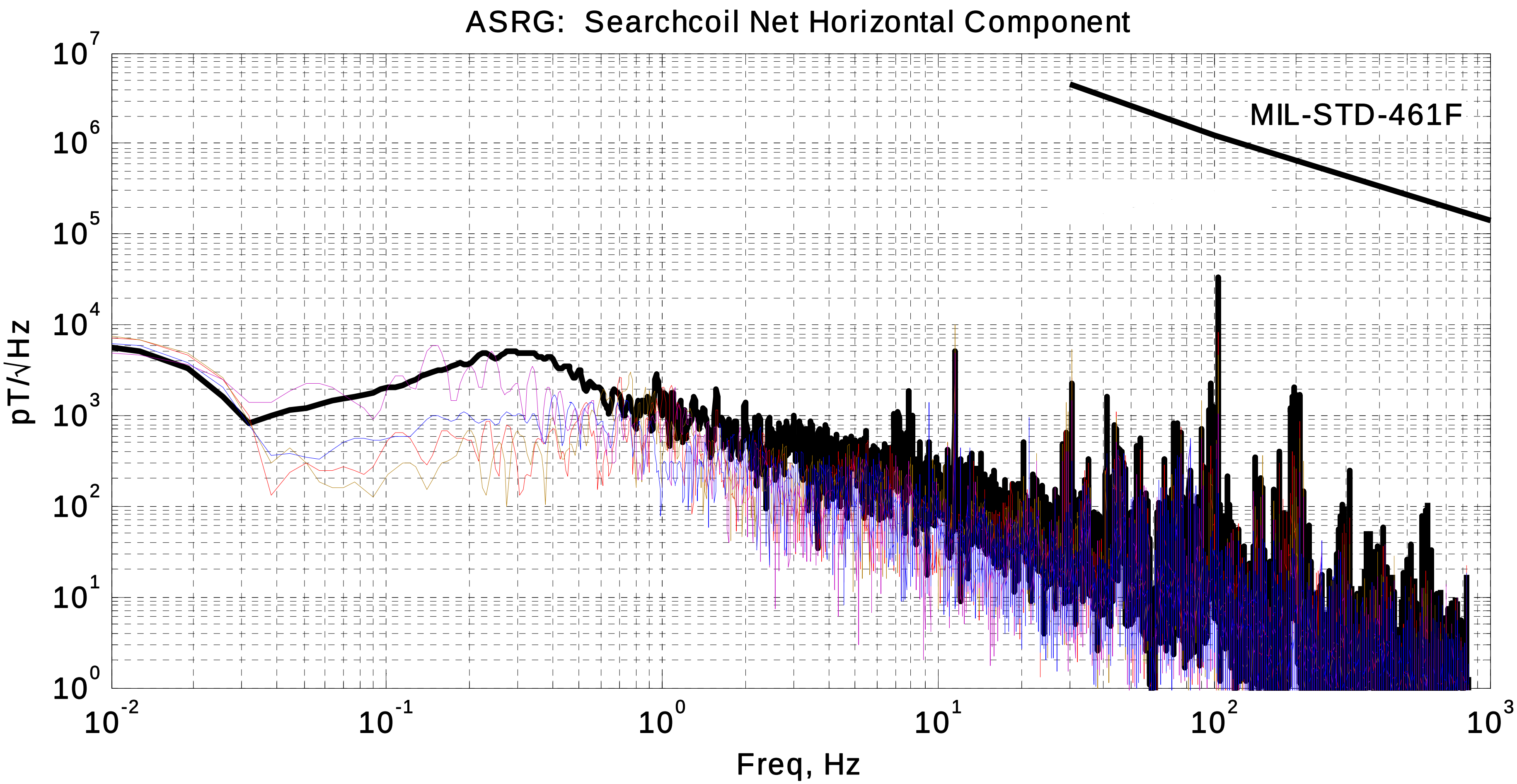


Figure 1. Low-frequency magnetic spectra in the vicinity of the ASRG EU, measured with custom search coils. The quantity plotted is the square root of the sum of the horizontal power. The ASRG EU piston frequency near 100 Hz is the largest signal; other narrowband signals are likely other lab equipment. Overall amplitude spectrum behavior is near 1/f and is ~80 dB down from the Army standard in MIL-STD-461F (plotted) and at least 40 dB down from the Navy standard. Broadband amplitudes are nonetheless high relative to nominal environments.

Black – 1 m distance, Red – 1.5 m, Brown – 2 m, Violet – 3.2 m, Blue – 5.7 m.

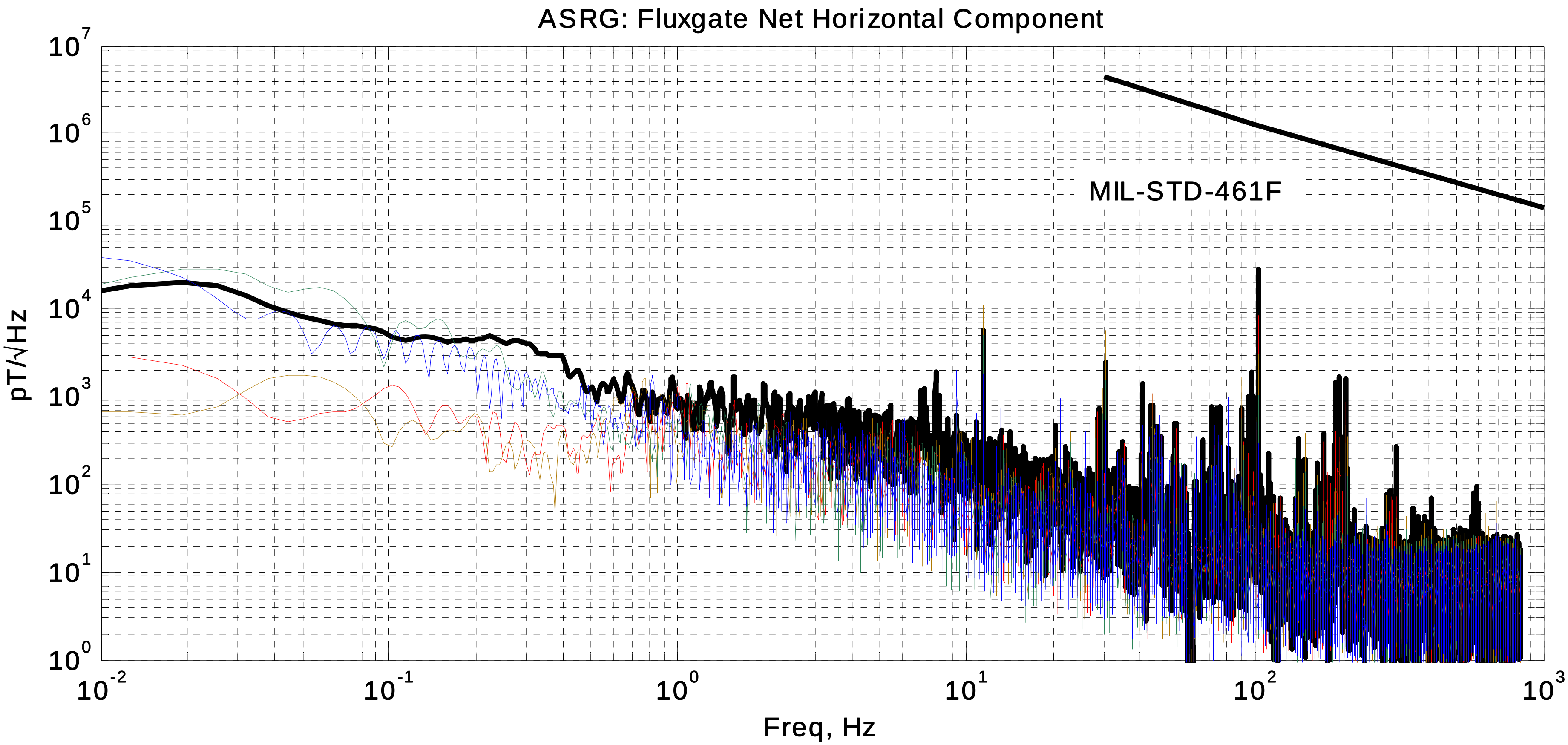


Figure 2. As Fig. 1, measured with commercial fluxgate. Although the broadband spectrum of the ASRG cannot be distinguished from background, the upper limit to magnetic emissions is no worse than 1/f and is ~1 nT/√Hz at 1 m.

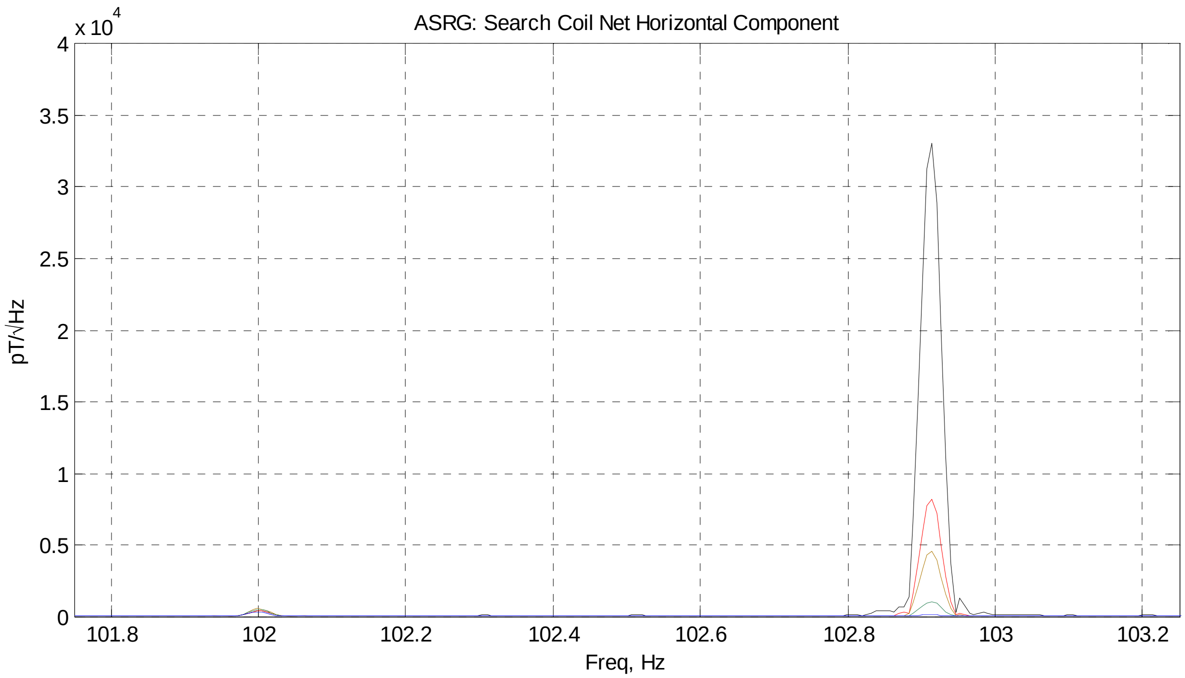
Black – 1 m distance, Red – 1.5 m, Brown – 2 m, Violet – 3.2 m, Blue – 5.7 m.

3.2 ASRG EU Piston Frequency

The signal at the ASRG EU piston frequency of 102.9 Hz has the largest amplitude of the entire measured AC spectrum (Fig. 3). The signal is clearly identified with the ASRG EU because of its regular falloff with distance from the unit. The amplitude of a nearby narrowband signal at 102.0 Hz changes very little with station position, indicating the source is distant. This was confirmed on-site as a second Stirling generator in an adjacent room. Note that DDOC-16 cites the ASRG EU piston frequency as 102 Hz.

The vertical component (not shown) was found to be much smaller than the net horizontal component, down by a factor of 2−4. This is not consistent with a vertical dipole geometry: the horizontal (radial) component should be small and the vertical component large in the nearly side-on configuration with respect to the presumed dipole axis. However, both the horizontal and vertical component amplitudes fall off as distance to the 2.8±0.3 power, consistent with the dipole value of 3. Therefore the field likely follows a non-vertical dipole, one that may have different orientational distortions with position due to static interference (scattering). It is clear that the movement of the dual piston magnets in the ASRG EU do not interfere to form a multipole, but preserve an overall dipole geometry.

MIL-STD-461F requires that the coil is rotated until the maximum signal is received. The vertical component would add only several percent to the total amplitude, justifying its neglect in comparing to MIL-STD-461F. The maximum piston-frequency amplitude at 1 m is ~30 nT/√Hz or ~90 dBpT/√Hz. This is ~30 dB below the Army standard but exceeds the Navy standard at 100 Hz by 9 dB. Recall that these figures are translated to 1-Hz bandwidths; returning to the actual MIL-STD-461F 10-Hz bandwidth, the narrowband signal is averaged out and 10 dB is gained back. The ASRG EU then just meets the Navy standard. The interpretation of a measured 120 dBpT AC limit in DDOC-16 without a frequency or bandwidth specification is still unclear; the 10-Hz standard bandwidth would result in a maximum emission of 100 dBpT at 100 Hz and 1-m distance.



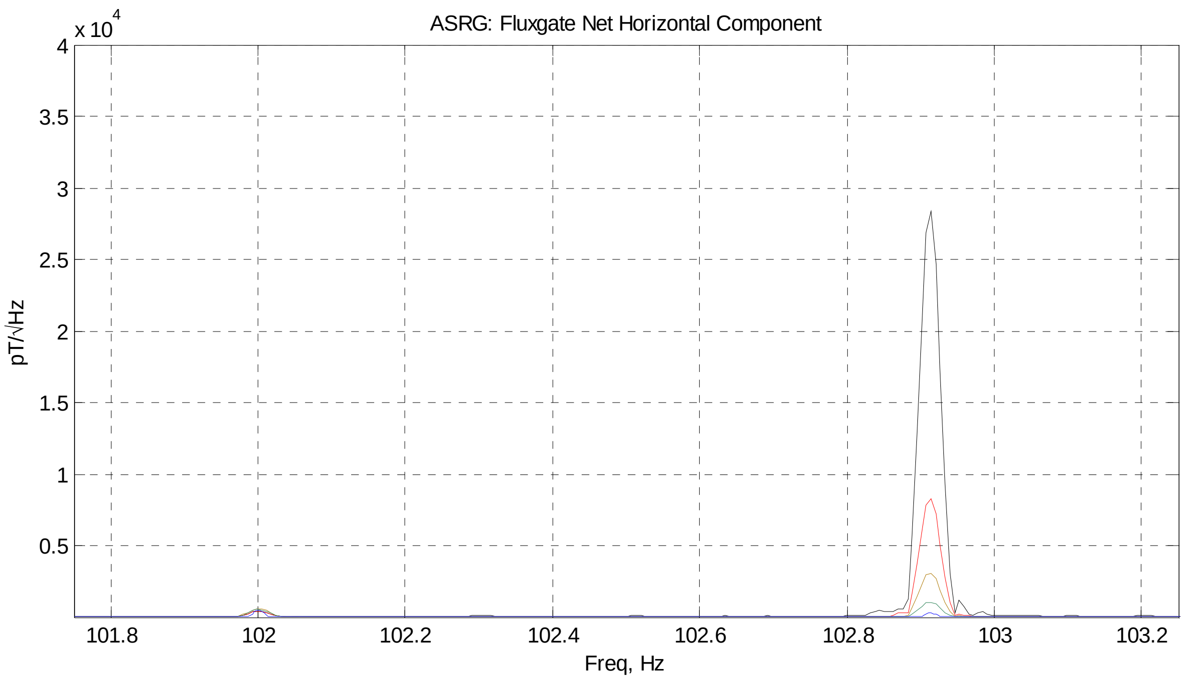


Figure 3. Linear zooms of Fig. 1 (top) and Fig. 2 (bottom) showing ASRG EU piston signal at 102.9 Hz and signal from a second Stirling converter in an adjacent room at 102.0 Hz. Piston signal falloff with distance from the ASRG EU is dipole-like.

3.2 DC Magnetic Anomaly

An extraordinarily large DC magnetic anomaly, >30,000 nT at 1-m distance, was apparently associated with the ASRG EU—nearly canceling Earth's field near the unit! This field fell off regularly with distance with the ASRG EU but was not a simple dipole. Nonetheless, textbook formulas for dipole fields, magnetic moments, and magnetization pointed to a ~10-cm^3 permanent magnet, far larger than those in the ASRG EU. The anomaly at 1-m distance from the magnets that might be accommodated in the ASRG EU should be <1000 nT, and DDOC-16 indicates a 90 nT limit. It was subsequently discovered that a vacuum pump containing a large magnet was just on the other side of the ASRG EU: this explains both the large anomaly and distance falloff that should be centered on the pump, not the ASRG EU.

4. Conclusions

The working laboratory environment was acknowledged to be non-ideal before these measurements were made. The project was undertaken with the objective of a "go/no-go" decision for low-frequency EM measurements on an ASRG-powered Discovery mission. A sensor standoff distance (e.g., boom length) of 10 m would bring the specified DC signal to <0.1 nT and the worst-case AC signal at 1 Hz to ~1 pT/√Hz—even smaller values of the latter are desirable. Accommodation of standoff distances of 10 m or more may be strongly mission-dependent. Publication or acquisition of full spectra acquired in a magnetically controlled environment is necessary to determine the true nature of the magnetic emissions of the ASRG.

5. Acknowledgements

I thank Michael New (NASA HQ), Dick Shaltens (NASA Glenn), and Ed Lewandowski (NASA Glenn) for facilitating this work, and Yongming Zhang of Quasar Federal Systems for loan of the search coils.

6. Appendix: In Situ (ASRG Lab) EMI Measurement Log

This log and the original data were left at NASA Glenn on the day of the measurements, 10/23/09. Files 16, 21, 2, 5 and 27 were used to construct Fig.1; files 15, 22, 1, 6, and 33 were used for Fig. 2, for distances of 1, 1.5, 2, 3.2, and 5.7 m, respectively.

Data are 3-component fluxgate and 2 component search coil.
Always acquired in pairs, but order varies according to port assignment (by Labview?)

Data files are ASCII, comma-delimited.
For the fluxgates, t, vx, vy, vz, junk (volts) (Junk = unused ADC channels)
For the search coils: t, v1, v2, junk,junk where v1 = x or z and v2 = y or z.
x-axis always points at the ASRG, y is horiz orthogonal, z is vertical

Fluxgate pT = 7e6 * fluxgate volts at 60 Hz
Coil pT = 3.3e4 * coil volts at 60 Hz

All measurements made at 42" elev, equivalent to ~1/3 height up ASRG

File Number	Position	Data	Comments
1	Stn 1: Az 180, Range 2.0 m	Fluxgate	60 sec
2		Coil	XY coils
3		Coil	Tech came in
4		Fluxgate	Tech came in
5	Stn 2: Az 225, Range 3.2 m	Coil	XY, 60 sec
6		Fluxgate	
7		Fluxgate	
8		Coil	XZ coils
9		Coil	YZ coils
10		Fluxgate	
11		Coil	YZ coil repeat
12		Fluxgate	
13	Stn 3: Az 180, Range 1.0 m	Coil	
14		Fluxgate	
15		Fluxgate	Repeat with coils superimposed
16		Coil	Repeat with coils superimposed
17		Missing file	Missing file
18		Coil	120 sec
19		Fluxgate	XZ coils
20		Coil	XZ coils

21	Stn 4: Az 135, Range 1.5 m	Coil	XY coils
22		Fluxgate	
23		Coil	XZ coils
24		Fluxgate	XZ coils
25		Coil	XY coils, 120 sec
26		Fluxgate	XY coils, 120 sec
26-a		Missing file	Missing file for fluxgate
27	Stn 5: Az 245, Range 5.7 m	Coil	XY, 60 sec
28		Coil	XZ coils
29		Fluxgate	XZ coils
30		Coil	YZ coils
31		Fluxgate	YZ coils
32		Coil	XY coils, 60 sec
33		Fluxgate	XY coils, 60 sec

NOAA Magnetic Field for this location and time was
N +19,161 nT
E -2,719 nT
Z 50,372 nT (+ down)