Cryocooler Integration and Testing for the Ultra Compact Imaging Spectrometer Airborne (UCIS-A) Instrument

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ABSTRACT

Objects of interest to the DoD community require higher resolution and broader spectral range compared to typical commercial cameras. While commercially available Hyper-Spectral-Imagers (HSI) have typical spectral ranges of 500 to <1,100 nm or 1,300 to 2,000 nm, a wider spectrum of 400 to 2,500 nm is optimum for the broad range of objects of interest to the DoD community. Additionally, high Signal-to-Noise-Ratio (SNR), low scatter, and low Ground Sample Distance (GSD) are needed for desired detection properties. The Ultra Compact Imaging Spectrometer Airborne (UCIS-A), being developed by Jet Propulsion Laboratory with support from West Coast Solutions and others, embodies all of these characteristics at state-of the-art levels. The cryogenic cooling requirement on UCIS-A is met with an AIM SF070 flexure-type linear Stirling cryocooler for the lower stage (focal plane assembly) and a similar but larger SF100 cooler for the upper stage (optics). An aggressive < 2-hour cool-down time from takeoff drove the need for two cryocoolers. This paper describes how this and other unique mission requirements drove the cryocooler selection and integration, the detailed and system level thermal cryocooler modeling approach and results, and experimental data (bench-top and in-situ).

SPECTROMETER DESCRIPTION

UCIS-A achieves its spectral range with a variable blaze, structured groove grating. This has been achieved with very low scatter by JPL's Micro Devices Lab (MDL) [1,2]. High SNR is with a low noise, high sensitivity Focal Plane and electronics, and large collecting angles. Signal is proportional to the product of solid angle and detector area (étendue). Faster optical f-numbers (f/#, ratio of aperture to focal length) and larger detectors will allow more signal to be collected. UCIS-A electronics are designed to be read noise limited, which means the detector Read-Out-Integrated-Circuit (ROIC) determines the noise floor.

The UCIS-A Opto-mechanical design, highlighted in Figure 1, features a one-piece aluminum bench and mounts with aluminum mirrors. This makes the instrument insensitive to temperature changes and minimizes temperature gradients. The sides of the bench are open to allow direct access for adjustments, baffle assembly and cleaning. Precision cross-blade flexure mounts are used for the grating and FPA assemblies to allow clocking de-coupled from other adjustment. The clocking is

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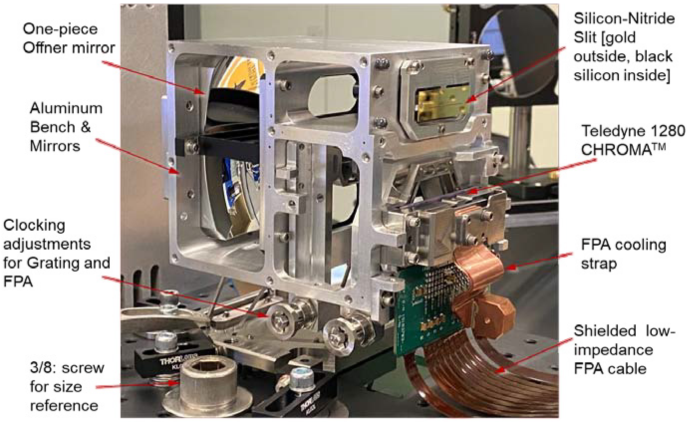


Figure 1. UCIS-A Engineering Model (EM) spectrometer during assembly at Jet Propulsion Laboratory (JPL). Shown prior to cryocooler and optical closeout shield installation to optimally reveal the key optical components

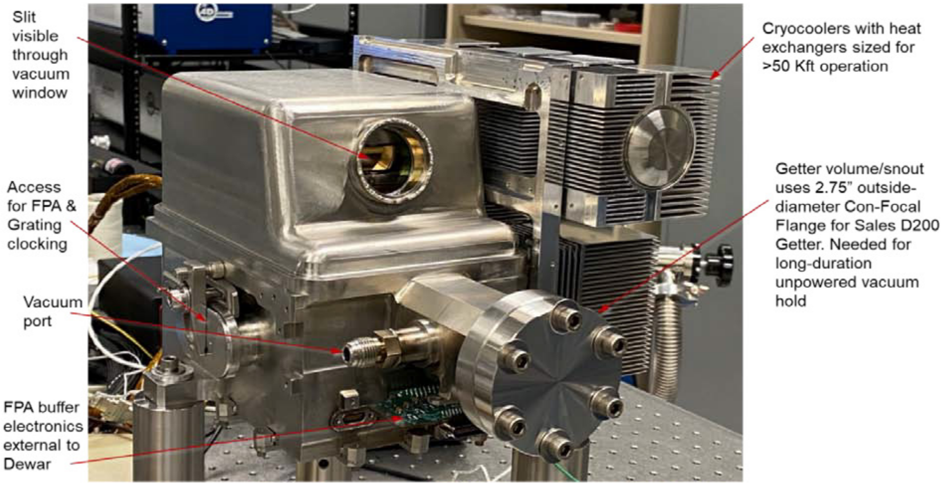


Figure 2. UCIS-A Engineering Model (EM) fully integrated in vacuum enclosure with cryocooler subsystem.

accomplished using differential adjusting screws with micro-radian resolution. The clocking nuts can be adjusted while the instrument is under vacuum and cold using a linear-rotary feed-through tool (not shown). Using this tool, near perfect alignment can be achieved.

The instrument optics are housed inside a vacuum Dewar designed for use in limited access aircraft installation; see Figure 2. The Dewar seals are welded at the final integration stage to assure no leakage. The cryocooler cold fingers inside the Dewar have a welded seal to the external expander and compressor. High surface area heat exchangers are needed for the low-density air of the UCIS-specified 50K ft alttude and above; operation at a ceiling of 30K ft may enable some mass and volume reduction on the heat rejection subsystem. High performance ducting and three high altitude fans (not shown) are included with the UCIS-A Assembly.

The cryocooler heat rejection system with air ducting and three high altitude fans is shown in Figure 3. For UCIS-A, WCS engineered the cooling system shown for a conservative worst-case hot day at 50K ft operation. This allows improved efficiency by lowering the temperature of the

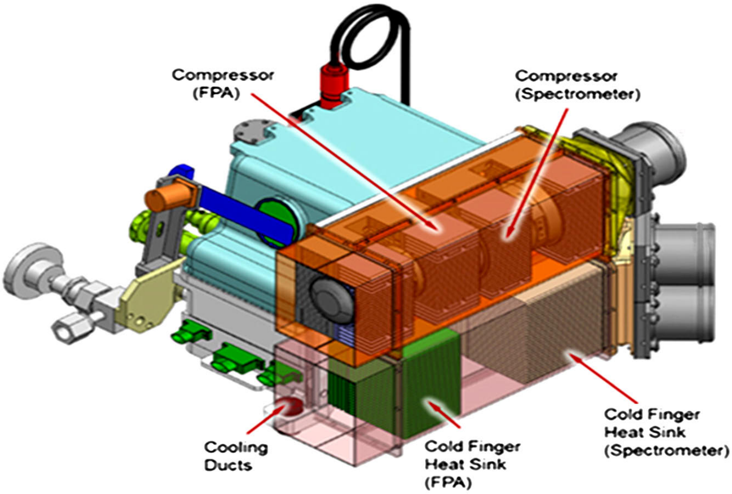


Figure 3. UCIS-A cryocooler and heat reject subsystem.

cooler bodies under high-power, high-altitude operation, which typically occurs as the aircraft reaches 50 K ft but is still operating the coolers at full power to achieve operating temperature. The system shown was carefully optimized through extensive computational fluid dynamics (CFD) analysis, with this end result being highly-tuned for the UCIS-A mission. This paper focuses on the cryocooler subsystem design, testing, and projected in-mission performance.

CRYOCOOLER SELECTION

The original design concept was optimized for size and mass and utilized small rotary coolers, which were selected based on the steady-state cooling loads. The resulting > 4 hour cooldown time was deemed too long by the program office, which provided a worst "Design-To" case to drive what ultimately became the final cryocooler selection:

1. Initial temperature = 26.7 ºC at ground altitude (0 ft).
2. Operational altitude (50K ft) achieved 60 minutes after takeoff; temperature at altitude = 22.0 ºC.
3. Initial operational capability required within 60 minutes of reaching altitude (120 minutes total after takeoff).
4. Approximately <160K required for FPA.
5. Approximately <240K required for the Optical Bench.
6. Stable temperatures and full functionality within 180 minutes of reaching altitude.

A broad industry survey was performed to determine the optimum off-the-shelf solution for the UCIS system. Key considerations and decision rationale were as follows:

- Dedicated cooler at each stage as opposed to one larger cooler at the colder stage yielded faster cool down and better control over the stage temperatures.
- Linear cryocoolers instead of rotary coolers with the resulting increase in target capacities of >9W @ 200K and >3.5W @ 150K to achieve the cool down time.
- Linear cryocoolers also preferred because the exported vibration remains predictably at the harmonics of the drive frequency, whereas in a rotary cooler the speed and thus harmonic content of the exported vibration varies.
- Package size was a key discriminator, which quickly led to the decision to use Stirling rather than pulse tube coolers.

- Desire to have the FPA and bench cryocoolers be provided by the same vendor for purchasing and systems engineering simplification;
- Cryocooler vendor responsiveness to requests for engineering data to support the trade study.

Thales Cryogenics, L3, Cobham, and AIM were all found to have competitive offerings, with the combination of an AIM SF070 and AIM SF100 [3] selected based on the results of Pugh matrix-based study weighing all of the factors provided above.

CRYOCOOLER SUBSYSTEM RISK REDUCTION TESTS

The UCIS Cryocooler Subsystem consists of one SF070 and one SF100 cryocooler, each driven with a dedicated AIM DCE100 controller, and a custom two-channel input ripple filter (IRF) that feeds both DCE100s. A photograph of the UCIS-A IRF is shown in Figure 4. The purpose of the IRF is to reduce what would otherwise be over 8 amps of low frequency (100 Hz) ripple from the SF100, plus about 3 amps from the SF070 at 110 Hz, down to <250 mArms at all frequencies below 1 kHz in order to ensure the current ripple from the cryocoolers does not have deleterious effects on the other payload electronics. The IRF provides the additional benefit of boosting the 28 VDC power from the payload bus to 32.5 V output to the DCEs, near the maximum rated input voltage limit, which as described later in this paper later turned out to be very important to boost the cooling output from the SF100 cryocooler.

A block diagram of the cooling subsystem, together with the critical test equipment including a high performance Yokagawa 1800WT power analyzer, is provided in Figure 5. The setup was configured to mirror the real system while incorporating the Yokogawa to take accurate measurements of the power out to each of the DCE100s and then out to each of the coolers. The DCE100s were controlled through an AIM-provided GUI with two instantiations of the application active, one for each cooler. Note that DT670 Lakeshore temperature diodes were used for temperature feedback to the DCE100s. The DCE100 temperature channel is configured for a 2N2222 diode-wired transistor, so a measurement offset error is expected. To help characterize the offset and ensure accurate knowledge of the cold tip temperatures, each cryocooler cold tip was equipped with a copper block housing with two DT670 diodes. One of the diodes was controlled and measured by a calibrated Cryocon Model 22C temperature controller to provide "truth," and the other diode was wired to its

Figure 4. UCIS IRF. Measured results: >90% above 25W, peak efficiency 97.2% at 151W.

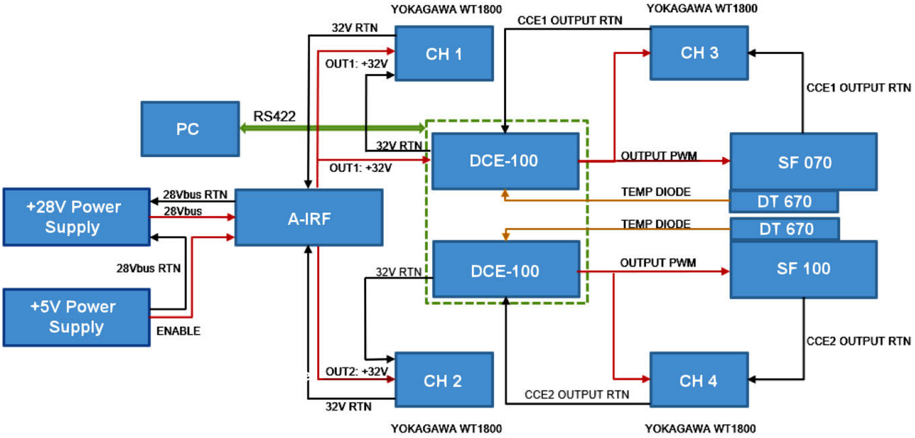


Figure 5. UCIS-A Cryocooler Subsystem Benchtop Block Diagram

respective DCE100 for use in the temperature control loop. In addition, each cold block included a resistive heater to enable application of known thermal loads (not shown in the figure).

The hardware test configuration is depicted in Figures 6 and 7, which are opposite views of the same model. To help ensure the compressor and expander housings stay under the target +50 ºC on the previously-defined worst case hot day, with cooling dependent on the rarefied air of 50K ft, the warm end housings are mounted in CFD-optimized aluminum heat sinks within tightly fitting ducts with forced air pulled through the system by a set of fans. For this test, the actual flight heat sinks were available and therefore used. Because of part availability and in the interest of reducing cost, the ducts were a combination of sheet metal and 3D printed parts to closely approximate the flight design, and two (2) COTS fans were used to mimic the pressure-flow characteristics of the three (3) flight AXIMAX 415YH long-life fans. The heat sinks, ducts, and fans are shown together in Figure 6.

The cold fingers can be seen in the opposite view in Figure 7. This figure actually shows an earlier test when the cold fingers were operated in an "open dewar," i.e., a box that temporarily took the place of the vacuum dewar for testability prior to final assembly into the dewar. The open frame shown facilitated a convenient dry nitrogen bagging of the cold tips to enable cold testing without ice formation. As noted, the cold tips were instrumented with copper blocks, each with a heater and two temperature diodes, prior to insertion into the final vacuum setup.

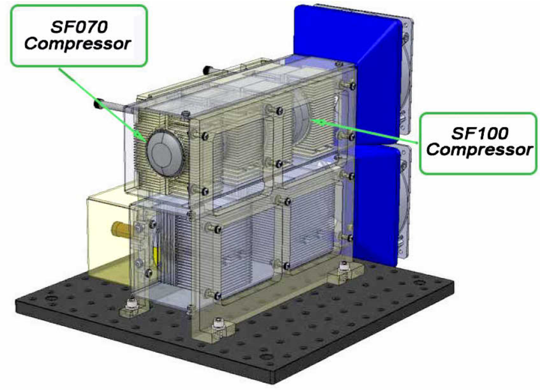


Figure 6. Cryocooler Subsystem Test Setup – Cryocooler Housing View

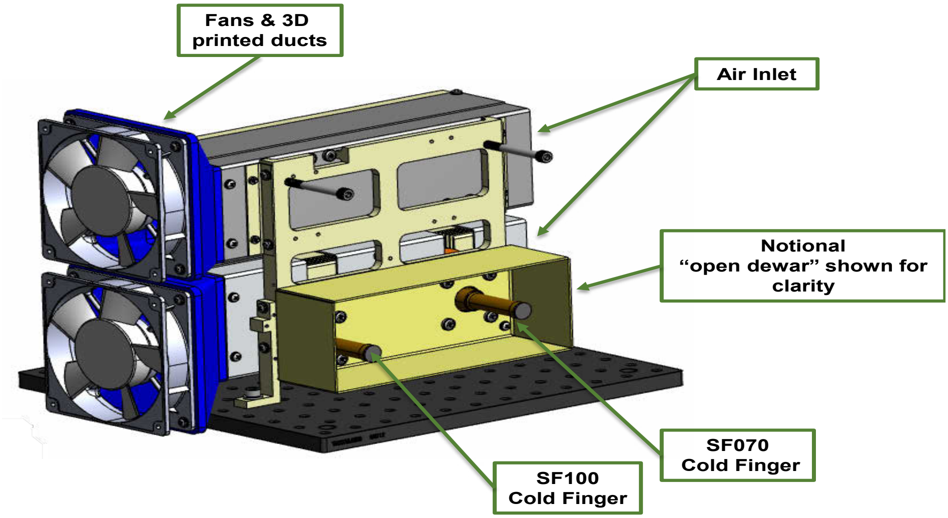


Figure 7. Cryocooler Subsystem Test Setup – Cryocooler Cold Tip View

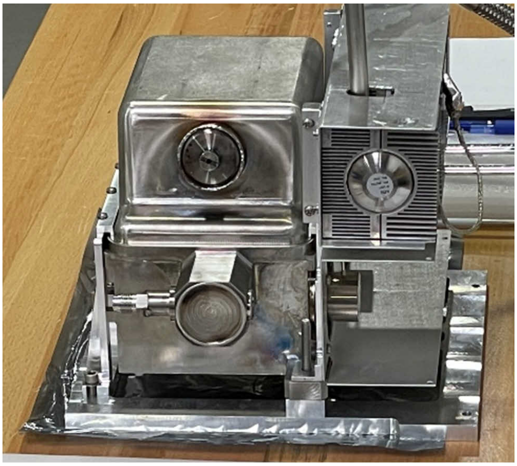


Figure 8. In-process assembly photograph of cryocooler risk reduction subsystem. Photograph taken after cold heat instrumentation and vacuum integration, during purge-charge, and before final duct close out.

A photograph of the nearly fully-assembled test article is shown in Figure 8 during helium purge-charge of one of the cryocoolers. The left side of the photograph is the vacuum test dewar, which was adapted from the real system design and thus includes features of the spectrometer not necessary for this level of testing, it should be noted. The expander heat sinks and the final duct closeouts had not yet been installed at the step in the build sequence depicted.

An extensive set of tests were performed to verify and characterize the performance of the cryocooler system to reduce risk for later integration into the spectrometer. Those tests included:

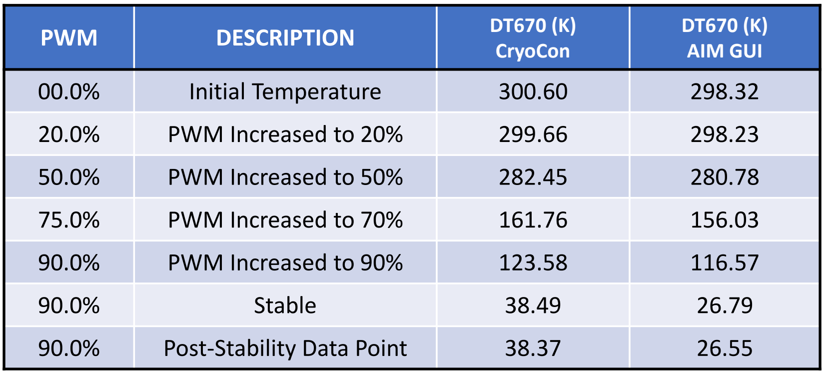
- Manual Cool Down / Functional Checkout
  - Turn on both coolers at 10% PWM; verify both cold blocks are cooling and electronics are functioning nominally.
  - Staying within the safe operating area (SOA), increase both coolers as a pair in nominally 10% steps up to maximum power for each.

  - To ensure a clean fill of gas has been achieved, i.e., to screen for condensing/freezing volatile contamination, monitor stability of cold tip temperatures at No Load, constant input power, and constant reject temperature.
- Steady State Closed Loop
  - Put the DCE100s into Temperature Control Mode with the SF070 setpoint = 140K and the SF100 setpoint = 210K.
  - When the cold tip temperatures are attained, apply 1.7W heat to the SF070 and 3.4W to the SF100, which approximate the expected steady state loads within the spectrometer. Allow the system to reach equilibrium and take a complete data set (power and temperature measurements).
- Maximum Cooling Power
  - Reduce setpoints to 130K (SF070) and 200K (SF100).
  - Increase the heat load of the SF070 in 0.25W steps, allowing the cooler to restabilize between setpoints. Keep increasing power until the cooler can no longer maintain temperature.
- Repeat for the SF100.

The overriding objective was, through execution of the above and other tests, to verify as-expected operation prior to insertion into the spectrometer and this objective was accomplished. Some particularly noteworthy results are depicted in Figures 9 and 10. Figure 9 summarizes one of the tests in which the DT670 actual value (DT670) was compared to the as-read value by the DCE100 and as reported on the AIM GUI, which as a reminder assumed a 2N2222 wired as a diode temperature sensor. Note that towards the bottom of the range of interest for UCIS-A, the offset around 150-160K is considerable (about -6K). In order to achieve the target temperatures in the real system, the DCE100s will be set to about 6K lower than the desired value for the FPA cooler and about 2.5K lower for the Bench cooler.

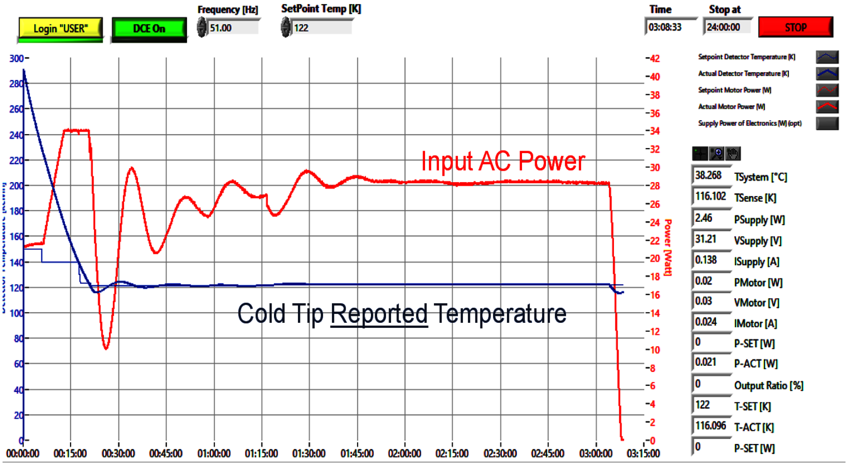
Figure 10 shows a typical cooldown, this one for the SF070, in Temperature Control Mode. For this test case the setpoint was 120K, which corresponds to about 127K actual (see Fig. 9). The AC power to the cooler starts out around 20 W, quickly ramps up to the DCE100-determined safe maximum of about 34 WAC, and then backs off and controls as “120K” is achieved and stable operation is attained with the power leveling off around 28 WAC. This was the desired and expected behavior and typical of the many SF070 cool downs.

The SF100 performance curves were similar, but it was observed that unlike the SF070, the DCE100 was not able to drive the SF100 to the maximum safe limits of the cryocooler hardware, which resulted in the SF100 coming up a little short of the target 9.0 W at 200K (8.6 W achieved).



PWM	DESCRIPTION	DT670 (K) CryoCon	DT670 (K) AIM GUI
00.0%	Initial Temperature	300.60	298.32
20.0%	PWM Increased to 20%	299.66	298.23
50.0%	PWM Increased to 50%	282.45	280.78
75.0%	PWM Increased to 70%	161.76	156.03
90.0%	PWM Increased to 90%	123.58	116.57
90.0%	Stable	38.49	26.79
90.0%	Post-Stability Data Point	38.37	26.55

Figure 9. Comparison of actual (CryoCon) and DCE100-meaured (GUI) temperatures during the manual testing. Note that these measurements were not necessarily taken at steady operating points.



Frequency [Hz] 51.00
SetPoint Temp [K] 122
Time 03:08:33
Stop at 24:00:00
38.268 TSystem [°C]
116.102 TSense [K]
2.46 PSupply [W]
31.21 VSupply [V]
0.138 ISupply [A]
0.02 PMotor [W]
0.03 VMotor [V]
0.024 IMotor [A]
0 P-SET [W]
0.021 P-ACT [W]
0 Output Ratio [%]
122 T-SET [K]
116.096 T-ACT [K]
0 P-SET [W]

Figure 10. Typical automated AIM SF070 Cryocooler cool down behavior as recorded on the AIM-provided GUI main display. “Input AC Power” and “Cold Tip Reported Temperature” labels added to the GUI display for clarity. Factory-setting temperature control loop settings were used; no attempt was made to tune the loop parameters.

The output PWM percentage was seen to reach 100% and stay there during cool down, indicating that the DCE100 firmware was not limiting the power. This was observed during both initial operation with a 28V power supply, and later during operation in the full-up configuration with the constant 32.5V supplied by the IRF. Therefore, it was concluded that the power to the cooler, and thus nearly identically the cooling capacity, is proportional to the input voltage the SF100 DCE100 controller over the range of UCIS-A interest.

IN-SITU PERFORMANCE

The next and final step in the test sequence was to integrate the cryocoolers into the spectrometer to complete the correlation of the UCIS-A Thermal System Model, depicted at a very high level in Figure 11. The ten (10) node, control volume-type energy and heat flow model shown was created

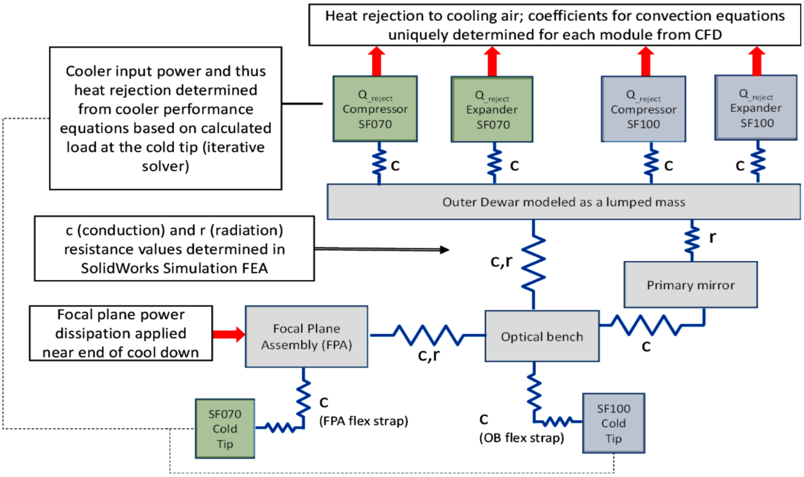


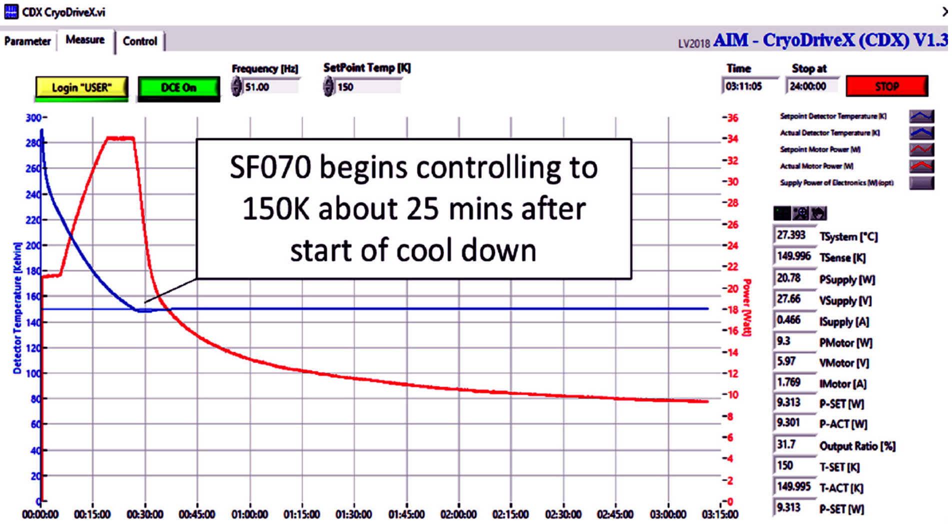
Figure 11. Block diagram of UCIS-A Thermal System Model. This model combines the CFD results for the heat sinks, the conduction and radiation thermal FEA results, and the cryocooler performance curves.

in Engineering Equation Solver (EES). The parameters used to model the heat rejection from the cryocooler warm ends to the air stream were determined using ANSYS Fluent computational fluid dynamics (CFD). The initial values for the conduction and radiative heat transfer links between the nodes were extracted from the results of a detailed SolidWorks Simulation finite element analysis (FEA) model. The cryocoolers were initially modeled based upon vendor data, and then updated based on the results of the above-described cryocooler subsystem test. By using these three software packages, ANSYS Fluent, SolidWorks Simulation, and EES in tandem in this manner, a full multi-physics system model was achieved that could run a full transient case out to 8+ hours of real time operation in just a matter of minutes.

The cryocooler subsystem was relocated from West Coast Solutions to Jet Propulsion Laboratory for the spectrometer thermal testing. The WCS-JPL Team installed the cryocoolers into the spectrometer along with the heat sinks and test fans and ducts. However, the IRF was not available due to other program needs at the time of this testing, so the DCE100s were powered directly from a 28V laboratory power supply. The voltage of the supply sagged to about 27.4V during cool down with both cryocoolers at maximum power, so the delivered SF100 cooling capacity in this test setup was only about 84.3% (27.4/32.5) of the capacity expected in the payload with the IRF providing a solid 32.5V at the controller input. This was taken into account in the model correlation.

The results for the SF070 / FPA cool down are provided in Figure 12. The cryocooler power up is essentially identical to that observed in the lower-level testing (Fig. 10). In this case 150K was used for the temperature setpoint. Evidently, the substantially larger thermal mass of the real instrument results in much less power oscillation. In fact, even after 3 hours, the power is still dropping, showing that the spectrometer still has not reached steady state. As noted, the data showed that the cold tip reached 150K (actually ~156K; see Fig. 9) after about 25 minutes. The similar cool down curve for the SF100 / Bench showed the setpoint temperature, in that case ~210K, was achieved in 90 minutes. These results were used to "tune" the numerical model by adjusting the effective thermal strap numbers to represent the combination of thermal strap resistance and internal resistance within the FPA and Bench nodes. In the case of the FPA, this was a small adjustment to the strap conductance value, but in the case of the substantially larger and more complex Bench, the effective strap conductance had to be reduced by about 50% to match the as-measured results.

With just the adjustment of those two parameters, i.e., the cold tip thermal strap effective conductance, excellent correlation was achieved as shown in Figure 13. The Bench cooldown time



Frequency [Hz] 51.00
SetPoint Temp [K] 150
Time 03:11:05
Stop at 24:00:00

27.393 TSystem [°C]
149.996 TSense [K]
20.78 PSupply [W]
27.66 VSupply [V]
0.466 ISupply [A]
9.3 PMotor [W]
5.97 VMotor [V]
1.769 IMotor [A]
9.313 P-SET [W]
9.301 P-ACT [W]
31.7 Output Ratio [%]
150 T-SET [K]
149.995 T-ACT [K]
9.313 P-SET [W]

SF070 begins controlling to 150K about 25 mins after start of cool down

Figure 12. SF070 cool down results in the spectrometer. The SF070 is connected to the Focal Plane Assembly with a flexible thermal strap. The temperature control diode is on the cryocooler-end of the cold strap. A similar arrangement and analogous results were obtained for the SF100 / Optical Bench cryocooler.

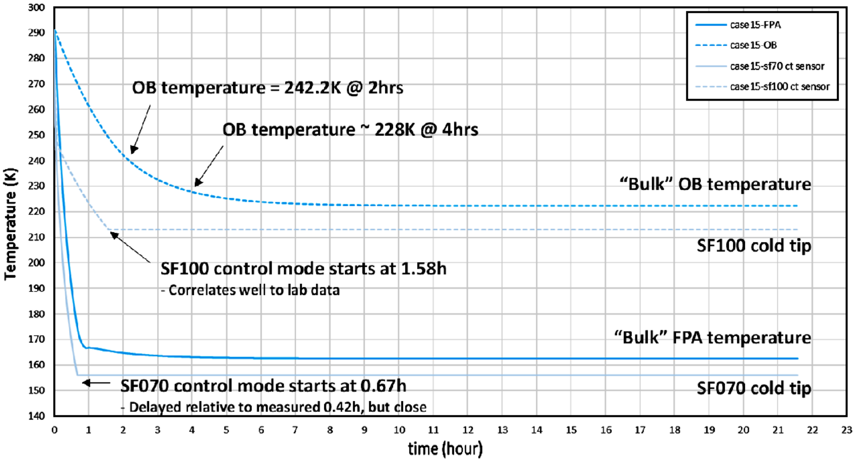


Figure 13. UCIS-A Thermal System (EES) Model output. Showing the correlated modeling results for the lab case.

matches almost exactly, while the FPA cooldown time is slightly conservative at 40 minutes versus the 25 minutes measured.

The results predicted for the airborne Worst Case are provided in Figure 14. The first key observation is that a quick comparison to Figure 13 reveals that the lab ambient results are quite similar, and, if an IRF had been used for the lab case, it would have been even more similar to the point of being almost indistinguishable. The result becomes much less surprising when one considers that the lab ambient and "worst case" airborne temperatures are about the same and the thermal loads are largely driven by the Dewar temperature, which is going to track with the surrounding air temperature. Furthermore, with the efforts taken to optimize the heat sinks and fans so that thermal performance is not limited by the rarefied air at the operating altitude, the rejection temperature in both cases ends up being about the surrounding air temperature. Therefore, it has been shown that ground thermal testing is an excellent proxy for the actual instrument.

The second key observation is that these worst-case cooldown times and temperatures are acceptable. The Optical Bench (OB) is very close to the 240K target at the 2 hour mark, coming up

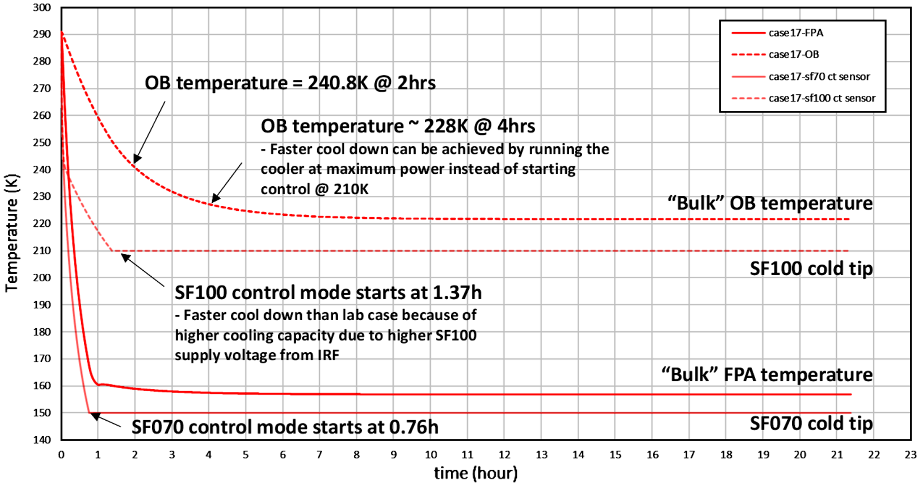


Figure 14. UCIS-A Thermal System (EES) Model output for the Worst-Case Hot Day flight case. The UCIS-A Cryocooler System meets the program's cooldown requirements.

just a little short because of the small deficit in cooling power versus the design capacity as noted previously. The implementation of a slightly higher power controller in follow-on designs is being considered to better maximize the SF100 capabilities, in which case the 240K mark will be met with margin. The FPA reaches temperature (<160K) well within 2 hours.

CONCLUSION AND NEXT STEPS

A cryocooler system consisting of two differently-sized linear cryocoolers, each driven by a dedicated off-the-shelf controller, and with both controllers powered through a custom 2 channel Input Ripple Filter has been developed and demonstrated for the UCIS-A instrument. The development effort consisted of key risk reduction setups, most notably the performance of extensive cryocooler subsystem testing with dummy loads, and also the development and correlation of a system model that combines the CFD and FEA results into a single integrated design tool that is executed very quickly. Based on the modeling and test results, the UCIS-A Team has high confidence that this combination of AIM cryocooler components and the custom WCS-Creare input ripple filter will meet the cryogenic subsystem requirements of UCIS-A.

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