Low Temperature RSP2 Production Cryocooler and Electronics Performance

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ABSTRACT

The Low-Temperature Raytheon Stirling / Pulse Tube 2-stage (LT-RSP2) hybrid cryocooler is a long-life, robust machine designed to operate efficiently at a first stage temperature of 55K with a capacity of 5W and a second stage temperature of 10 K with a capacity of 300mW. The LT-RSP2 design was finalized in mid-2009, with fabrication of the prototype unit taking place in late 2009 and early 2010 and execution of the production program in 2011 – 2016. It has recently been mated to a set of production electronics and subsequently undergone characterization and dynamometer testing. The results of this testing are presented along with aspects of the production cryocooler and electronics designs.

INTRODUCTION

The development of practical low temperature (sub-12K) closed-cycle cryogenic coolers is being actively pursued by Raytheon Space and Airborne Systems due to the beneficial detector chemistries that are enabled by such a system. Arsenic doped silicon (Si:As) focal planes offer exceptional performance for Long Wave Infrared (LWIR) astronomy and earth sensing applications; however, cryogenic cooling to temperatures below 12 K is required for operation. Existing state of the art space and airborne closed cycle cryocooler systems are generally incapable of simultaneously holding the required loads below 12 K / 55 K, and stored-cryogen systems have typically been employed instead. The amount of cryogen required is considerable and can easily exceed the mass and volume of the instrument. Launch mass and volume limitations thus provide severe constraints on mission lifetime. A closed loop cryogenic solution would therefore offers not only smaller mass and volume, but longer mission lifetime and reduced logistics costs. To date Raytheon has designed, built and tested three different Thermo-Mechanical Units (TMUs) that meet the requirements of Si:As and other systems: the AFRL funded High Capacity-RSP2 (HC-RSP2), an IRAD funded LT-RSP2, and a production LT-RSP2.

BACKGROUND

Stirling / Pulse Tube Hybrid Cryocoolers

Raytheon's Stirling / Pulse Tube Hybrid 2-Stage (RSP2) cryocoolers have been matured through an active development effort spanning approximately 15 years [1, 2]. They combine an actively driven Stirling first stage with a passive pulse tube second stage. The architecture of each RSP2

Cryocoolers 19, edited by S.D. Miller and R.G. Ross, Jr.

expander module is identical, the main differences being the sizing of the compressor module and the size of the Stirling piston and the pulse tube on the expander. In this way, the RSP2 architecture can be adapted to accommodate a wide variety of 1st and 2nd stage temperatures and load requirements. Nominal design temperatures (1st stage / 2nd stage) for the RSP2 coolers have included 55 K / 10 K for the LT-RSP2, 85 K / 35 K for the HC-RSP2, and 110 K / 58 K for the Mid-Capacity (MC-RSP2). Even with the compressor and expander sizes fixed, however, there remains a great deal of flexibility in operating temperature and load capacity for each of the RSP2 coolers. For example, the initial 60 K / 12 K testing at the beginning of the LT-RSP2 development effort was performed using the HC-RSP2, nominally designed for 85 K / 35 K operation [3].

The flexibility in operating temperatures and capacity of the RSP2 cryocoolers is due in large part to their ability to load shift between their first and second stages. This capability is unique to the Stirling / pulse tube hybrid architecture and provides a means for temperature control without the need for trim heaters [4]. Load shifting allows for the ratio of refrigeration capacities at the two stages to be altered via a simple software command of the Stirling phase angle (ø), without a significant loss of overall efficiency.

The capability to load shift is extremely valuable to systems utilizing two-stage cryocoolers, providing benefits during the system design, integration, and operational phases of a typical mission. During the design and integration phases, the operating temperature and capacity demands placed on the cryocooler are often revised, with the final requirement being determined during an integrated system test. The load shifting capability allows the Stirling / pulse tube hybrid coolers to efficiently adapt to the changing requirements without adding trim heat to one or both stages. Similarly, using operation load shifting and the related capability to perform independent temperature control at each stage, the cryocooler can maintain its operating temperatures even as its heat rejection temperatures, parasitic loads, and the instrument power dissipation vary over time.

LT-RSP2 Development History

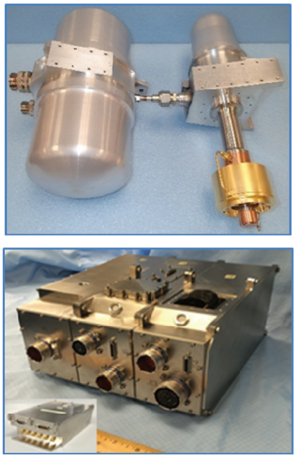
The development of the LT-RSP2 cryocooler will only be briefly summarized here as more detailed descriptions have previously been presented [1-3]. Initial testing at second stage temperatures of 12 K and below was performed starting in 2008 using the HC-RSP2 cryocooler, initially developed with support from the Air Force Research Laboratory (AFRL) for cooling at 85 K and 35 K. Upon completion of the testing internal investment was secured to develop an RSP2 cryocooler optimized for operation at 55 K and 10 K, capable of efficiently producing relatively large amounts of cooling at 2nd stage temperatures <10 K. The design of the IRAD LT-RSP2 cooler was started in 2009 and initial testing was performed in 2011. The IRAD unit successfully achieved its performance goals, leading to the design and fabrication of the first production unit. The evolution from the IRAD to production unit involved mostly minor changes aimed at improving robustness, incorporating standard connectors, and optimizing heat rejection interfaces. The design work on the production cooler began in late 2011 and fabrication was completed in 2013.

PRODUCTION LT-RSP2 PERFORMANCE

Thermodynamic Performance

Initial characterization testing of the production LT-RSP2 cryocooler began in July of 2013 with no-load temperature test showing 35.5 K on the 1st stage and 5.46 K on the 2nd stage for an input power of 466 W, as shown in Figure 1. After optimizing the fill pressure in the production cooler, thermodynamic performance characterization was performed at its nominal operating temperatures of 55 K and 10 K. This is summarized in the load map shown in Figure 2.

Figure 2 shows that the LT- RSP2 cryocooler is able to produce a range of cooling capacities at each of its stages depending upon the input power and Stirling phase angle. Variation in the Stirling phase angle acts to modify the ratio of first and second stage capacities for a given input power. For example, at 350 W of input power the capacity can be varied from 4.4 W at 55 K and 0.2 W at 10 K to 2.2 W at 55 K and 0.36 W at 10 K by adjusting the Stirling phase angle from 85 degrees to 65 degrees. This was the tested range of Stirling phase angles for this cooler and these temperatures,



Parameter	Test Data
No Load Temperature and Power	35.5 K and 5.46 K at 466 W of TMU Power
Nominal Operating Point	4.3 W at 55K + 0.18 W at 10K 367 W TMU Power / 434 W System Power
Power Limit	600 W TMU / 800 W Electronics
Exported Forces and Torques at Nominal	< 325 mN or N-m in all Axis up to 243 Hz
Temperature Control	< ± 50 mK on Both Stages No Trim Heaters Required

Figure 1. Production LT-RSP2 Cryocooler and Control Electronics (left) and typical operating parameters (right).

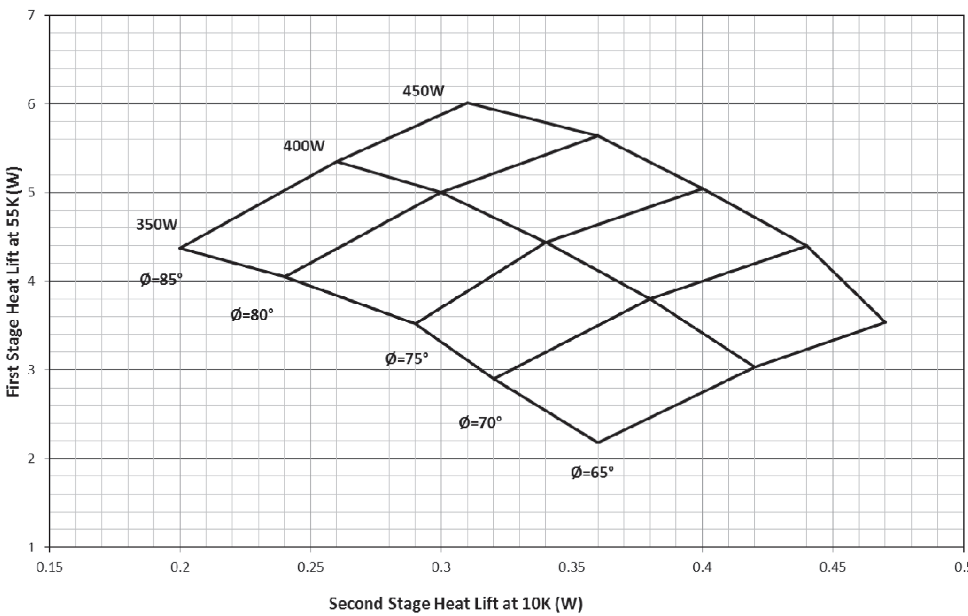


Figure 2. Production LT-RSP2 heat load capacity at 55 K and 10 K for input powers of 350 W to 450 W and Stirling phase angles of 65° to 85°.

however both higher and lower phases are possible, and thus additional range in stage cooling capacities is possible as well. This unique capability of Stirling / pulse tube hybrid cryocoolers to trade capacity between their stages through variation of the Stirling phase angle is referred to as load shifting. For the LT-RSP2 cryocooler, it is implemented very easily through modulation of the displacer drive waveform produced by the cryocooler electronics.

Cryocooler Thermal Control Electronics (CTCE)

During 2014-2016 the Raytheon Cryocooler Product Line designed, assembled and tested a modern set of common control electronics that is capable of powering and controlling all Raytheon cryocoolers. The Cryocooler Thermal Control Electronics (CTCE) combines modular, high-power

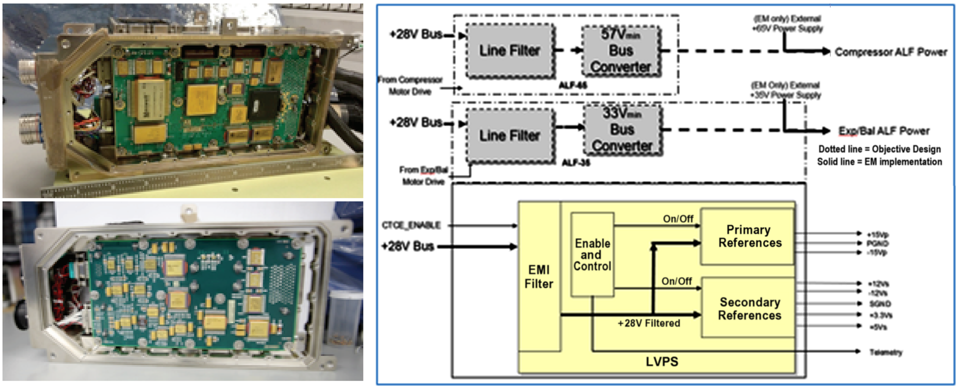


Figure 3. CTCE Individual Slices (left) and Cryocooler Drive Electronics Block Diagram (right).

motor drives with precision telemetry capabilities in a design that utilizes radiation hardened components and is capable of driving cryocoolers with maximum power requirements up to 800W. The CTCE is comprised of the following slices: Expander-Balancer-Control (EBC), Compressor Drive (CD), Low Voltage Power Supply (LVPS)/ Active Line Filter-35V (ALF-35), Cryocooler Mounted Electronics (CME), and the Active Line Filter-65V. Currently, these electronics slices are at TRL 5 having been tested with the LT-RSP2 cryocooler at power levels ~ 400W. An Engineering Model (EM) version populated with space prototype-grade components has been successfully tested with the RSP2 cooler with two stage temperature control with stability < 50mK on both stages and vibration control resulting in less than 350mN over the first 10 harmonics in all axes (X,Y,Z).

The Expander/Balancer Control processor hosts the piston position, temperature and vibration control algorithms. It generates all the power amp commands, stores vibration and Adaptive Feed Forward (AFF) drive signal data in memory, and provides piston position control. The driver amp circuits convert commands into motor drive Pulse Frequency Modulated (PFM) signals, compensates motor drive power with varying input voltages, and provides telemetry feedback. There are three drive circuits of 800W (Compressor) or 150W (Expander/Balancer) maximum drives supporting a range of cryocoolers. The LVPS and Active Line Filter block diagram is shown in Figure 3 and shows that the input power required is +28V from one or two feeds (dependent on cryocooler selection).The low-rate digital computations (AFF, Temperature Control and CTCE Control) are performed within the space-qualified microprocessor. The high-rate digital computations (Piston Position and Motor Current servos, Telemetry Data Acquisition) are performed in the FPGAs. The Low Voltage Power Supply (LVPS) provides the low voltage power to the CTCE system via high efficiency switching regulators. The active line filters (ALF) provides 35V and 65V cryo motor drive power while actively controlling conducted emissions back onto bus power, which is a significantly smaller and lighter solution than traditional passive EMI filters used on legacy designs.

The overall reliability of our third generation cryocooler electronics is excellent. Figure 4 shows the overall electronics reliability plot using dual string electronics and GSFC level 2 grade parts which achieve over 97% reliability at 10 years. The reliability is high, as our third generation electronics use fewer total parts than legacy systems. Our high density packaging design allows excellent thermal management keeping most components less than 20 degrees above our baseplate temperature and our hottest components junction temperatures at just under 35 degrees above our base plate temperature. Raytheon's third generation electronics are built from a tightly managed bill of materials as part of the Core Payload Architecture efforts, and the parts were carefully selected to enable procurement to support class A through class D missions. This provides a range of price points and reliability options just from changing the component quality. The architecture also allows single or dual string configurations, which further control costs on short life lower reliability missions. Testing in 2016 without the ALFs demonstrated efficiency in the rage of 87% - 89% without AFF vibration control active and 84% - 87% with AFF active controlling the vibration to the levels

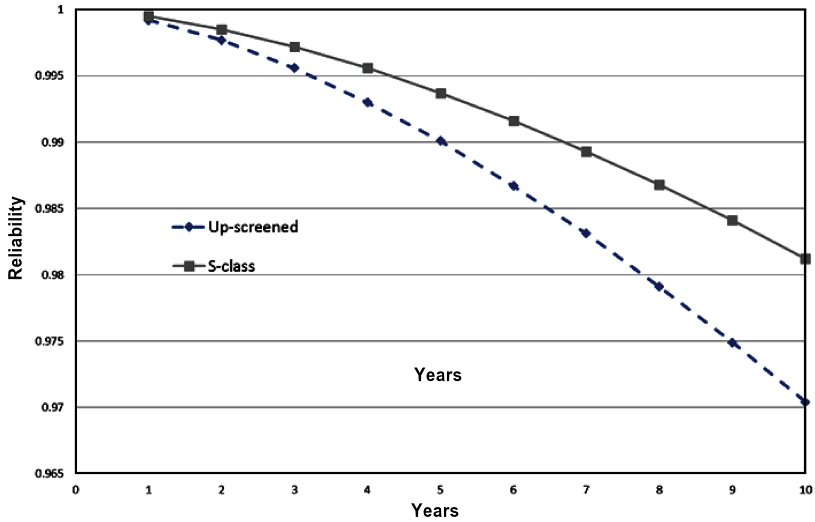


Figure 4. Calculated CTCE reliability depending on part types.

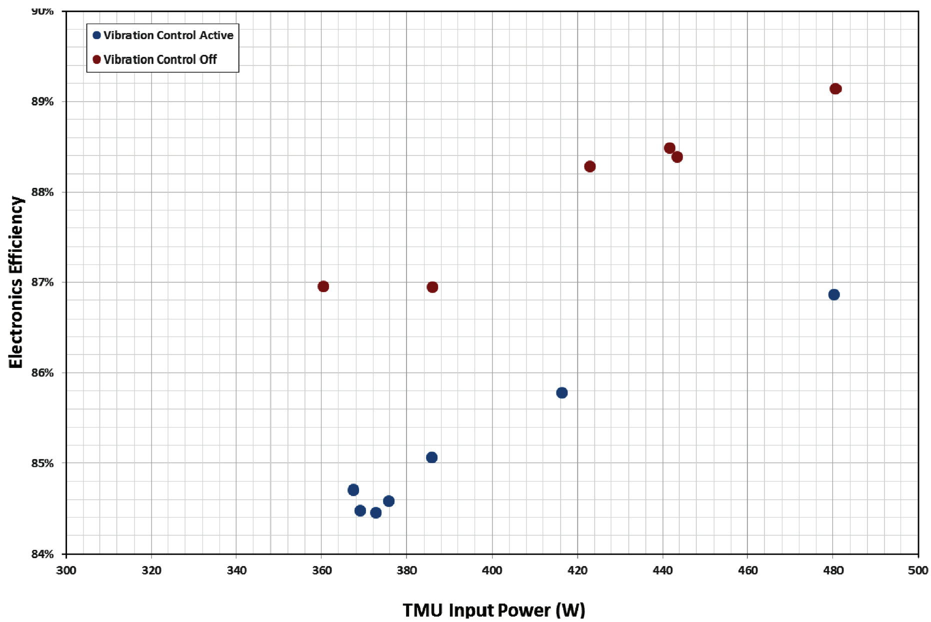


Figure 5. LT-RSP2 CTCE measured efficiency with production LTRSP2 TMU at 55K and 10K with vibration control on and off.

shown in Figure 5. Once the ALFs are integrated into the system the efficiency is expected to be close to 75%.

Exported Disturbance

Prior to the integration of a cryocooler with an instrument, the exported disturbance of the cryocooler must generally be characterized to ensure that it will not degrade the instrument's performance. Such characterization testing has been performed for the production LT-RSP2, which was operated on a dynamometer to determine its exported disturbance levels in the X, Y and Z axes. Prior

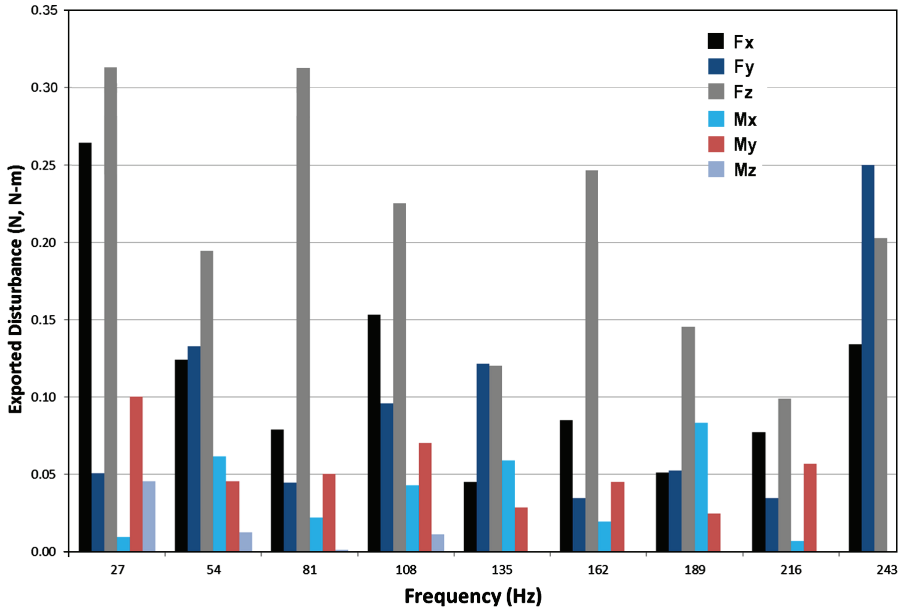


Figure 6. LT-RSP2 cryocooler system production unit exported disturbance levels. Note: levels not shown were not able to be determined due to STE interactions with dynamometer.

to this testing, the dynamometer fixture itself was characterized in order to determine its frequency-dependent transfer functions. Figure 6 shows measured exported disturbance levels for the production LT-RSP2 utilizing Raytheon's Adaptive Feed Forward (AFF) vibration cancellation algorithm implemented while operating at a compressor input power of 367 W. What is interesting is that these exported disturbance levels are similar to what was seen on a Raytheon single stage Stirling cryocooler at 115 W of input power. The results of the exported disturbance testing demonstrate that the production LT-RSP2 produces relatively low levels of exported disturbance, particularly for a cryocooler of its capacity, and that Raytheon's patented AFF algorithms are capable of handling a wide variety of input power levels.

Independent Dual Stage Temperature Control

The capability of the LT-RSP2 cryocooler to shift loads between its first and second stages also provides the basic mechanism for performing independent temperature control at each stage. From Figure 2, it is apparent that each combination of first and second stage loads is accomplished by a unique input power and Stirling phase angle. In its most basic form the two stage temperature control algorithm can be described as automatically seeking this combination of input power and phase, thereby finding the minimum input power which can hold the combination of loads. The actual implementation is a little more complex, as any combination of loads and stage temperatures within the cryocooler's capacity envelope can be commanded and a unique combination of input power and Stirling phase will be determined by the control algorithm. In a typical application the loads are not actually commanded; rather, they are the sum of the instrument parasitic and dissipative loads. The desired stage temperatures are simply commanded to the temperature control algorithm and the required input power and Stirling phase are generated by the controller.

Figure 7 shows a demonstration of the control algorithm's response to step changes in applied loads on each stage and the resulting cryocooler performance. The top chart in the figure shows a history of the first and second stage loads, which were varied during the test. The middle chart shows the Stirling phase and compressor input power adjustments made by the algorithm in response to the load changes. At the bottom, the resulting first and second stage temperature histories are shown. The temperature set points were 55 K and 10 K for the first and second stages, respectively.

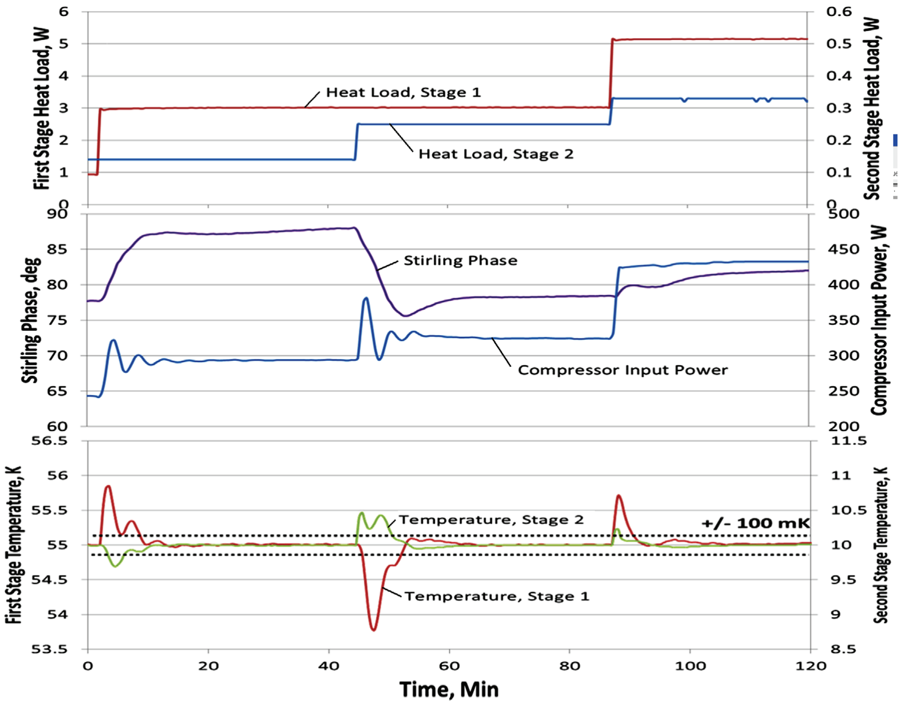


Figure 7. Demonstration of dual stage temperature control response to step functions in applied loads.

During the test, a step change in the first stage applied load was made, followed by a step in the second stage load and finally a simultaneous step at both stages. The control algorithm responded to the first step by increasing both the input power and Stirling phase, consistent with the load map of Figure 1 which showed that an increase in phase results in an increase in first stage capacity and a decrease in second stage capacity. Likewise, in response to the second load step which was on the second stage, the control algorithm again increased the input power but decreased the phase angle. Finally, in response to the simultaneous load step the input power increased and a smaller adjustment was made to the Stirling phase angle. In each case the temperatures at both stages exhibited a brief transient response before converging again to the commanded temperatures of 55 K and 10 K. Temperature stability outside of the transient responses was well within the range of +/- 100 mK, a typical cryocooler temperature stability requirement. The transient responses are exaggerated in this test compared to what would be expected in an integrated configuration due to both a lack of thermal mass attached to either stage, which would greatly slow the temperature responses, and the generally unrealistic step changes in load.

Integrated Performance

The production LT-RSP2 cryocooler has been integrated and tested with an instrument utilizing its cooling capacity at both stages. During this testing, the independent dual stage temperature control and adaptive feed forward vibration cancellation algorithms were successfully demonstrated along with the cryocooler's ability to meet the instrument's cooling requirements. In the integrated configuration, the adaptive feed forward algorithm was able to greatly reduce the magnitude of its feedback signals, provided by load washers, into or near their noise floor and significantly reduce the qualitatively observed level of exported force.

The dual stage temperature control algorithm was also demonstrated during the integrated testing. As shown in the top plot of Figure 8, the additional thermal mass of the instrument improves the temperature stability attained by the control algorithm. In this figure, a temperature set point change

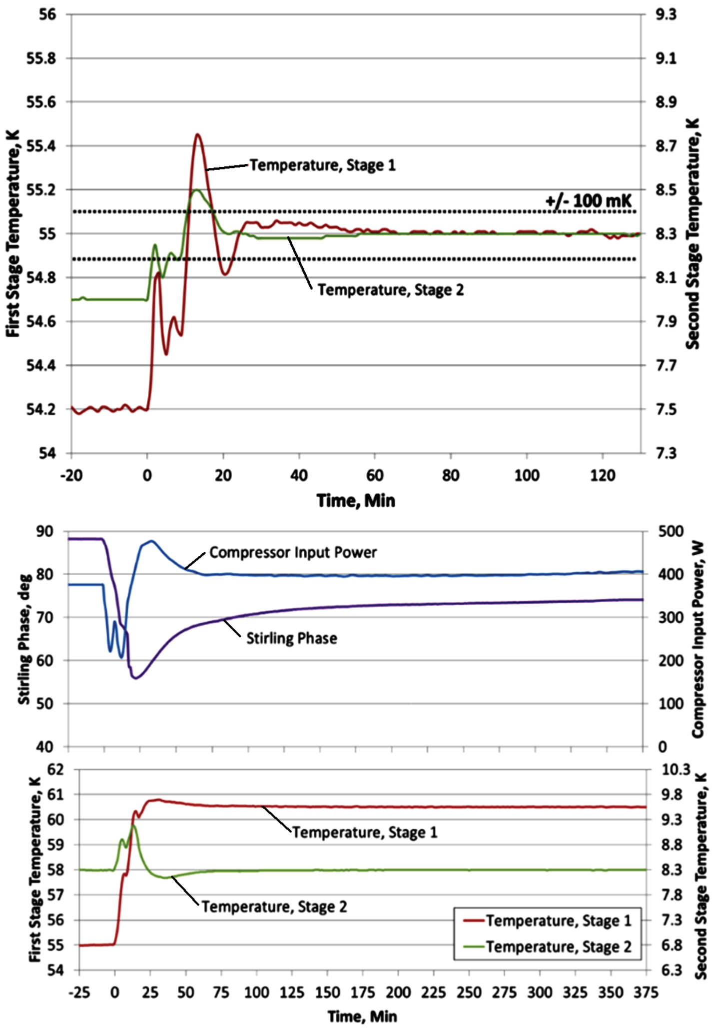


Figure 8. Integrated performance (top) and cryocooler temperature control response (bottom).

is commanded from 54.2 K and 8.0 K to 55 K and 8.3 K on the first and second stages, respectively. Both first and second stage temperatures converged within 100 mK of their set points within 20 minutes of the command being given at 0 minutes.

Similarly, the bottom plot in Figure 8 shows a set point change from 55 K to 60 K on the first stage, while the second stage is maintained at 8.3 K. In the top curves of the bottom chart, histories of input power and Stirling displacer phase are shown while the bottom curves of this chart show the two stage temperature histories. The transition begins at 0 minutes, but this time requires approximately 60 minutes to complete due to the thermal mass attached to the first stage. The control algorithm reduces the Stirling phase in order to change the ratio of first to second stage capacity and shift capacity to the second stage.

CONCLUSION

Raytheon has demonstrated that a relatively simple two-stage linear cryocooler can be used for 10 K refrigeration. The LT-RSP2 provides an attractive option for space and airborne sensors in this temperature range because it avoids the complexity of an auxiliary J-T cryocooler while providing the operational flexibility inherent to the RSP2 architecture. This flexibility results from the unique load shifting ability of the Stirling / pulse tube hybrid cryocooler, which has been harnessed to produce a dual stage independent temperature control capability for the RSP2 machines. The LT-RSP2 has been successively matured over three design iterations, resulting in the current production unit which has now undergone integrated testing with an instrument utilizing both stages of its cooling capacity and a set or control electronics. During this testing, the independent dual stage temperature control and adaptive feed forward vibration cancellation algorithms were successfully demonstrated along with the cryocooler's ability to meet the instrument's cooling requirements.

ACKNOWLEDGMENT

Raytheon would like to thank the Air Force Research Laboratory at Kirtland Air Force Base for their broad support of the RSP2 development and the use of the HC-RSP2 cryocooler in performing initial low temperature testing. The authors would like to further acknowledge the outstanding contributions of the LT-RSP2 design team.

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