ELECTROMAGNETIC COMPATIBILITY CHARACTERIZATION OF A BAe STIRLING-CYCLE CRYOCOOLER FOR SPACE APPLICATION

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ABSTRACT

The intended use of Stirling-cycle cryocoolers to cool infrared and submillimeter imaging instruments on 5- to 10-year missions brings with it major challenges to cryocooler development. In particular, the voice-coil driven cryocoolers need to be electromagnetically compatible with the host instrument's detectors as well as with neighboring instruments; specifically the cryocoolers must not generate levels of interference that degrade performance or cause malfunction of the cooled imaging detectors, payload instruments, or host spacecraft.

To support the design and successful operation of NASA space instruments, the Jet Propulsion Laboratory (JPL) has an ongoing extensive cryocooler characterization, test and analysis program to identify cryocoolers capable of meeting the stringent requirements. The characterization activity focuses on sensitive performance measuring techniques for quantification of thermal performance, vibration, electromagnetic compatibility (EMC), and life-limiting reliability degradation mechanisms. This paper describes the EMC measurements of a British Aerospace (BAe) 80-K Stirling-cycle cooler. The measurements, performed in the JPL EMC test facility, include DC magnetic field characterization, radiated magnetic and electric field emissions, and conducted emissions on the internal lines between the cooler electronics and the cooler. The measurements conform to both the MIL-STD-461C specifications as well as to the specifications for the NASA Earth Observing System (Eos).

INTRODUCTION

The intended use of mechanical cryocoolers to provide continuous cooling to infrared and submillimeter imaging instruments for multi-year missions requires the suppression of the cooler's vibrational motion and electromagnetic emissions to levels that will not interfere with the instrument detector, or with neighboring instruments. The Atmospheric Infrared Sounder (AIRS) instrument, for example, which is scheduled for Platform A of the Earth Observing System (Eos), is a grating-array spectrometer using sensitive HgCdTe detector arrays cooled to 60K with multiple coolers. While the detector array's vibrational susceptibility level is

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quite challenging (on the order of 1 micron to prevent image blur), the detector and cooler's level of electromagnetic compatibility needed to prevent image degradation is less well understood.

As part of the JPL cryocooler characterization program[1-3] measurements of the electromagnetic signature of a British Aerospace (BAe) 80K cooler have been made to provide an early indication of the level of electromagnetic compatibility of the cooler with the host spacecraft and its payload instruments. This paper focuses on measurements of the cryocooler's DC magnetic field and the radiated AC magnetic and electric field emissions. Measurements were made with the bare cooler -- no mu-metal shielding was attempted to lower the magnetic field levels. The cooler's ground support electronics were placed outside of the measurement facilities and were not included in the radiated emissions measurements. The measurement results are compared to both military specifications (MIL-STD-461C)[4] and to the October 1990 General Instrument Interface Specifications for Eos[5]. The Eos specifications are concerned with the electromagnetic interference (EMI) that any instrument puts out, and how the EMI may affect the host observatory or neighboring instruments. Of perhaps greater concern is the effect the cooler EMI will have on the detector it is to cool, since the cooler's expander will be operating very near the detector. Thus measurements taken at short range (7 cm) are also included in this paper, and are discussed with respect to detector sensitivities.

CRYOCOOLER ELECTROMAGNETIC STRUCTURE

The cryocooler is a mechanically resonant system that operates much like a loudspeaker. Both the compressor and displacer units have spring-suspended drive assemblies driven via a moving coil in a permanent magnetic field. Mechanical motion is generated by applying an alternating current through the coil at a frequency chosen to be near the mechanical resonance of the compressor, this minimizes the required drive power. The displacer is pneumatically driven, with the linear motor used primarily to control the stroke amplitude and phase angle relative to the compressor stroke. A flight cooler is likely to be driven with a switching power supply (having switching rates in the tens of kHz) using a synthesized sine wave to provide low distortion, low vibration operation. Electromagnetic position sensors (having excitation frequencies in the kHz range) are used to monitor the position of the linear drive assemblies.

ELECTROMAGNETIC COMPATIBILITY TEST FACILITY

All tests were made at the JPL EMC test laboratory. This laboratory is used for testing all JPL instruments for Deep Space missions. The magnetic field measurements were made in a DC magnetic measurement facility (Fig. 1). Utilizing three sets of Helmholtz coils, this facility is capable of suppressing all background magnetic fields to the 1 nanoTesla (nT) level over a volume of 1 m^3. The radiated emissions measurements were performed in a steel RF-shielded room (Fig. 2) with the facility electronics and cooler support electronics located in an adjacent room. The EMI data were obtained both with and without the cooler operating to measure cooler-contributed EMI relative to the ambient background levels.

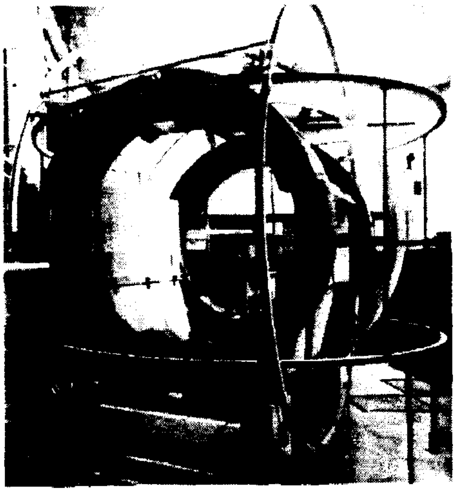

Fig. 1. DC magnetic field measurement facility.

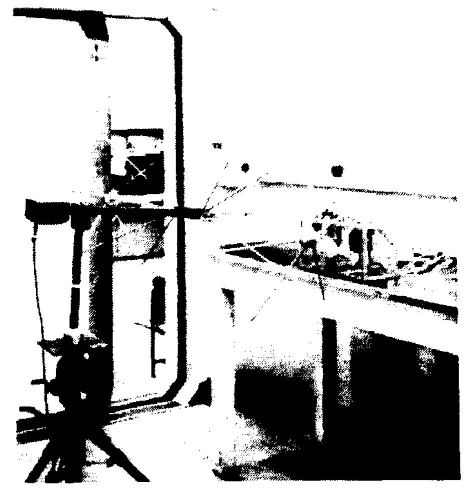

Fig. 2. RF-shielded room for radiated emissions measurements.

ELECTROMAGNETIC COMPATIBILITY MEASUREMENTS

DC Magnetic Field

Both the compressor and displacer units use permanent magnets with iron pole pieces to provide the magnetic circuit for the drive coil. The resultant DC magnetic dipole field of each component has a $1/R^3$ dependence. Measurement of this field was made with the cooler placed on a rotating platform within the DC magnetic field measurement facility. Three-axis global mapping of the cooler's DC magnetic dipole field was performed by rotating the platform through 360° while 1) the cooler was lying on each of its three orthogonal surfaces, and 2) the cooler was repositioned through various angles relative to one surface. The measurements were repeated for both a nonoperating and operating cooler, with nearly identical results. The maximum DC field strength measured at 1 m from the cooler was 2.6 μT (0.026 gauss); this is half the allowable 5 μT magnetic field strength as specified for an Eos instrument. Additional field measurements were made at the compressor and displacer casings using Hall generators and yielded 13000 μT and 9400 μT maximums, respectively (Fig. 3).

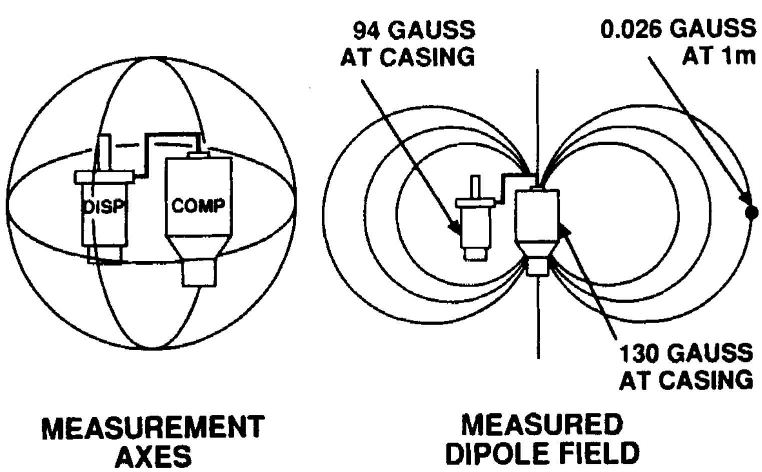

Fig. 3. The cryocooler DC magnetic field characterization.

Radiated AC Magnetic Field Emissions

The cryocooler was placed in the steel RF shielded room for radiated emissions testing. Low distortion drive electronics were placed outside the shielded room and connecting cabling was fed through a bulkhead plate to the cooler. The cabling consisted of twisted pairs of leads and was sheathed in aluminum foil and grounded to the copper laminated table top to minimize any contributing radiation. The cooler was placed on the copper table top and also grounded to it. The cooler was operated at nominal compressor/displacer amplitudes (7.2 mm/2.6 mm, respectively) for the radiated magnetic field emission measurements.

Two sets of measurements were made: 1) at a 1-m distance corresponding to an Eos specification using a modified MIL-STD-461C RE04 test method, and 2) at a 7-cm distance corresponding to the MIL-STD-461C RE01 (there is no corresponding Eos requirement). Fig. 4 shows the radiated magnetic field emissions of the operating cooler as measured at 1 m. The data are plotted in dB above 1 pT and are compared to the preliminary accepted specification for equipment emissions as set for Eos[5]. The peaks at 40 and 80 Hz correspond to the first two harmonics of the cooler operating frequency. The other low frequency peaks seen are the odd harmonics of the 60 Hz line frequency, and are at the same level as measured in the pre-test room ambient measurements. In fact, at a distance of 1 m, only the compressor emission levels at 40 and 80 Hz are at levels measurable above the room ambient level; the emission levels for the displacer were not measurable above room ambient. The breaks in the measured data are due to changes in the amplifier gain and bandwidth settings.

The 7-cm measurements were made using the same loop detector, but at a distance of 7 cm from the casing of either the compressor or the displacer unit. Measurements of each component were made with the other component not running so as not to contaminate the electromagnetic environment during the tests. The results for both the compressor and the displacer are shown in Fig. 5. Radiated EMI discernable above ambient levels are limited to the frequency harmonics below 1000 Hz.

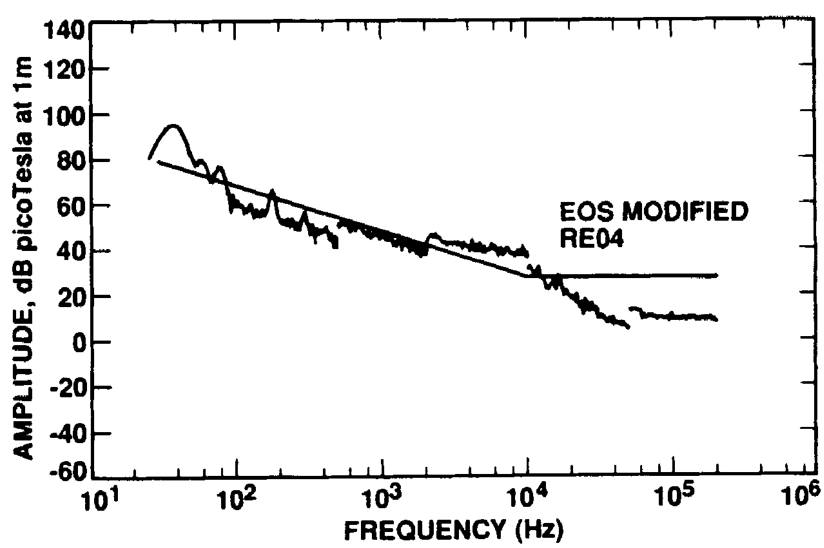

Fig. 4. The cryocooler radiated AC magnetic field emissions measured at 1 meter.

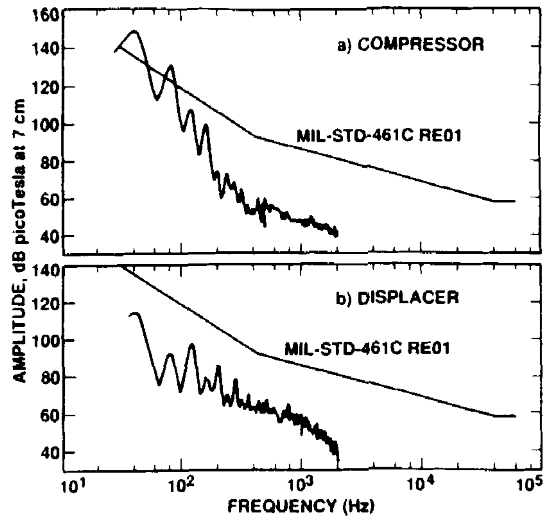

Fig. 5. The cryocooler radiated AC magnetic field emissions measured at 7 cm from a) the compressor, and b) the displacer.

Radiated Electric Field Emissions

Radiated electric field emissions were measured using the same general procedure as used with the magnetic field emissions. The antennas used for measuring the emissions at the different frequency bands were set up at a 1-m distance (Fig. 2). The narrowband and broadband measurements were made from 14 kHz to 500 MHz. The results are shown in Figs. 6 and 7 and have been compared to the MIL-STD-461C RE02 curves and the more stringent, modified RE02 requirements for Eos. Discontinuities in the data are changes in the antennas, amplifiers, and bandwidths used to cover the different frequency bands.

Low frequency electric field emission data were also measured for sake of completeness. These data are of interest because of the low frequency operation of the cryocooler. Fig. 8 shows the results for the low frequency narrowband emissions of the cryocooler as measured at 1 m. No MIL-STD specification for this

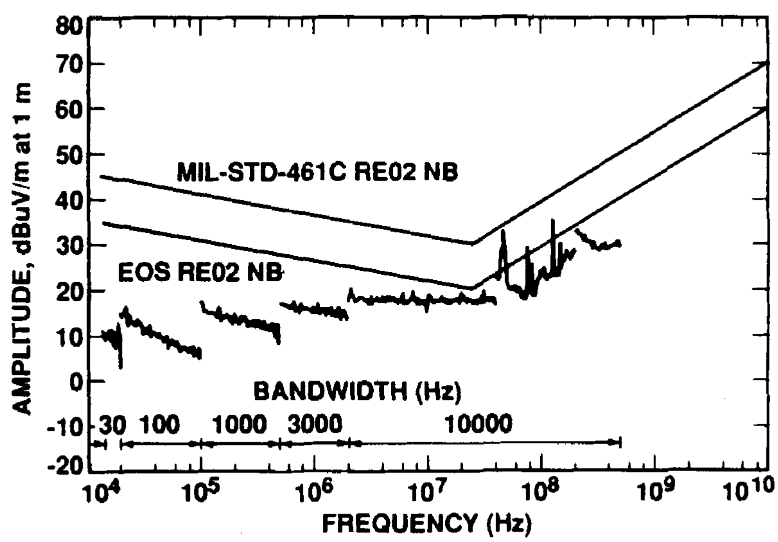

Fig. 6. The cryocooler narrowband radiated electric field emissions measurements.

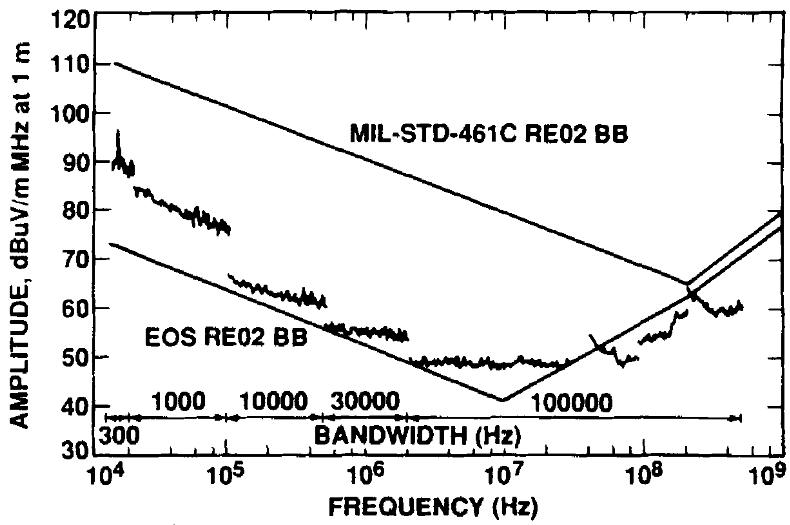

Fig. 7. The cryocooler broadband radiated electric field emissions measurements.

frequency range exists, and while not called out in the Eos guidelines, this frequency range is commonly called out by individual spacecraft, each with their own specifications. The NASA CRAF-Cassini mission specifications have been included in Fig. 8 for comparison. The 40, 80 and 120-Hz harmonics in the data are at levels above ambient background; the remainder of the data, including the odd harmonics of the 60-Hz line frequency, are all at the background levels. As in previous data, the breaks and discontinuities in the data represent amplifier, bandwidth, or antenna changes. The frequency range between 3 and 10 kHz represents a range where the best available antenna was not well matched to that frequency range.

Conducted Emissions

Conducted emissions measurements from 30 Hz to 50 kHz were made by placing a current probe around one line of the drive power cable. These measure-

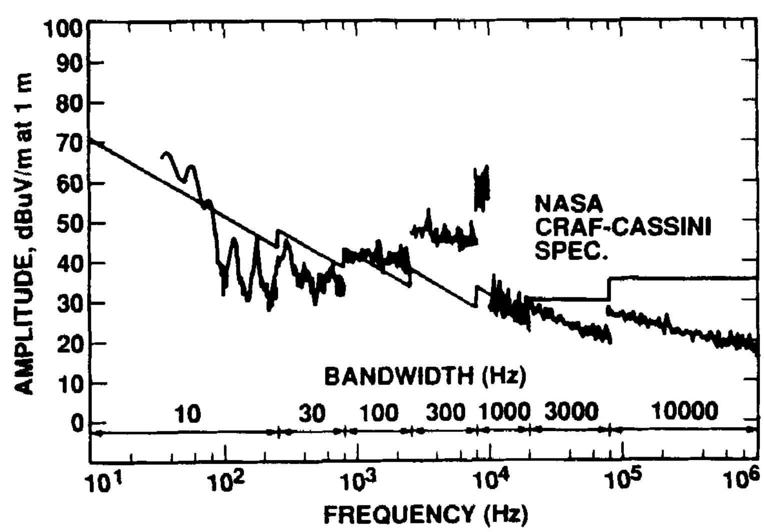

Fig. 8. The cryocooler low frequency radiated electric field emissions measurements (the NASA CRAF-Cassini specifications curve is shown for comparison).

ments were made looking at different sets of ground support electronics for comparison purposes of the electronics only. Since these are not flight qualified electronics, the measurement results have not been included here. The purity of the power supply drive current determined the conducted emission spectral purity in the data. What was representative in the data was the 3 ampere level of the 40-Hz harmonic, as this is the drive current required for the compressor using a 28 V power supply. The Eos requirements for the conducted emissions are for 3 amperes (at 120 V) for frequencies below 2 kHz.

DISCUSSION

The instrument interface requirements for Eos state that a science instrument on the platform shall not produce a magnetic field whose strength is in excess of 5 μT when measured a distance of 1 m from the perimeter of the instrument. The 5-μT value is an order of magnitude lower than the earth's magnetic field strength and two orders of magnitude lower than the magnetic field strength of the magnetic torquers used on the spacecraft platform. This value insures that the magnetic field does not interfere with the operation of other spacecraft instruments, nor produce significant magnetic torques on the overall spacecraft.

The 2.6-μT DC magnetic field strength measured for the cooler depicts a worst-case scenario because of the alignment of the magnetic dipole fields of the adjacent compressor and displacer. Even so, the measured value for the single cooler falls within the Eos requirement. The use of multiple coolers on the AIRS instrument will necessitate the revisiting of the DC magnetic field measurements when the cooler configuration on the instrument is established.

The radiated AC magnetic field emissions from the cooler as measured at 1 m were found to be above the ambient background levels for the 40- and 80-Hz harmonics only. These two harmonics are also seen to be above the Eos RE04 specification for the equipment radiated emissions. Similar measurements at a 7-cm distance when operating compressor and displacer individually showed measurable radiated emission levels below 1 kHz, with the radiated levels for the first few harmonics of the expander being 10 to 20 dB lower than that of the compressor. For comparison purposes, the 7-cm measurements have been plotted against the MIL-STD-461C RE01 curve in Fig. 8.

The results of the magnetic field measurements indicate that some level of shielding with mu-metal (perhaps 0.7 to 1.4 mm thick) will be required to lower the AC magnetic field levels to below the Eos specification. The thickness and geometry of the shielding will depend on the number of coolers required on the Eos instrument and how they are configured. A modest mass penalty may be imposed on the instrument by the requirement that the shield be made thick enough to facilitate the necessary shielding and have a fundamental vibration frequency high enough not to couple into the cooler vibration harmonics.

With the exception of a few narrowband electrical noise signals generated by the cooler support electronics in the MHz range, the radiated AC electric field emissions above 1 kHz were not measurable above ambient background. The radiated electric field emissions were well below MIL-STD curves for both narrowband (Fig. 7) and broadband (Fig. 8) cases and fall within specification for Eos in only the narrowband case. The Eos specification for broadband electric field emissions are presently more stringent than the present test equipment can measure for ambient background levels. The low frequency electric field emissions (Fig. 9), for which there is no present Eos specification, show the highest levels of emissions at the 40- and 80-Hz harmonics. If required, electrostatic shielding can be placed around instrument electronics to reduce the level of capacitive coupling of the electric field to the electronics.

These initial measurements of the cooler's radiated magnetic and electric field emissions provide the needed data to make estimates of the levels of induced voltages that may be coupled into the detector signal. These estimates can be made using near-field, common-mode coupling equations[6]. Assuming two operating coolers located 20 cm from a detector, the 40-Hz magnetic flux density and 40-Hz electric field intensity at the detector are 1 μT and 0.06 V/m, respectively. If, for example, these field levels are imposed on a 10-cm long unshielded twisted pair of leads having a separation of 1 mm, the induced voltages will be 10 nV for the magnetic field emissions and 0.001 nV for the electric field emissions. These order of magnitude values for the induced voltages are small compared to the 1-mV level of the detector signal, and do not raise any immediate concern for the initial instrument design. Future integrated detector/cooler tests will have to be conducted to determine final shielding requirements and insure electromagnetic compatibility.

The results of the conducted emissions measurements with the ground support electronics show Eos requirements can be met. The whole issue regarding powerline conducted emissions, voltage/current ripple and powerline voltage transients using the flight qualified electronics must still be considered. However, powerline transients due to the cooler operation should be of minimum concern because normal cooler operation uses soft startups whereby the cooler is powered up slowly until the piston stroke is increased to its operating amplitude. In addition, the drive power required to operate the cooler increases slowly from about 50% of full power to full power as the displacer cools from ambient temperature to 55 K.[1]

SUMMARY

Early EMC testing provides a sensitivity check on the generated EMI level and indicates whether mu-metal shielding or electrostatic shielding is required and sufficient to insure EMI levels are compatible with spacecraft instruments. The measured EMI of the BAe 80 K cooler meets specifications as set by the General Instrument Interface Specifications for Eos with the exception of the 40- and 80-Hz frequency harmonics of the radiated AC magnetic field emissions. Here mu-metal shielding will be required to reduce the emission levels to those specified for Eos. Even though the low frequency radiated magnetic field emissions are above the levels set by Eos, the estimated coupling of the cooler EMI to the detector indicate the EMI-induced voltages are orders of magnitude below the detector signal level and should not cause a degradation of the detector signal quality.

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