Thermal/Mechanical System Level Test Results of the GIFTS 2-Stage Pulse Tube Cryocooler

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ABSTRACT

The Space Dynamics Laboratory (SDL), in partnership with NASA Langley Research Center, is building the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument. The GIFTS focal plane assemblies (FPAs) must operate below 60 K to work properly. The aft optics and interferometer of the instrument must operate below 150 K. These two temperature zones will be cooled by a 2-stage pulse tube cryocooler built by Lockheed Martin. This cryocooler was designed to cool 1.5 watts at 55 K and 8.0 watts at 140 K with a 300 K reject temperature. System power consumed was to be less than 160 watts. SDL recently completed system level testing of the 2-stage cryocooler integrated into the GIFTS system. The thermal performance of the cryocooler as well as mechanical vibration characteristics observed during these tests will be presented. Preliminary analysis of the thermal data shows that cooling performance was achieved on both stages of the cryocooler with adequate thermal margin. Mechanical vibrations from the cryocooler were also found to be sufficiently low in that the perturbations did not prevent the instrument from meeting the NESR (Noise Equivalent Spectral Radiance) requirements. This paper discusses the effects of the cryocooler vibration on the performance of the GIFTS interferometer, which is highly susceptible to even the smallest vibration inputs. This paper also discusses the thermal performance data obtained during these tests.

INTRODUCTION

The GIFTS instrument combines new and emerging sensor and data processing technologies. Large area format Focal Plane detector Arrays (LFPA) and high speed data sampling, processing, and telemetry systems are combined with a Fourier Transform Spectrometer (FTS) to achieve geophysical measurements that will revolutionize atmospheric science and meteorological forecasting. The net result is a dense coverage of atmospheric temperature, moisture, and wind velocity soundings over the entire Earth's disk in view of the satellite with a temporal frequency that permits the dynamics of atmospheric phenomena to be observed [1].

The thermal control of the GIFTS instrument is complicated with many temperature zones isolated from each other. State of the art thermal control equipment such as cryogenic ethane loop heat

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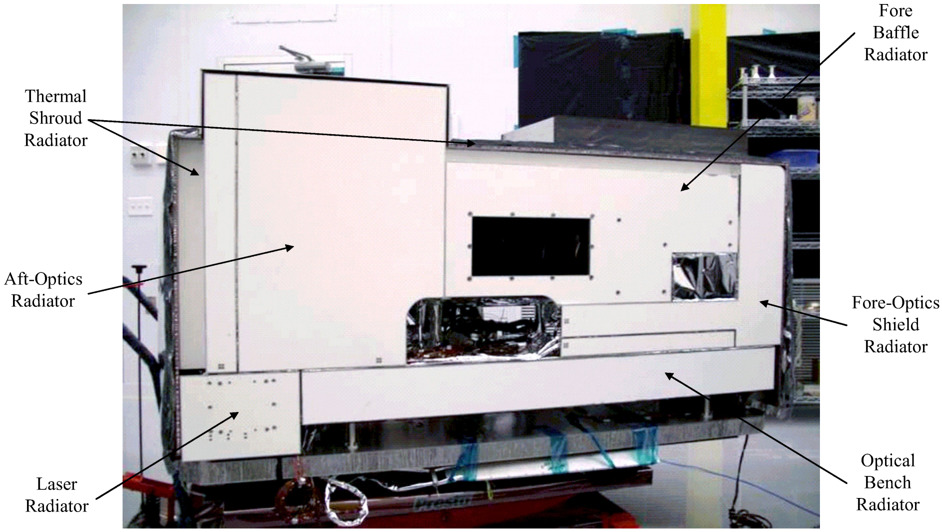


Figure 1. GIFTS Instrument.

pipes, ammonia loop heat pipes, thermal electric coolers (TECs), and a 2-stage pulse tube refrigerator are utilized in the thermal control concept. Of particular concern to the GIFTS team was the interaction between the cryocooler and an interferometer located in the spectrometer of the instrument. This interferometer is easily affected by even the smallest vibrations and therefore knowledge of this interaction and the impact it could have on instrument performance was one of the highest priority items prior to integrating the cryocooler into the GIFTS system. shows the fully integrated GIFTS instrument [2].

The LFPA and spectrometer of the instrument are cooled by a 2-stage pulse tube refrigerator built by Lockheed Martin. The first stage of the cryocooler cools 8 watts to 140 K. The second stage of the cryocooler cools 1.5 watts to 55 K. The system power consumed is approximately 180 watts at a reject temperature of 300 K. The mass of the entire cryocooler system is approximately 8.8 kg. A picture of the GIFTS cryocooler is shown in Figure 2. Table 1 shows top-level performance of the cryocooler compared to original design specification. In most cases, the Lockheed-Martin cryocooler performed as designed. Slight discrepancies in system power from the design point were within the margin of the system design.

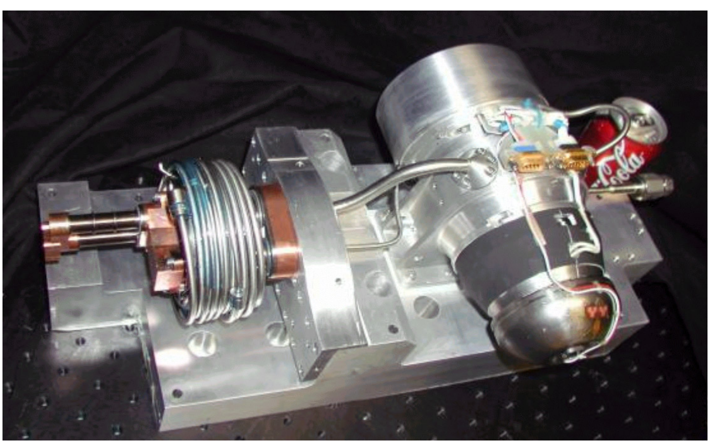


Figure 2. Lockheed Martin 2-Stage Cryocooler.

Table 1. Cryocooler Performance.

Specification Description	Specification Value	Delivered Value
Cooling at 55 K	1.5 watts	1.5 watts
Cooling at 140 K	8.0 watts	8.0 watts
System Mass	< 10 kg	8.8 kg
System Power @ 300 K Reject	< 160 watts	174 watts
Active vibration Cancellation	< 0.2 N	~0.2 N

System level testing and characterization of the GIFTS instrument was completed in May 2006. The cryocooler and instrument performed better than expected, and results from these tests will be presented to NASA in late June of 2006. The following sections of this paper will discuss the thermal and mechanical results obtained from this testing and the impact of mechanical vibrations from the cryocooler on system performance.

SYSTEM CONFIGURATION

The cryocooler was mounted to support structure and cooling apparatus and subsequently to the simulated spacecraft (S/C) NADIR deck. The NADIR deck is the Earth-pointing panel on the spacecraft that provides the support for the entire GIFTS instrument. The GIFTS cryocooler is a split configuration, 2-stage pulse refrigerator where the cold head is mounted directly to an ammonia loop heat pipe to reject the waste heat from the cryocooler. The cryocooler compressor and cold head both mount to a common structure that is in turn bolted to a simulated spacecraft structure through elastomeric dampers. This assembly, when oriented in the test chamber with the instrument, puts the cold head oriented 25 degrees down from the horizontal. This configuration, although necessary for system level testing, does not accurately simulate on orbit cryocooler performance. The results obtained from this test are degraded by 15-20% from what would be expected on orbit, due to 1-g orientation effects from the pulse tubes. A picture of the cryocooler assembly integrated to the simulated S/C NADIR deck is shown in Figure 3.

THERMAL RESULTS

Thermal performance of the cryocooler is well within acceptable limits to meet predicted GIFTS heat loads. Table 2 shows that, at the nominal operating frequency of 53 Hz, the necessary first and second stage temperatures were easily obtained with adequate system power margin to spare. Sys-

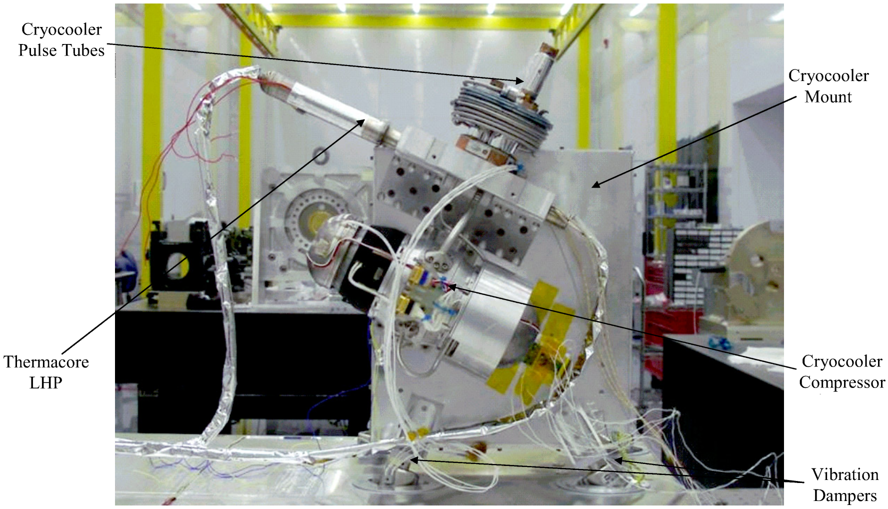


Figure 3. Cryocooler Test Setup

Table 2. Thermal Test Results for the GIFTS Cryocooler

Case	Stage 1 Temp (K)	Stage 2 Temp (K)	Stage 1 Heat Load (W)	Stage 2 Heat Load (W)	System Power (W)	Reject Temp (K)	Operating Frequency (Hz)
1	100	50	2.934	0.386	198	280	53.5
2	105	55	2.56	0.527	151	280	53.5
3	110	60	2.38	0.630	125	275	53.5
4	124	59	3.55	0.567	135	295	53.5
5	143	59	4.37	0.807	110	275	53
6	132	59	3.27	0.748	98	275	53

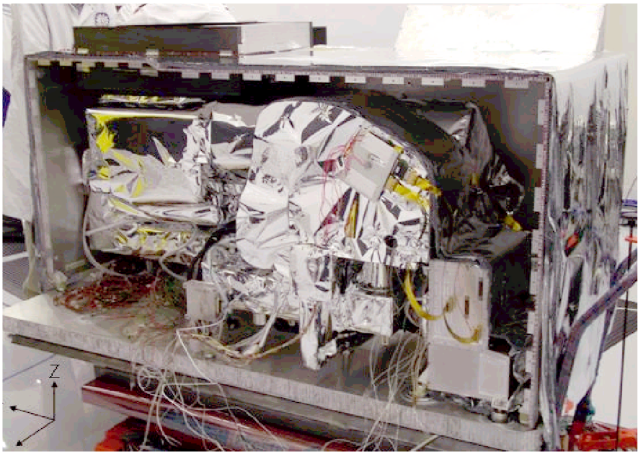


Figure 4. Cryocooler Location in the GIFTS Instrument

tem level thermal models for first and second stage heat loads were very accurate, leading to little utilization of the system margin being carried in the cryocooler design. A slightly off nominal operating frequency of 53.5 Hz was chosen as the baseline operating frequency due to system level vibration effects at the interferometer. Less mechanical vibration was coupled into the optics at 53.5 Hz than was the case at 53 Hz. Table 2 shows the thermal data points that were taken for each of the frequency cases.

GIFTS CRYOCOOLER VIBRATION RESULTS

The mounting location for the cryocooler in relation to the overall GIFTS instrument is shown in Figure 4. This support structure also provides support for the LWIR/SWIR focal plane electronics. The support structure is mounted to the S/C NADIR deck using four Barry isolators. These isolators were used in the design to limit launch loads into the cryocooler. However, the data shows they also help to minimize vibration into the Fourier Transform Spectrometer (FTS) of the instrument. Two flexible thermal links that provide the cooling path from the focal planes and FTS to the cryocooler pulse tube stages provide an additional path of vibration from the cryocooler to the FTS.

In addition to the isolators between the S/C NADIR deck and the cryocooler, there are four Barry isolators located between the S/C NADIR deck and the optical bench, which were also intended to reduce launch loads into the instrument. Unlike the isolators between the cryocooler and S/C NADIR deck, the data are inconclusive that the isolators between the S/C NADIR deck and optical bench reduced vibration inputs into the FTS from the cryocooler. Response results indicate that the vibration between the S/C NADIR deck and optical bench actually increased at the cryocooler operating frequency of 53 Hz while the first harmonic data shows a reduction.

Four different tri-axial accelerometer blocks were used to collect vibration data. These blocks were mounted on the support structure for the cryocooler, the S/C NADIR deck, optical bench, and

Table 3. Test Parameters.

Data Set	Operating Frequency (Hz)	Operational Mode	Stroke (count)	Reject Temp (K)	Stage 1 Temp (K)	Stage 2 Temp (K)
1				273		
3				282		
7		Constant Stroke	123	289		
5				292		
9				301		
11	52.97	Constant Temp	93 ±2		150	60
13			93			
15		Constant Stroke	103	285		
17			113			
19			123			

interferometer cube of the FTS. The accelerometer blocks for the S/C NADIR deck, optical bench and interferometer were aligned with the spacecraft coordinate system. The accelerometer block for the cryocooler was oriented so that one accelerometer was aligned with the piston axis of the compressor, one aligned with the axis of the pulse tube, and the last normal to the plane formed by the axes of the compressor piston and pulse tube. The cryocooler compressor is tilted 25 degrees with respect to the Y-axis of the spacecraft coordinate system.

The test results presented in this paper cover the parameter combinations defined by the ten different data sets in Table 3. Even though the cryocooler electronics has the capability to minimize the vibration affects for the fundamental, second, and forth harmonics, only the fundamental and second harmonic were cancelled in the data presented. Vibration into the interferometer was lower when only these two modes were cancelled than when all three were cancelled. The effects of vibration cancellation were published in a previous paper [2]. Operational heaters were used to maintain a constant temperature on the focal planes and FTS anytime the stroke of the cryocooler compressor exceeded 93 counts.

Cryocooler Vibration Results (Individual Axes). Vibration response levels for each axis of the cryocooler are depicted in Figure 5. The results are based on the parameters given for Data Set 11. As can be seen, levels for all axes of the fundamental and harmonics 2 – 5 are <10 milli-g., and with the exception of the pulse tube axis for the fundamental and the piston axis for the fourth harmonic, <5 milli-g. Levels for the first harmonic (106 Hz) are considerably higher for all axes in comparison to the fundamental and other harmonics.

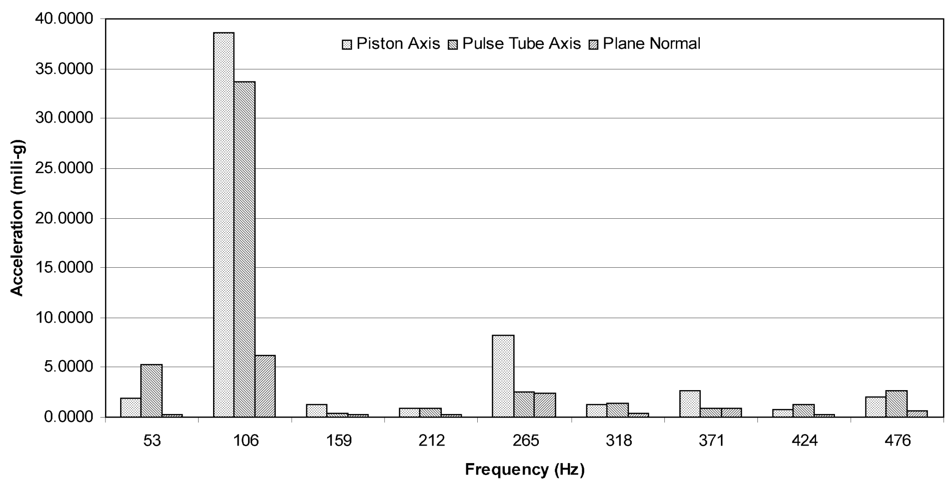


Figure 5. Cryocooler Vibration Results (Individual Axes).

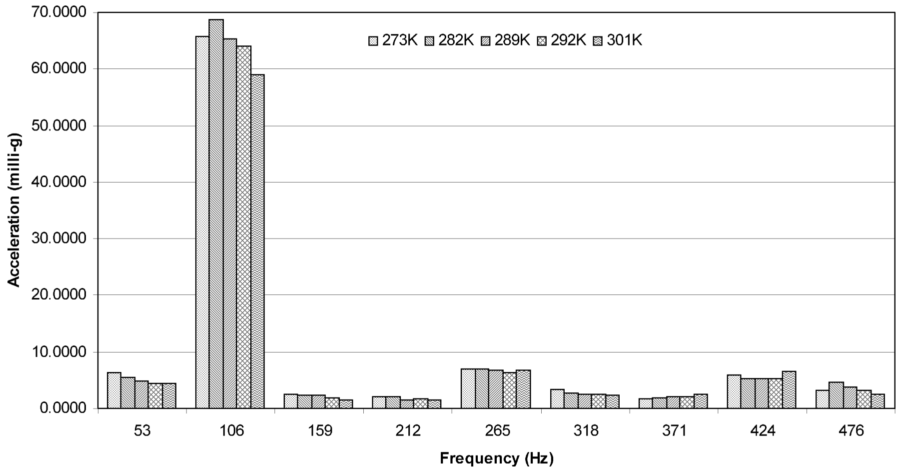


Figure 6. Cryocooler Vibration Results Based on Variable Reject Temperature.

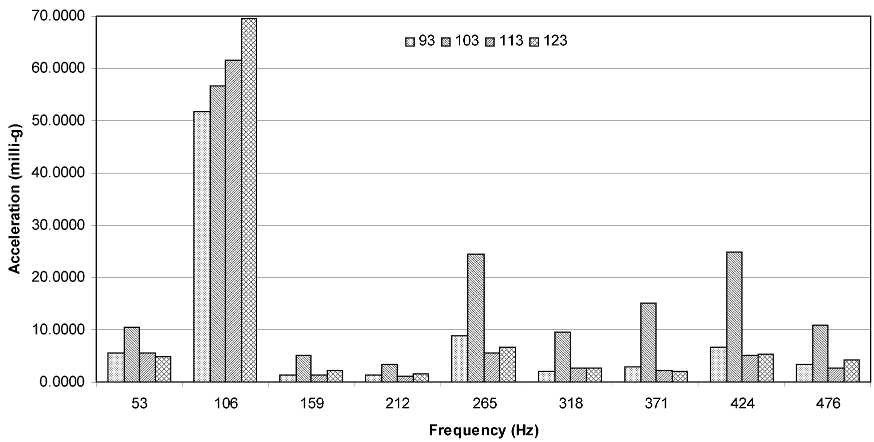


Figure 7. Variable Stroke − Constant Reject Temperature Response Levels.

Constant Stroke – Variable Reject Temperature Vibration Results. Results for Data Sets 1 to 9 are shown in Figure 6. The response levels for the fundamental and first through fifth harmonics are presented and represent the root-sum-square (RSS) values for all three axes of the cryocooler. The results indicate that with the exception of the first harmonic, the response levels are <10 milli-g. It also appears that there is an overall reduction trend in the response as the reject temperature increases. This is true for all but the sixth harmonic. The seventh harmonic is inconclusive. While this phenomenon is not completely understood, it is best explained by a change in gain in the control loop. As the gain appears to decrease with a decrease in temperature, the vibration control loop has a more difficult time doing its job, hence an increase in vibration.

Constant Temperature – Variable Stroke. When the cryocooler operates in constant temperature mode, the stroke is varied as needed to maintain the Stage 2 temperature at the desired value – in this case 60K. The average stroke was observed to be ~93 counts with a deviation of ±2 counts. (It should be noted that this would be the operational mode for the instrument during orbit.) Figure 5 shows the results for this setup.

Variable Stroke – Constant Reject Temperature. Figure 7 shows the results when the reject temperature is held constant at 285 K (the nominal on-orbit condition) and the stroke is varied from 93 counts to 123. These results reflect the test parameters for Data Sets 13 – 19. The first harmonic,

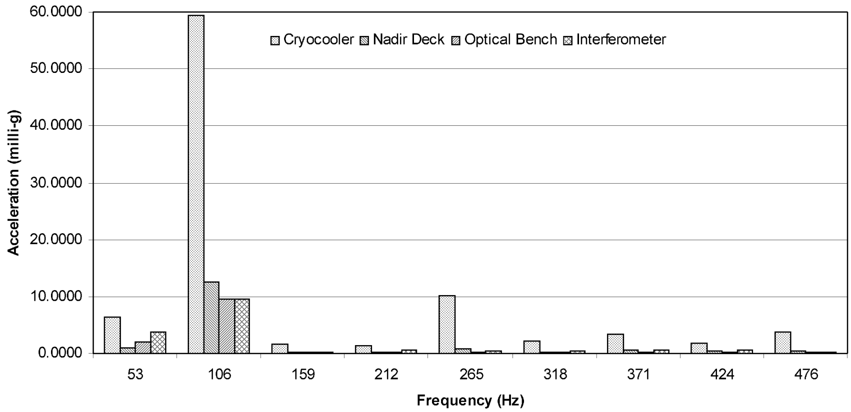


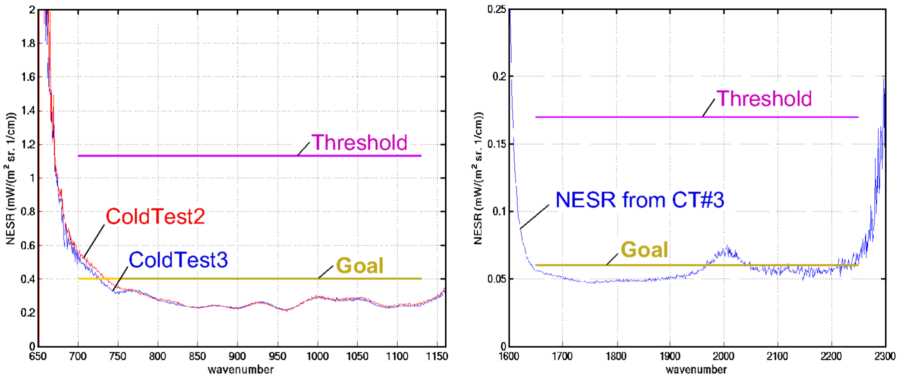
Figure 8. Vibration Impact on the GIFTS Instrument.

which is not cancelled by AFFECS (Analog Feed Forward Error Correction System), reflects the anticipated result that the vibration increase is proportional to the stroke count. Also as expected, when the results for Data Set 13 are compared with those from Data Set 11, the response levels are identical for all harmonics except the seventh. It is also unclear at this time why the response levels for Data Set 15 (103 counts) are higher in proportion to the other sets for all harmonics except the first. Unfortunately, the GIFTS instrument completed its calibration tests shortly after the results presented were taken and analyzed. Therefore the test could not be repeated to verify that response levels were not an anomaly. It is possible that the instrument will undergo further testing; if this happens, this test will be repeated.

Vibration Impact on the GIFTS Instrument. The interferometer, which is part of the FTS, is a very sensitive and vital part of the GIFTS instrument. In order for the instrument to provide useful data, the velocity errors of the moving parts within the interferometer must be kept as low as possible (<3%). If the control system for these moving parts is not robust, disturbances >5 milli-g into the system can drive the velocity error higher than is allowed. The vibration generated by the cryocooler, in addition to spacecraft perturbations (e.g. momentum wheels, solar-array drive motors, etc.) was a concern from the beginning of the project. Working the problem as a team effort between the cryocooler manufacturer, the controls engineers, and the mechanical engineers, a viable solution was obtained that met the requirements.

The results of how the vibration from the cryocooler rippled through the overall system are depicted in Figure 8 and are based on Data Set 11. In order to fully understand the response levels delivered into the S/C NADIR deck, optical bench, and FTS, the results for the cryocooler were transformed into the spacecraft coordinate system. This meant that responses from the piston and pulse tube axes would combine to create larger disturbances in the Y and Z-axes in the spacecraft coordinate system. Response levels in the plane normal of the cryocooler system created accelerations in the X-axis of the spacecraft coordinate system. With the exception of the first and fourth harmonics, the vibration levels from the cryocooler never exceeded 7 milli-g. The isolators used between the cryocooler, S/C NADIR deck, and optical bench reduced the acceleration seen at the interferometer cube at 106 Hz (first harmonic) by a factor of six. With this information, the control engineer was able to optimize the control system until velocity errors were 2.35%. As a result, the GIFTS instrument was able to meet its engineering NESR requirement for both the LWIR and SWIR/MWIR focal planes. In addition, it also met the flight requirements over most of the range for both focal planes (see Figure 9).

The vibration and velocity error data collected also indicate that even though the largest vibration levels induced by the cryocooler were in the spacecraft Y and Z axes (>50 milli-g), they were also the least likely to amplify into the S/C NADIR deck. Figure 10 shows how vibration in the spacecraft X-axis was amplified into the S/C NADIR deck. From the S/C NADIR deck to the interferometer, it was attenuated to <5 milli-g. Vibration for the Y-axis is shown in Figure 11. Vibration



Longwave (675 – 1150 cm^{-1}) Short / Midwave (1650 – 2250 cm^{-1})

Figure 9. NESR Results for the GIFTS Instrument.

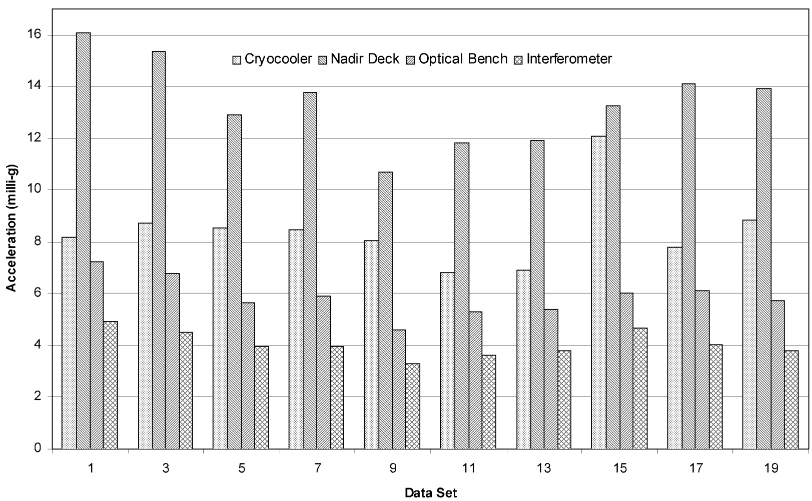


Figure 10. Acceleration for all Components in the X-axis.

into the S/C NADIR deck was greatly attenuated. Levels remained essentially unchanged into the optical bench and then slightly amplified into the interferometer. However, interferometer vibration remained <5 milli-g. Results for the Z-axis (see Figure 12) are the opposite of the X-axis.

Vibration from the cryocooler into the S/C NADIR deck is greatly attenuated. From the S/C NADIR deck to the interferometer it is amplified with levels as high as 13.7 milli-g. Since the controller could only react to disturbances in the Y-axis, the fact that vibration into that axis was below the desired levels greatly assisted in the instrument being able to meet the requirement and goal. However, vibration in the two off-axes must also be limited as much as possible since the controller cannot compensate for their contribution in the velocity error. While GIFTS met its requirements, the lesson learned is that the control and mechanical engineers must work closely together in optimizing the design to limit disturbances in the axes that cannot be controlled as well as in the axis that can. The vibration problem must be addressed from a system level and not solely from the cryocooler, structural, or controls point of view.

SUMMARY

The data presented provide four important observations: 1) Initial studies suggested that the best vibrational modes to cancel were the fundamental, second, and fourth harmonic. Testing clearly

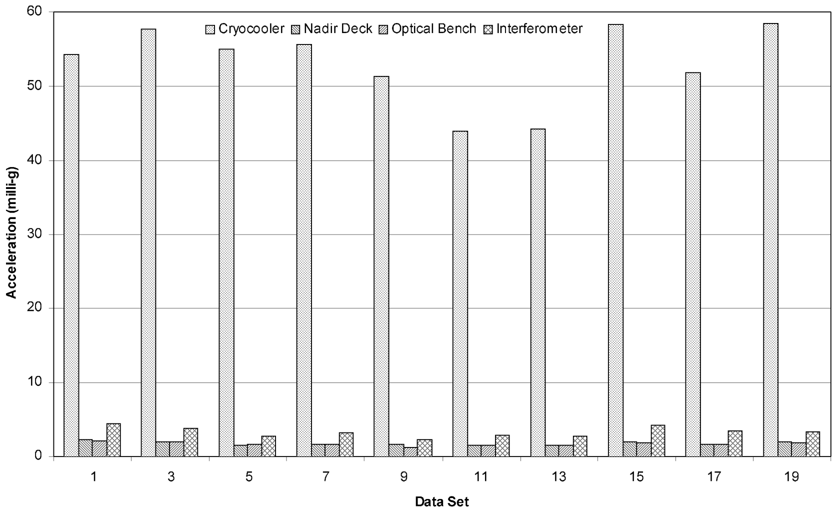


Figure 11. Acceleration for all Components in the Y-axis.

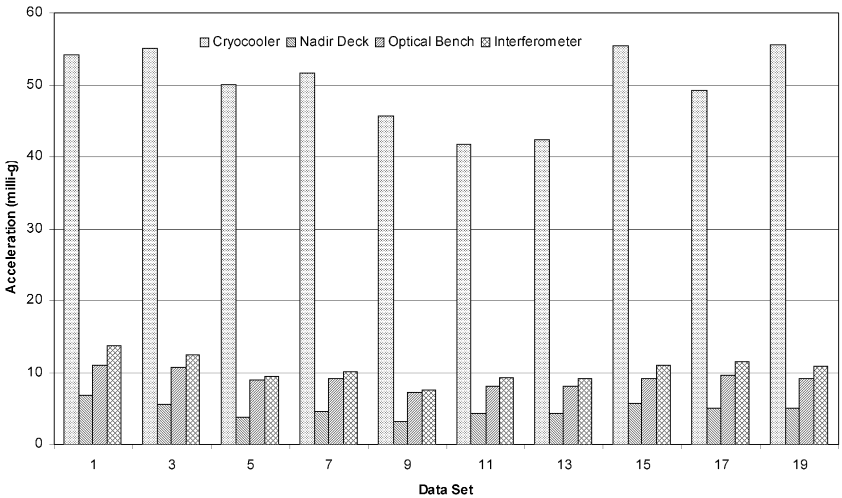


Figure 12. Acceleration for all Components in the Z-axis.

shows that the first three modes should be cancelled. This change is easily made in the electronics and will be implemented for further testing. 2) System level mechanical solutions are necessary in solving the cryocooler vibration issue. A low vibration cryocooler by itself is not necessarily a solution to the problem. 3) Thermal performance of the cryocooler is sufficient to meet the cooling needs of the GIFTS instrument even considering the reduced performance expected from the orientation effects of the cryocooler. 4) Vibration levels consistent with those in this paper yielded very good instrument results even for an instrument with a sensitive component such as the GIFTS interferometer and laser metrology system that have modes excited by the first harmonic.

During the design process, it is advisable to identify any components that are susceptible to vibration. Modes should be identified and communicated with the cryocooler vendor so that any possible harmonics that could cause problems can be cancelled. For example, a vibration mode at ~160 Hz has been identified in the GIFTS interferometer. It is fortunate that the second harmonic of the cryocooler, which is ~159 Hz, can be cancelled.

ACKNOWLEDGMENT

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