Testing of a Closed-Cycle Cryocooler Compressor for Deployment Aboard SOFIA Aircraft

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ABSTRACT

This paper outlines the regimen of developmental and verification tests performed on a Sumitomo Heavy Industries (SHI) model CSA-71A cryocooler compressor intended for installation in the Stratospheric Observatory For Infrared Astronomy (SOFIA) main cabin to support the upGREAT science instrument.

The first series of tests were performed on a large moving platform at the NASA Ames Research Center's Vertical Motion Simulator (VMS), with low frequency (1Hz) bouncing of the compressor to various g-force levels of 0.1g to 0.5g, at 0.1g intervals, simulating turbulence events characterized during typical missions. The next series involved tilting the running compressor over a range of angles to be expected in flight on board SOFIA. After this sequence the compressor was mounted on a shake table where it was subjected to 3-axes random vibrations from 10 to 2000Hz over a range of g-forces.

For the last sequence of tests the compressor was placed inside an environmental chamber to simulate the range of conditions required by NASA for compliance with acceptance criteria established for both mission assurance and airworthiness for flight on board SOFIA.

INTRODUCTION

SOFIA Background

SOFIA is a joint project of NASA and the German Space Agency (DLR). It is an airborne infrared observatory featuring an open port 2.5m gyrostabilized and vibration isolated reflecting telescope integrated into a highly modified Boeing 747-SP aircraft. Flying at altitudes of up to 13.7km (45,000ft), SOFIA is able to make observations above about 99% of the atmospheric water vapor and most clouds, opening a window to the universe in the mid to far-infrared portion of the spectrum that is not available to ground-based observatories, even those on the highest mountaintops.

The SOFIA Program Office is located at the NASA Ames Research Center (ARC) at Moffett Field, CA, while flight operations are nominally based out of the NASA Armstrong Flight Research Center (AFRC) B703, in the Mojave Desert city of Palmdale, CA. An airborne observatory is that it can indeed be strategically deployed to remote locations to enable observations that cannot be achieved from a fixed location, and SOFIA is routinely deployed to Christchurch, New Zealand during the Southern

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Figure 1. The SOFIA Boeing 747-SP, shown here on the tarmac at NASA Ames Research Center (ARC) at Moffett Field, CA, parked just forward of its predecessor, the Kuiper Airborne Observatory (KAO) Lockheed C-141A.

Hemisphere winter to observe targets in the southern skies and to take advantage of the exceptionally cold and dry conditions. SOFIA was deployed to New Zealand at the time of the ICC19 (2016).

SOFIA is the successor to several generations of earlier airborne infrared observatories operated by NASA, which over the years included a Convair CV-990 named "Galileo" (infrared solar and planetary observations from 1967 through 1969), a Learjet with a 12" open port reflecting telescope (1968 through the 1970's), and more recently a Lockheed C-141A Starlifter with a 36" open port reflecting telescope which flew missions from 1974 to 1995 as the "Kuiper Airborne Observatory" (KAO) [1]. See Figure 1 for a photograph showing SOFIA and KAO observatories.

Science instruments that observe in infrared wavelengths must maintain very low and stable temperatures for their focal plane detector arrays, often at or even below 4.2K. While closed-cycle cryocooler (CCC) technologies are ubiquitous in various medical and industrial applications and are commonly used in ground-based observatories. All SOFIA science instruments, like those that flew aboard earlier airborne observatories, have previously relied on expendable liquid cryogens (LN2 and LHe) to cool their cryostats to the required cryogenic temperatures. The SOFIA observatory set the stage for technological advancement towards using a CCC system.

The Science Case for Use of Closed-Cycle Cryocoolers Aboard SOFIA

A number of considerations supported the development of a CCC system qualified for use as an observatory mission system aboard the SOFIA aircraft. These include airworthiness and flight safety issues surrounding the storage and use of volumes of LHe, the increasing cost of LHe, lead-times and logistical complexities associated with procuring and delivering enough LHe to support extended observing campaigns (including deployment to remote bases of operations), and the value of providing infrastructure and support facilities comparable to those to which world-class observatories PI teams and instrumentalists have become accustomed at other.

In addition, the use of CCC systems has enabled the development, commissioning, and use of state-of-the-art detector technologies, such as those being developed and used with the GREAT instrument, designed and built by the Max Planck Institut für Radioastronomie (MPIfR) in Bonn, Germany. GREAT features a modular design that allows two distinct channels, housed in separate and interchangeable cryostats, to be integrated with the telescope on a common structural, optical and electronics "bus" such that they both simultaneously observe the same sky position. Between 2011 and early 2015, four channels were flown and commissioned for use with GREAT on SOFIA, all single-pixel heterodyne THz detectors cooled with liquid cryogens.

The next generation of GREAT channels, appropriately dubbed upGREAT, features a significantly higher number of detector pixels for enhanced observing efficiency, with a corresponding increase in power dissipation from associated active electronics. Volumetric constraints in the modular cryostats preclude use of LN2 and LHe cryogen volumes adequate for hold times at 4.2K as needed to support a full night of observing, further driving the requirement for use of a CCC system.

The upGREAT Low Frequency Array (LFA) channel that was flown and commissioned in May 2015 is a 14 pixel, dual polarization heterodyne receiver array that covers the 1.9-2.5THz range [2]. A 7 pixel High Frequency Array (HFA). which will observe at 4.745THz, is presently in development by MPIfR and is scheduled for commissioning in Fall 2016.

Encouraged by the excellent performance, successful operations, and commissioning of the upGREAT LFA channel and Cryocooler System aboard SOFIA, MPIfR is presently also developing another next-generation 4GREAT cryostat, which will use CCC pulse tube technology, and when combined with the upGREAT HFA channel, will replace all four of the 1st generation liquid cryogen cooled channels. All of these upGREAT and 4GREAT channel developments were made possible by the adoption of CCC technologies, and the development and integration of the enabling CCC infrastructure aboard the airborne SOFIA observatory.

The MPIfR upGREAT team specified a customized two-stage pulse tube cold head from transMIT GmbH (Giessen, Germany), based on its heat sinking capacity, thermal performance with relative insensitivity to tilt angles (important due to normal operational variations of the SOFIA telescope elevation angle), high reliability, and low vibration levels imparted to the instrument cryostat.

NOVEL AIRBORNE APPLICATION OF CCC SYSTEM FOR ASTRONOMY

Development of Closed-Cycle Cryocooler Infrastructure for SOFIA

In close coordination with the SOFIA Science Instrument and Mission Systems development groups, candidate CCC He compressors were evaluated to drive the transMIT pulse tube cold head, with the primary consideration being adequate integrated system thermal performance within a total power budget (for 2 compressors) of 20kVA (3-phase, 400Hz) aircraft power. Several trade studies were conducted, evaluating use of air-cooled versus water-cooled compressors, and use of 60Hz compressors with external frequency converters versus R&D needed to produce a 400Hz compressor. An air-cooled, 60Hz CSA-71A compressor from Sumitomo Heavy Industries (SHI) was selected, despite the fact that this compressor is qualified by SHI for use only with their own Gifford-McMahon (GM) technology cold heads.

The MPIfR upGREAT team already had experience using this compressor in their laboratory as well as in some high elevation ground-based observatories, but significant additional developmental testing was needed to show that it would perform acceptably in our dynamic airborne environment. For example, the SHI documentation included several cautionary statements advising against the use of the compressor downstream of inverters (e.g., frequency converters), and compressed He line runs approaching 40m, considerably longer than the standard 10 to 20m lengths, would be necessary, due to constraints surrounding the location of the compressor in the aircraft cabin, and the need for the flexible lines to traverse a cable wrap with an adequate “service loop” to allow the full range of motion of the telescope.

Typical industrial applications for CCC systems are relatively “static” with the compressors either on casters for portable use on level floors, or mounted to a level concrete pad for a more permanent installation. The technical documentation for the selected SHI compressor specifies a maximum tilt of ±15° for storage / shipping, and only ±5° during operation. In contrast, the SOFIA 747-SP aircraft routinely sees pitch angle variations from about 1° nose down while on the tarmac, to nearly 20° nose up during take-off. The accelerations associated with take-off and landing, as well as turns during ground maneuvers, also impart resultant effective tilt angles that must be considered for this dynamic application. Roll angles, e.g., during banked turns, though routinely higher than the pitch angle variations, are not generally an issue due to the dynamic properties of “coordinated turns,” in which centripetal acceleration effectively nulls the roll angle. Furthermore, an aircraft mounted compressor needs to be able to withstand shock loads, such as those during landing, as well as vibrational loads and airborne turbulence that are well outside the nominal operational environments envelope for these compressors.

Coordination with SHI technical staff indicated that their primary concerns associated with a scroll compressor in such operating conditions were, overheating of the sealed compressor/motor capsule resulting in possible permanent damage, temporary reduction in compressor performance, and reduction in effectiveness of the oil mist separator, leading to loading of the oil mist adsorber canister with potential break-through and migration into the downstream lines. Oil fouling of the cold head, though deemed a very low probability, would almost certainly curtail a flight campaign and require extensive and time-consuming clean-up, and therefore carried a high enough consequence to warrant study. Armed with these concerns, the development team based at NASA ARC devised a development analysis and testing regimen to inform the design, as well as features to mitigate environmental perturbations and associated risks to mission success.

The first step involved characterization of the dynamic environment. Flight data (1Hz rate) representing both nominal and exceptional flight conditions was retrieved from the SOFIA archives, and analyzed to determine quasi-steady load factors on all 3 axes, as well as the resultant effective tilt vector angle. High frequency triaxial vibration measurements were acquired and analyzed to determine both the composite g_{rms} acceleration levels, as well as the power spectral densities (PSDs) from 1 to 2000Hz, characterizing the frequency content and amplitude of shock and turbulence loads. Careful review of these measurements and analyses led to a compressor mount design featuring cable coil vibration and shock isolators, as well as a damped pitch-axis gimbal to keep the compressor level regardless of the attitude of the aircraft and longitudinal accelerations during take-off and landing events.

Developmental Test Hardware and Testing Regimen

An existing test cryostat with its set of internal radiation shields was modified in order to accommodate the geometry of the mounting flange and heat sinks of a SHI RDK-408D2 GM cold head which was procured with the compressor. The headplate of the cryostat was outfitted with wiring feedthroughs and pressure relief valves. Four LakeShore diode thermometers (1 calibrated, 3 uncalibrated) were installed on the 2nd stage heat sink, and wire-wound heating elements were installed on the 1st and 2nd stages of the cold head.

The data acquisition system (DAS) was configured with a data rate to support statistical analyses (Mean, Standard Deviation, Skew) and anti-aliasing, to ensure that temperature oscillations caused by low frequency pressure cycling of the cold head could be effectively filtered out as noise while quantifying the non-oscillatory temperature trends.

This test setup was designed to allow the thermal performance of the integrated CCC system to be characterized and monitored with varying thermal loads, while subjecting the SHI CSA-71A compressor to the regimen of environmental tests organized into test sequences and test cases. In addition to monitoring of the integrated system thermal performance, the internal oil mist adsorber within the SHI CSA-71A compressor was removed and weighed between the test sequences to determine if and to what extent these dynamic stimuli can be correlated with increased rates of oil capture.

The details of these test operations and sequences are documented in several formal test procedures and test reports and are not repeated here but rather summarized in the following paragraphs.

Following initial setup and preliminary baseline performance test runs in the NASA Ames Cryolab, the compressor and test cryostat with the integrated cold head was transported to the Vertical Motion Simulator (VMS), with its large moving platform capable of simulating the low frequency (~1Hz) "bouncing" motion characteristic of typical flight turbulence or "chop." During this test, the He compressor was subjected to simulated turbulence ranging from 0.1g to 0.5 g in 0.1g intervals, for durations of 20 minutes at each level. At the higher g levels, the motionwas applied in bursts, each limited to 10 seconds, to avoid exciting resonance at the natural frequencies of the VMS facility structure and building.

The next series of test sequences back in the Cryolab was designed to study the effects of 2 axes tilting on compressor and integrated CCC system performance. In this test, the thermal performance of the system was measured while the compressor was tilted in both lateral and fore-aft directions (corresponding to aircraft pitch and roll axes) up to the maximum specified tilt level of ±5°.

Random vibration testing of the compressor – now mounted to its shock isolated pallet structure was conducted in the NASA ARC Engineering Evaluation Laboratory (EEL), in accordance with

Figure 2. The instrumented test cryostat with the SHI RDK-408D2 GM cold head is shown in the foreground of the left panel, with the SHI CSA-71A He compressor shown in the background on the moving platform of the NASA ARC Vertical Motion Simulator (VMS) to simulate low-frequency turbulence events. In the right panel, the compressor is shown mounted via its shock isolation mounts to the vibration table in the NASA ARC Engineering Evaluation Lab (EEL) configured for Z axis random vibration environmental acceptance testing. (Not shown here are the test setups for the tilt evaluation testing or the thermal vacuum environmental acceptance testing.)

NASA AFRC airworthiness and mission assurance environmental acceptance standards for equipment mounted in the pressurized cabin of a transport category turbojet aircraft such as the SOFIA 747-SP. During this test, the compressor was subjected to random vibration for 20 minutes in each primary axis, with a composite level of $0.78g_{rms}$ and spectral content per a prescribed PSD profile ranging from 10 to 2000Hz in all axes, and the full -6dB attenuation factor allowed for equipment with mass of ≥ 160lbm (≥ 72.7kg).

Figure 2 shows the test setups for the low-frequency turbulence developmental testing on the VMS platform, and Z-axis random vibration environmental acceptance testing on the EEL vibration table.

Finally, thermal-vacuum chamber testing was conducted as a formal verification to assure compliance with NASA AFRC environmental acceptance airworthiness and mission assurance standards. During this portion of the testing, the compressor was operated within a test chamber capable of the specified range from 0°F to 160°F, and pressures corresponding to altitudes from sea level to 50,000ft. Based largely on concerns voiced by compressor manufacturer SHI related to the operating and storage temperature specifications of some electrolytic capacitors within the compressor's internal power supply, the Cryocooler System project successfully pursued a deviation from the AFRC standard, such that the compressor was to be subjected to only 130°F, while considerably lower than the nominal upper limit of 160°F is still quite high relative to even the highest temperatures that could reasonably be expected aboard SOFIA, even considering extended daytime ground operations out on the flight line during the hot Mojave Desert summer. Because the SOFIA power bus powering the Cryocooler System is protected by a decompression relay that immediately disconnects power in the event of a cabin decompression event, the compressor was shut off for test sequences in which the pressure altitude was ≥ 20,000ft. Given the importance of cooling air mass flow for rejecting the waste heat from air-cooled compressors, particularly when operating at elevated ambient temperatures compounded by the reduced pressures characteristic of a pressurized aircraft cabin at cruising altitudes, some additional attention was focused on the effects of partial obstructions to the cooling air inlet and outlet vents.

Though beyound the scope of this paper, it is also worth mentioning that in addition to the environmental acceptance testing outlined above (colloquially referred to as "Shake & Bake" testing), low-level (0.125g) 3-axes 5 to 150Hz sine sweep modal surveys of the compressor on the vibration table were also conducted, with the compressor/motor capsule and other heavy subassemblies instrumented with accelerometers to identify any resonances, with particular attention to any natural frequencies and resulting magnifications below 20Hz, as excitation of these lower frequencies are not effectively attenuated by the selected shock and vibration isolation mounts. Several structural modifications were made to stiffen such subassemblies and raise their natural frequencies to above 20Hz. Additional proof and burst pressure testing of pressurized systems was also conducted to satisfy FAA qualification and acceptance criteria for pneumatic systems.

Summary of Results, Discussion and Conclusions

As with the details of the various test procedures and sequences, a quantitative analysis of the measurements and statistical parameters is outside the scope of this paper but are summarized in the paragraphs below.

One very important finding was that despite the concerns voiced by SHI technical staff, the operations and thermal performance of the integrated CCC system appeared to be largely insensitive to most of the dynamic and environmental conditions to which the compressor was subjected during this testing regimen. The low frequency simulated turbulence, compressor tilting, and 3-axiesrandom vibration testing all resulted in barely detectible performance effects, considering the temperature readout precision and noise.

The one test in which a statistically significant perturbation in thermal performance was noted (manifested as a readily measurable increase in the mean temperature of the cold head 2nd stage heat sink) was the environmental acceptance testing of the compressor operating in the thermal vacuum chamber. However, correlation of the observed temperature increases with the variations in positioning of the compressor within the constrained interior dimensions of the test chamber supports the conclusion that even modest obstructions in the compressor's cooling airflow had a more significant effect than either the ambient temperature or pressure on the thermal performance of the integrated system.

Additional mitigating features implemented in the design include augmented instrumentation of the compressor to enhance visibility into the nominal operating temperatures and pressures and identify any trends that might indicate an incipient failure, coupled with a programmable logic controller (PLC)-based control system to monitor these conditions as well as housekeeping signals from the compressor, with programmable warning and alarm thresholds for these parameters, and logic to shut down the compressor if deemed necessary or prudent. An external oil mist adsorber canister and molecular sieve filter were installed in the high pressure (supply) line, as well as a sight glass between the internal and external adsorbers, to provide a visual indication of any oil mist that somehow made it past the internal adsorber to migrate outside of the compressor.

Though some of these tests and mitigations may well have erred on the side of caution, they provided the development team, the SOFIA Program, and PI team stakeholders the confidence to proceed, as well as quantitative dynamic limits which were used to establish compressor cut-off thresholds that were programmed into the PLC-based controller.

The result is a robust and reliable system that, despite operations well outside the nominal, meets specified environmental conditions, has now performed flawlessly on several flight series, including the successful commissioning of the upGREAT LFA channel and several observing campaigns. The Phase 1 Cryocooler System is presently aboard SOFIA in Christchurch, New Zealand for its first Southern Hemisphere deployment, where it continues to operate flawlessly in support of observations with the upGREAT LFA channel. Figure 3 depicts the Phase 1 Cryocooler System and the GREAT instrument (with the upGREAT LFA channel) installed and operating aboard SOFIA.

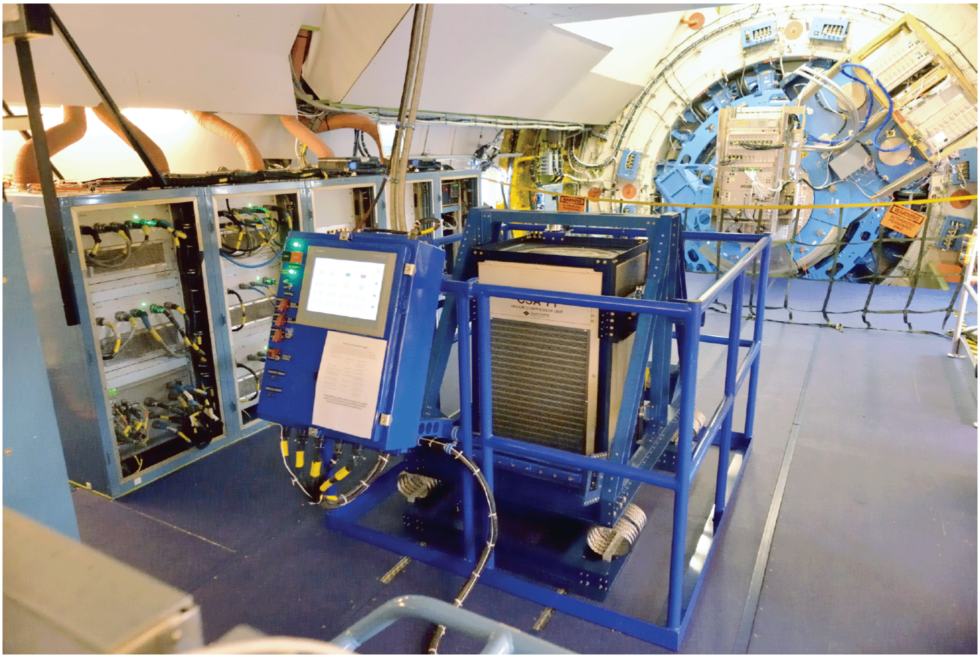

Figure 3. The Phase 1 Cryocooler System SHI CSA-71A He compressor shown installed here in the foreground on the SOFIA main cabin in its shock isolated pitch-axis gimbal mount, with the GREAT Science Instrument in the background, mounted to the SOFIA Telescope instrument mounting flange. The Programmable Logic Controller (PLC) based Cryocooler System control system with the touchscreen Graphical User Interface (GUI) is mounted to the guard rail surrounding the gimbal mounted compressor.

At the time of this publication, the SOFIA Program is investigating options for development of a Phase 2 CCC system, with two He compressors which will support simultaneous and parallel operation of two cold heads, and allow concurrent operation of both the upGREAT LFA and HFA channels, as well as the upGREAT HFA and 4GREAT channels. Unlike the Phase 1 Cryocooler System, which is installed aboard SOFIA temporarily when needed by a Science Instrument, the Phase 2 Cryocooler System will represent a permanently installed observatory mission system.

It is notable that both of the candidate 3rd generation SOFIA Science Instruments selected by NASA early in 2016 for competitive Phase A Instrument Concept Studies and follow-on development to support integration, test and commissioning flights planned for summer of 2018 will also use CCC technology in lieu of expendable liquid cryogens for cooling to cryogenic temperatures.

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