Active Thermal Architecture: Design and Status

Lucas Anderson, Charles Swenson
Utah State University
4170 Old Main Hill, Logan, Utah, 84322; 435-797-2958
l.s.anderson@aggiemail.usu.edu

A.J. Mastropietro, Jonathan Sauder
Jet Propulsions Laboratory, California Institute of Technology
4800 Oak Grove Dr. Pasadena, Ca 91109; 818-354-4338
A.J.Mastropietro@jpl.nasa.gov

ABSTRACT

This paper presents a design update for the Active Thermal Architecture (ATA) project. ATA is a joint effort between Utah State University and the Jet Propulsion Laboratory, funded by the NASA Small Spacecraft Technology Program (SSTP). The objective of the ATA is to develop advanced active thermal control technologies for Small Satellites in support of cryogenic electro-optical instrumentation.

Specifically, the development of a 1U ground-based prototype of a single-phase, two-stage mechanically pumped fluid loop based active thermal control subsystem targeted at 6U CubeSat platforms and above. The first stage utilizes a micro-pump to circulate working fluid between an integrated heat exchanger and a deployed tracking radiator. This heat exchange provides general thermal management to the ATA system and CubeSat. The second stage consists of a miniature cryocooler, which directly provides cryogenic cooling to payload instrumentation. Ultrasonic Additive Manufacturing techniques simplify and miniaturize the ATA system by embedding the flow channels directly into the heat exchanger and the external radiator. The ATA system features dual rotary union fluid joints that, along with a micro-motor, allow for a two-axis deployment of the radiator and solar tracking. The ATA also includes a passive vibration control system which, isolates the optical payload from the jitter induced by the active systems. ATA has been fully prototyped and tested for radiator deployment and tracking,

ATA is a second phase effort with the integrated pumped fluid loop and radiator previously demonstrated by the Active CryoCubeSat SSTP. This technology is suited for the thermal control of any high-powered spacecraft subsystem or the general thermal maintenance of a CubeSat's environment. This project hopes to maturate all relevant technologies to a TRL of 5 or 6

INTRODUCTION

The Active Thermal Architecture (ATA) project is a Small Satellite technology development effort funded by the NASA Small Spacecraft Technology Program (SSTP) and operated in partnership by the Center for Space Engineering (CSE) at Utah State University (USU) and the Jet Propulsion Laboratory (JPL). The projects primary objective is to develop an advanced Active Thermal Control technology for Small Satellite platforms.

The ATA subsystem targets at 6U CubeSat form factors and above and is based on a single-phase mechanically pumped fluid loop (MPFL) design and utilizes a two-stage architecture for Active Thermal Control. The ATA system is capable of thermal management of large thermal loads, on the order of 100 W or more within advanced and high-powered CubeSat's[1]. When coupled with an integrated miniature cryocooler the ATA system is capable of providing CubeSat wide thermal management and temperature control while also delivering cryogenic cooling to advanced IR based Electro-Optical instrumentation payloads in the 60-100 K MWIR and LWIR spectrums[2].

The ATA project is focused specifically on the development, and TRL advancement, of a two-stage deployable radiator via a rotationally flexible fluid joint, a solar tracking drive system for the deployed radiator, and a passive vibration isolation system, to reduce the induced jitter from the ATA system to the CubeSat structures and payload. To this end, the ATA team has developed a relevant ground-based prototype featuring each of the relevant technologies in an integrated 6U CubeSat assembly. The prototype will be leak and fit checked, characterized for exported jitter, tested for launch vibration survival, and thermally characterized in a relevant thermal vacuum (TVAC) environment.

This research effort will advance each of the ATA thermal control technologies as well as the integrated CubeSat system to a TRL of 5 or 6. The ATA system is a unique thermal management technology enabling a new generation of advanced CubeSat based missions in the fields of Deep Space exploration, Heliophysics, and Earth Science otherwise thought impossible for such small satellites.

A summary of the primary objectives and requirement benchmarks for the ATA project is given in Table 1.

Table 1: ATA Project Objectives and Benchmarks[3]

ATA Project Objectives	
1)	Develop a mechanism for deploying a stowed radiator panel from a 6U CubeSat.
2)	Develop a one-axis pointing system for a deployed radiator panel.
3)	Develop a mechanical and thermal isolation system for an integrated cryocooler and an IR-detector assembly.
Required Performance	**Performance Goal**
Two-Stage Flexible Fluid Joint/Hinge Deployed Radiator	
Fluid line dia.: ≥ 5mm deploy distance: > 0 *Mass*: < 0.3 kg *Volume*: < 3x3x10 cm	Fluid line diameter: ≥ 6mm Deploy distance: > 20 cm *Mass*: < 0.2 kg *Volume*: < 2x2x3 cm
Tracking Radiator	
Pointing resolution: < 5° Commanded tracking Turning Range: ±90° Avg. Power: < 50 mW	Pointing resolution: < 2.5° Solar avoidance tracking Turning Range: Continuous Avg. Power: < 10 mW
Vibration Isolation/Cancellation	
Jitter Amp.: < 0.005° Detector Thermal Parasitic: < 200 mW *Mass*: < 0.1 kg *Volume*: < 4x4x1 cm	Jitter Amp.: < 0.001° Detector Thermal Parasitic:< 100 mW *Mass*: < 0.05 kg *Volume*: < 3x3x0.5 cm
Enabled Optical Instrumentation Capabilities	
Cryogenic Instrumentation: Detector Temperatures ≥ 60K MWIR, LWIR Bands (3 – 15 µm)	
IR optical instruments with IFOV > 0.01°	
IR Optical instruments with integration times < 20s	

BACKGROUND

The ATA project is a continuation of the Active CryoCubeSat (ACCS) development effort. The ACCS focused on the design, fabrication, and testing of an MPFL Active Thermal Control subsystem with an integrated miniature cryocooler for Small Satellites. The ACCS also developed a series of analytical and numerical based model design tools and system-based design methodologies, which when coupled with an integrated thermal approach to Small Satellite systems engineering, allows for the rapid parallel design of MPFL active thermal control systems for Small Satellites[1,2].

ATA utilizes several novel technologies, including pumped fluid loops for space applications[4], miniature tactical cryocoolers, miniature accumulators, and Ultrasonic Additive Manufacturing (UAM) technology. UAM is a hybrid additive fabrication process that uses low-temperature solid-state ultrasonic metal welding of foil sheets and tapes along with traditional CNC contour milling to create net-shape solid parts. The technology uses an Ultrasonic weld head to break up material oxides and local surface asperities. A low temperature/pressure high strength, cold state metallurgical weld can then be formed between the two surfaces/materials[5]. These UAM parts can include voids, embedded channels, or integrated instrumentation or electronics[6]. The welded materials can be similar or dissimilar, and material gradients are possible. Parts builds can be as large as 6ft x 6ft x 3ft at a print rate of 30 cubic inches per hour[7,8,9]. Several Down selected COTS parts from the previous ACCS program are used by the ATA project. The first is a miniature tactical cryocooler. The Ricor K508N is a Stirling cycle based cryocooler featuring an integrated rotary system. This cryocooler was down-selected due to its appropriate size for CubeSat applications, its favorable ambient, rejected temperature to input power ratio and its expanded lifetime[10]. In addition, the Ricor K508N has an impressive flight history, including its successful implementation onboard the Curiosity Rover[11]. Figure 1 shows the Ricor K508N cryocooler, while Table 2 details its operating specifications.

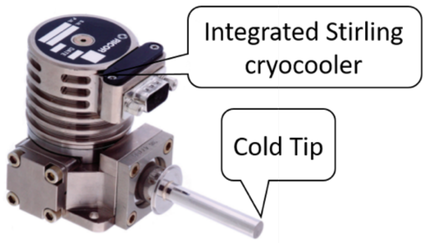


Figure 1. Ricor K508N Cryocooler[10]

Table 2. Ricor K508N Performance Specifications[10]

Ricor K508N Cryocooler (Integrated Stirling Cycle)	
Cold Tip Temperature	77 K
Cold Tip Heat Load	~550 mW
Compressor Input Power	5-10 W (5.5 W Typ.)
Ambient Reject Temperature Range	-40 ºC to +85 ºC
MTBF	+28,000 hr
Mass	475 gm
Form Factor	115.5x58x71 mm

The ATA MPFL relies upon a Micro-Pump from the England manufacturer TCS Micropumps[12]. Specifically, their line of low power high flow centrifugal pumps and high flow high-pressure micro-geared pumps, i.e., the M510 and MGD1000F models. The M510 features an expanded flow range for more diverse Reynolds numbers, while the MGD1000F offers a larger pumping differential. The design of the ATA system can accommodate either pump for a variety of applications.

The parameters considered in the down selection of a micro-pump for an MPFL based active thermal control subsystem include: Large Potential Flow Rate

- Available Pressure Head
- Form Factor
- Mass
- Power
- Mechanical Noise (Vibration)
- Operational Lifetime
- Cost
- Efficiency
- Availability

Figure 2. TCS Micro-Pumps

Table 3. TCS Micropump Specifications[12]

TCS MGD1000F Operating Characteristics	
Maximum Flow Rate	up to 1150 mL/Min
Available Pressure	<4 Bar
Power	<21.6 W
Form Factor	65 X 32 X 30 mm
Mass	110 grams
Mech. Noise	<15 dB
MTBF	>20,000hr
TCS M510 Operating Characteristics	
Maximum Flow Rate	up to 9000 mL/Min
Available Pressure	<10 psi
Power	<28 W
Form Factor	64 X 32 X 31 mm
Mass	100 grams
Mech. Noise	<15 dB
MTBF	>100,000hr

Most MPFL systems require an accumulator to improve performance/efficiency and accommodate the fluid's incompressibility. This change in system pressure can be due to variations in the system's fluid temperature or transient conditions. An accumulator can also serve as a reservoir of working fluid in the case of a small system leak. The ATA team down-selected the HAWE AC-13 diaphragm accumulator due to its appropriate size, fluid reserve volume, and manifold mounting options[13]. Figure 3.

Figure 3. HAWE AC-13 Miniature Diaphragm Accumulator[13]

OPERATIONAL THEORY

The ATA system's operational concept is that of a two-stage active architecture, with a single-phase MPFL serving as the first stage and a miniature cryocooler as the second stage. In the first stage, a Micro-Pump circulates a working fluid between a hot side Heat Exchanger (HX) internal to the CubeSat and an external deployed cold side radiator. UAM techniques embed the working fluid channels directly into the HX and radiator. These integrated channels improve the thermal performance of the HX and radiator by circumventing traditional epoxy or brazed joints and allows for more rapid fabrication and customizable design. Furthermore, UAM helps to simplify and miniaturize the MPFL loop, which is essential for CubeSat applications. The second stage couples to the first stage via the HX plate. Fundamentally, the MPFL serves as an ambient temperature control system for the miniature cryocooler. A customized two axes rotary fluid joint transports the working fluid from the CubeSat internal HX to the external deployed radiator. A Contorque based spring deployment system allows for a one-time deployment of the radiator. A geared micro-motor system than rotates the radiator. These technologies allow for an external deployable radiator, to continuously track throughout the CubeSat orbit. Figure 4 details the ATA CONOPS.

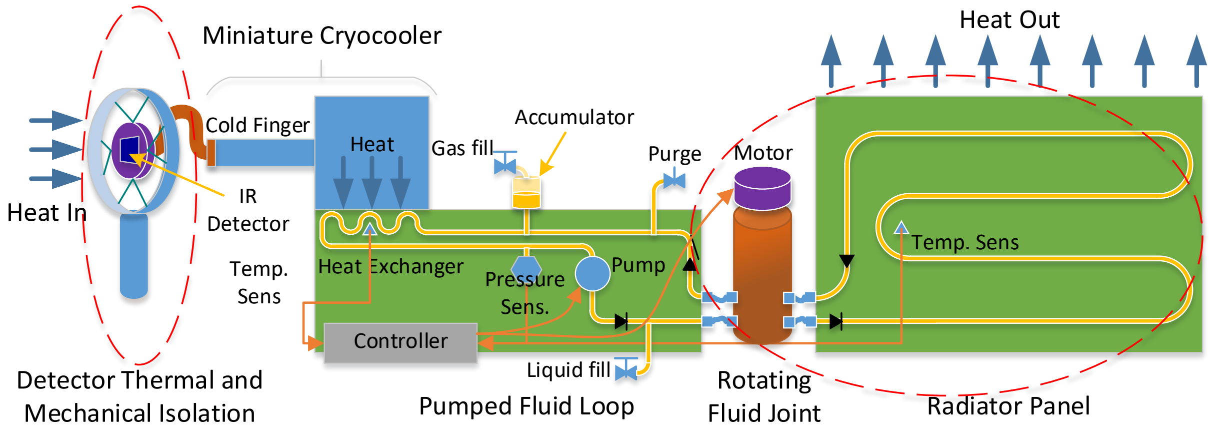


Figure 4. ATA CONOPS[3]

The ATA is an active system and has exported vibe-based jitter, which can affect CubeSat structures, payloads, and the sensitivity of IR instruments. To counteract this exported jitter the ATA system has built in vibration cancellation and isolation. The entire 1U ATA system floats on a series of steel wire-rope isolators. These provide spring-based isolation and wire fiber damping. A customized cold tip particle damper reduces the exported vibration of the Stirling cryocoolers cold tip. A customized pyrolytic graphite thermal strap further isolates the cryocooler assembly from vibe sensitive instruments. Finally, a customized Kevlar string IR detector mount offers superior thermal isolation over traditional detector mount designs while still providing mechanically stable and rigid support. The optical detector orientation can also be fine-tuned via the Kevlar strings and a series of worm-gears. Figure 5 below details the ATA's vibration isolation CONOPS.

Ultimately, the ATA system is a complete end to end thermal solution for advanced CubeSat missions and future IR instrumentation. In addition, the ATA, as an integrated 1U solution, can be scaled to accommodate a variety of thermal design between a 6U CubeSat and a traditional satellite.

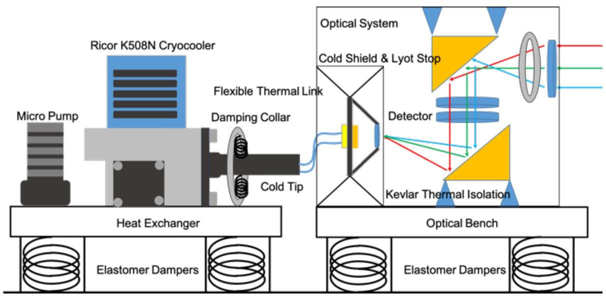


Figure 5. ATA Vibration Isolation CONOPS[3]

REFERENCE MISSIONS

The ATA program was initially proposed as an innovative technology development effort to further advance and support future CubeSat based IR instrumentation for Heliophysics and Earth Science missions. The original inspiration for this was a CubeSat replacement of the Sounding of the Atmosphere in Broadband Emission Radiometry (SABER) instrument on the TIMED mission[14].

SABER is an atmospheric broadband limb-scanning infrared radiometer covering the spectral range of 1.27 – 17 µm for mesosphere and thermosphere emissive trace species. The research returns of the SABER mission included the study of the fundamental process governing the chemistry, dynamics, and energetics of the upper atmosphere as well as vertical profiles of kinetic temperature, pressure, geopotential height, and volume mixing ratios[15]. Figure 6 below is a diagram of the original TIMED satellite with the SABER instrument indicated.

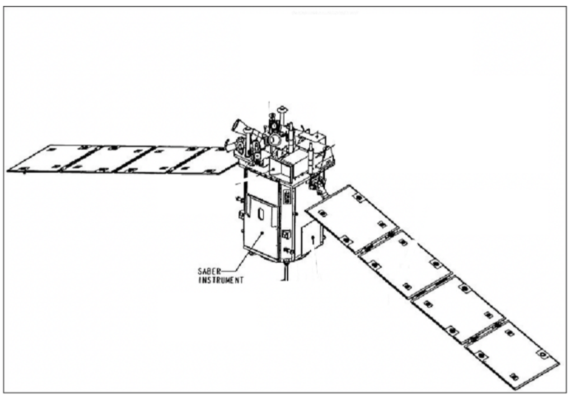


Figure 6. Original SABER instrument on the TIMED satellite[16]

The CSE at Utah State University developed a miniaturized 3-channel version of the SABER instrument for a 6U or 12U CubeSat platform know as SABER-Lite or (TriClops). The SABER-Lite instrument offered research returns similar to that of the original SABER mission with greatly improved global and temporal coverage via CubeSat constellations. In addition, SABER-Lite reduced the operational complexity, time to development, and cost while maintaining many of the original SABER mission capabilities.

The SABER-Lite instrument is unique in that it separates the various emission spectral bands (wavelengths) into distinct optical paths and provides a unique set of optics for each. SABER-Lite than combines groups of these spectral bands onto different portions of the same Focal Plane Array (FPA). The SABER-Lite reference mission provides the strictest requirements on focal plane jitter control and cryogenic detector cooling. Therefore, SABER-Lite drives the ATA requirements for vibration isolation as well as cryocooler performance. A potential SABER-Lite mission CONOPS is shown in the following diagram as well as the fabricated prototype[3,17].

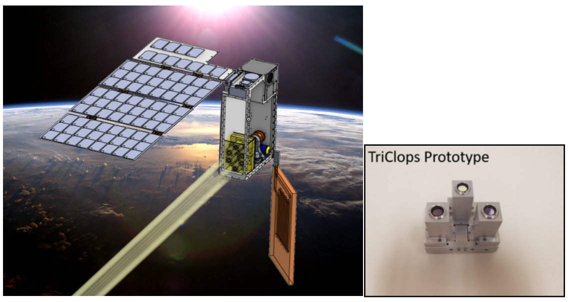


Figure 7. SABER-Lite mission CONOPS featuring the ATA system[3]

Another CubeSat reference mission studied by the ATA project is the National Oceanic and Atmospheric Administration (NOAA) Earth Observing Nanosatellite (EON) IR mission under development with JPL. EON-IR hopes to mitigate gaps in sounder data of temperature and water vapor profiles in the lower troposphere[3]. NOAA would like to extend CubeSat remote viewing capabilities into the Long Wave IR (LWIR), however rejection of large thermal loads, integrated cryocoolers, cryogenically cooled detectors and sub-cooled thermal zones within a CubeSat have offered significant technological challenges. So far, these technical difficulties among others have prevented advanced LWIR CubeSat missions from flying. ATA hopes to change that. Figure 7 shows the design of the NOAA-EON-IR CubeSat[18].

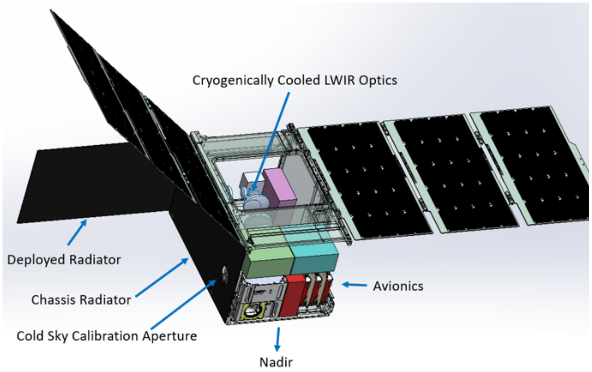


Figure 8. NOAA and JPL EON-IR CubeSat design[18]

ATA DESIGN

The ATA active thermal control system is composed of a variety of technologies. The following sections will detail the basic designs for each of the major components and provide insight into how they function as an integrated whole. The design methodologies utilized for the ATA project include parallel system engineering, multi-disciplinary design, as well as the model-based design tools and strategies developed by the ACCS project.

The ATA subsystem has been integrated into a ground-based prototype 6U CubeSat. This was done to best represent the technology and to advance not only the individual TRL of each subsystem but the integrated whole as well. Figure 9 below shows the CAD-based design of the ATA system as well as the prototyped model.

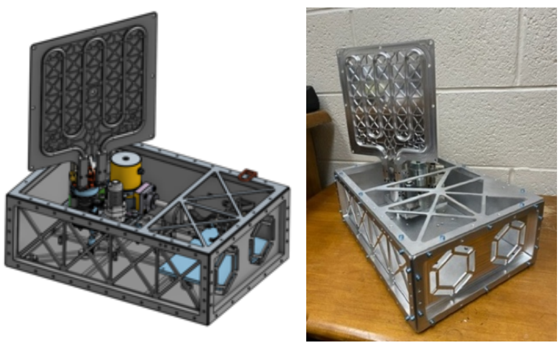


Figure 9. ATA system: Integrated ground-based CubeSat prototype

The ATA system is designed as a 1U solution with the HX, supported by wire rope isolators and a launch lock assembly, forming the footprint and base of the system.

The TCS Micro-Pump, Ricor Cryocooler, Accumulator, Purge & Fill (P&F) valve, and fluid rotary joint/deployment mechanism are mounted vertically in quadrants on the HX surface. This design has several advantages. The primary of which is that the Cryocooler can maintain direct thermal contact with the heat exchanger which offers an improved thermal rejection environment. The flow paths are simplified in a flat plate design and integrated with the Micro-Pump, rotary union, P&F, and accumulator reservoir. All of the components are manifold mounted to the HX allowing easy access and reducing the size and complexity of the various static seals. Finally, an integrated HX design allows the vibration isolation and cancellation system to service the entire ATA system. The UAM HX assembly is shown below, in Figure 10, in a deployed state. The Cryocooler is attached via the thermal link to the dummy optical bench and detector assembly prototype.

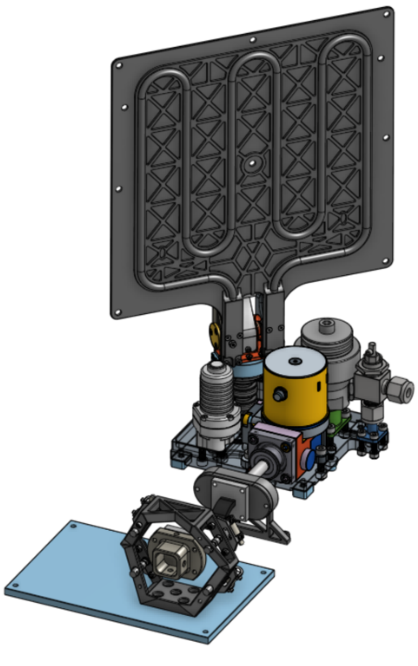


Figure 10. ATA Heat Exchanger Assembly

CubeSat Chassis Design

The ATA CubeSat chassis is a 6U bus custom-designed to accommodate and support the ATA technology. The design is loosely based on a standard 6U Blue Canyon technologies CubeSat bus[19]. The ATA bus has a wire-framed 6U internal volume, CNC machined from a single piece of Aluminum. Each of the sides is light-weighted and reinforced with cross-hatched ribbing patterns. Some panels are fully machined out to allow for visual access to the bus interior. Others are solid to improve stiffness. The bottom of the bus is reinforced and laid out to accommodate the mounting and launch locks of the ATA system.

The external dimensions and design of the ATA CubeSat bus are not exactly that of a standard flight model. However, the bus provides an exact 6U internal volume, a realistic structural stiffness and shape for vibrational transfer analysis, and a sturdy base for launch load vibration testing. In addition, the ATA CubeSat chassis is a realistic representation of a 6U CubeSat with an integrated Active Thermal Control prototype. Figure 11 below shows the customized ATA 6U CubeSat chassis prototype.

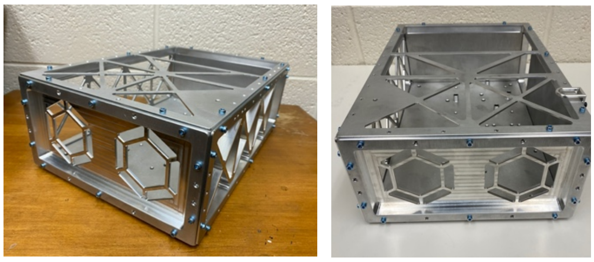


Figure 11. ATA CubeSat Chassis

ATA Deployment

The deployment and operational mechanics of the ATA system are shown below in Figure 12. The ATA CubeSat is in a stowed state during launch. Once in a stable orbit, a frange bolt locking the radiator will fragment. Next, the radiator tracking system will engage and swing it out from the stowed state. This action will clear the deployment radiator vertical launch lock. Once cleared, the Contorque spring deployment system will rotate the radiator 90 degrees into a deployed state. The continued force of the springs along with the natural friction of the rotary joint will keep the radiator deployed. Once deployed a second frange bolt locking the HX into its custom-made launch locks will release and the compressed wire rope isolators will lift the entire ATA assembly by little more than half an inch into a floating deployed state. This vertical movement will clear the ATA assembly from all locks. Finally, the ATA tracking system is free to rotate the radiator continuously and track either deep space or the Sun. Figure 12 below graphically represents this deployment sequence.

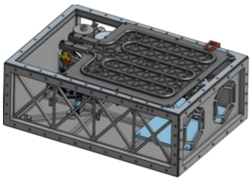
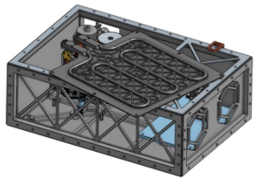
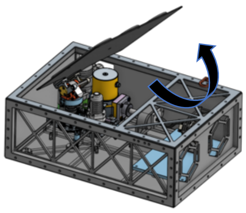
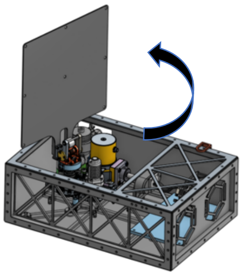
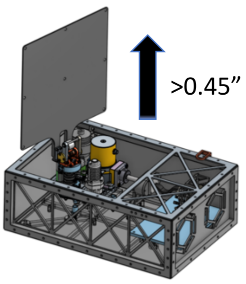
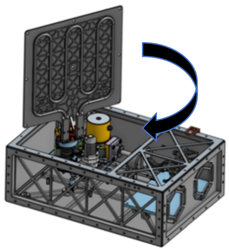
	
Stowed State	Release Launch Locks—Radiator 15 deg, initial rotation
	
Radiator Begins to deploy	Radiator full deployment
	
HX Launch Locks release. System floats on wire rope vibration isolators	Radiator Continuous dual direction rotation

Figure 12. ATA Deployment & tracking concept

ATA UAM Radiator & Heat Exchanger

The key technology represented by the ATA system is that of UAM based additive manufacturing techniques and their ability to embed fluid channels directly into the CubeSat chassis, HX and radiator of the ATA system. The fabrication company Fabrisonics LLC[5] has patented the use of UAM and provided the manufacturing of the radiator and HX for the ATA system.

The ATA radiator is a 4U, 6 mm thick black anodized deployable structure (front + back: 8U of total radiative surface area). The UAM fluid channels form a six-pass sweep through the length and width of the radiator with a working fluid hydraulic diameter of 1/8”. Cross-hatched ribbing provides light-weighting while maintaining structural stiffness. Several prototypes were fabricated with the majority consisting solely of monolithic UAM 6061 Aluminum. A single radiator prototype was built with a thirty-thousandth layer of Copper backing added to the Aluminum. This model provides a unique comparison to the standard AL models in terms of thermal performance. Figure 13 shows the monolithic AL and Copper backed radiator prototypes.

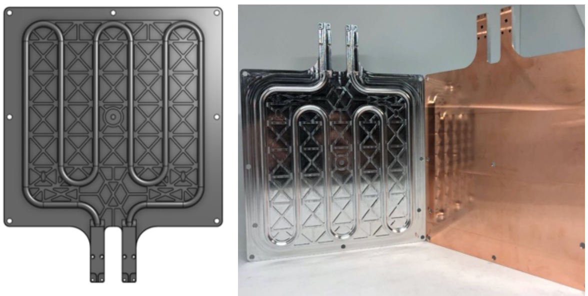


Figure 13. ATA UAM radiator design

The ATA HX is a more complicated design than that of the radiator and must accommodate a great deal more integrated technology. At an exact 10 cm X 10 cm (1U) footprint the ATA HX’s are fabricated via UAM entirely out of Aluminum 6061. Mounting points for each component of the ATA system are included for direct surface mounting. The primary MPFL components and the rotary fluid joints are mounted to the top surface of the HX while the launch locks, tracking drive gears, and wire vibration isolation are underneath. Berms designed around the TCS micro-pump and the rotary unions allow for additional sealing if required. The UAM fluid path design maximizes the coolant area under the high power cryocooler for better thermal rejection. Figure 14 shows the CAD design of the HX and the UAM prototypes.

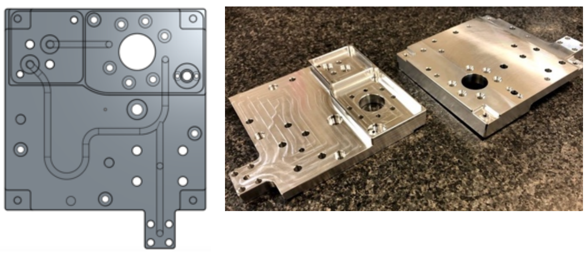


Figure 14. ATA HX UAM design

Fluid Rotary Joints

An original goal of the ‘ATA project was to accommodate a deployable tracking radiator. The various flight-ready technologies available often require the use of flex lines. However, this dramatically increases size, reduces flexibility, negates continuous tracking while also requiring advanced deployment techniques. An alternative option is that of a fluid-based rotary union. Rotary Unions are rotationally flexible fluid joints that allow for continuous fluid flow from a static to a dynamic side. Often used in hydraulic applications, a commercial rotary union did not exist that was mechanically appropriate for the ATA system. Therefore, the ATA team developed a custom continuous 360º tracking rotary union and a single-use 90º deployment rotary union. These two rotary unions are then combined to form a rotary union double-axis deployment and tracking fluid joint.

The ATA continuous rotary union design features a simple double-channel piston O-ring design. A central core contains two vertical fluid paths that branch horizontally at the top. O-ring channels are cut into the core and provide dynamic rotational sealing. A sleeve with manifold mounted vertical fluid paths forms the second half of the fluid joint. Fluid enters and exits via the stationary outer sleeve and transfers to the dynamic core via the fluid channels. In this way, a single-phase flow path can be formed between a stationary internal HX and a dynamically rotating radiator. The ATA rotary union has a custom manifold mount design with an outer diameter of 1.5" and a height of 1.87". Figure 15 shows the cross-sectional design of the ATA rotary union as well as the fabricated part. Bearings are fitted to the top and bottom of the core to help with rotational friction and prevent the O-rings from being asymmetrically compressed during operation. Three O-rings are used to seal the internal fluid channels from the vacuum environment and each other.

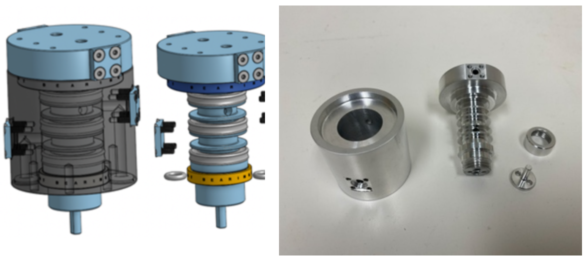


Figure 15. ATA continuous two-channel rotary fluid union

The 90º fluid rotary union (Nano90) operates similarly to the previous continuous rotary union. The primary difference is that the Nano90 features a dual-core design with a total of four rotary piston dynamic seals. A central horizontal sleeve forms the second half of the fluid flow paths. The Nano90 is designed to fit within the 1.5" diameter footprint of the continuous rotary union and works in tandem with the with it to transfer the ATA working fluid from the deployed radiator to the internal HX. One-inch deployment arms are featured on the Nano90 and help to deploy the radiator from a stowed state. Figure 16 shows a complete CAD based model of the Nano90 system and a de-integrated prototype.

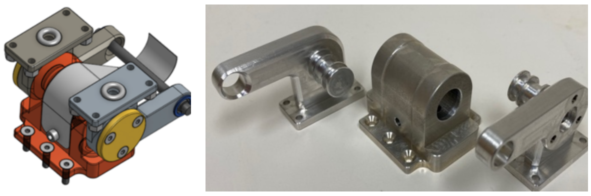


Figure 16. ATA 90 Degree rotary fluid joint: Nano90

Deployment Mechanism

The ATA deployment mechanism is based upon a Contorque (Constant Torque) coil spring design. A series of layered Contorque springs are fixed to the horizontal sleeve of the Nano90 and form a recurved fixed spool deployment design. This method of deployment is ideal for the ATA system because it is simple, robust, reliable, and can be fine-tuned to nearly any torque level by adding or removing layers from the coil springs. Bearings are attached to the deployment bar and arms of the Nano90 and ensure that the Contorque spring force vector is always normal to the deployment arm angle. This optimizes the force exerted on the radiator throughout the 90º deployment angle and ensures that even when fully deployed, the radiator is held in place with the full torque of the layered springs. The ATA deployment mechanism has been demonstrated in benchtop tests, even with the force of gravity applied. Figure 17 shows several up-close views of the Contorque spring deployment mechanism of the ATA system.

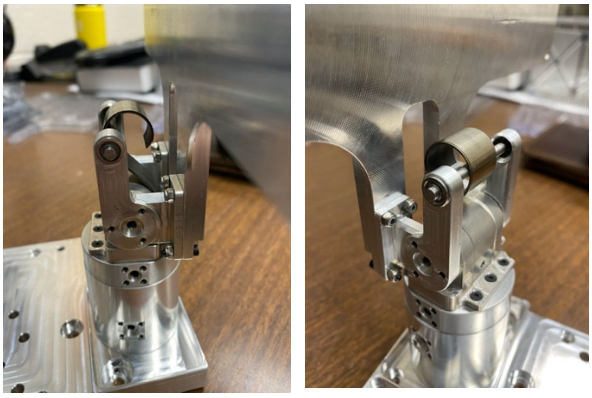


Figure 17. ATA deployment contorque spring mechanism

Radiator Tracking Mechanism

The deployed radiator can be tracked to deep space or kept edge on to the sun/solar-flux for optimized thermal performance. Ideally, a radiator would optimize its view to deep space, however, in an active dynamic system, the radiator can be canted towards the sun for additional thermal input if needed. To accomplish this, a Faulhaber 1226 series brushless micro-motor is used to drive the dynamic core of the continuous rotary union. The micro-motor is geared down via an integrated planetary gearbox and connected to a 3-to-1 external spur gear reduction system for maximized torque. The radiator in solar tracking mode needs only to keep itself edge on to the sun throughout its orbit. This amounts to little more than a single revolution per orbit. The radiator has a built-in encoder and utilizes the CubeSat ADCS system to track its angle to the sun. The radiator's tracking builds up CubeSat wide momentum that needs to be corrected by the onboard flywheels. However, this addition to the CubeSat's angular momentum is small and can easily be dumped via magnetic torquers or de-spun by counter-rotating the radiator during the orbital eclipse. The exact control methodology of the radiator can be customized for the given mission. Figure 18 shows the mounted Faulhaber 1226 series micor-motor and the spur gear reduction system mounted to the underside of the ATA HX.

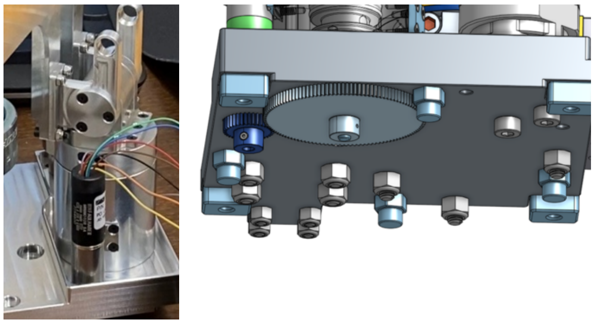


Figure 18. ATA radiator tracking drive system

Vibration Isolation and Damping

The ATA is an active system and therefore produces exported vibration and jitter. To counter this, a series of passive vibration isolation technologies have been implemented. The first of which is that the entire ATA system floats on a set of four-wire rope isolators. These isolators provide isolation from the vibrations of the ATA system to the CubeSat chassis and delicate payload instrumentation. In addition, a custom made cryocooler cold tip particle damper and a flexible thermal link further help to mitigate the transferred jitter from the cold finger of the cryocooler directly to the dummy prototype detector system. Finally, the entire optical bench floats on a further set of wire rope isolators. When combined, these passive vibration cancellations methods should help to mitigate the transfer of jitter from the ATA system.

The exported vibrations of the various active elements of the ATA system will be characterized via Force Dynomometer testing. This will enable the ATA team to create a series of analytical and numerical models of the ATA system and quantify its effect on any given satellite. In addition, Force Dynomometer testing of the ATA system integrated with the vibration isolation technologies will demonstrate the reduction in exported jitter that each of these passive technologies will provide. Furthermore, the jitter effect these exported vibrations will have on the detector prototype system will be characterized by a capacitive displacement sensor. This sensor will be integrated into the TVAC test and will give direct feedback on the effectiveness of the ATA vibration isolation and cancellation technologies. Figure 19 shows some of the various technologies used by the ATA system to counteract and isolate vibration.

Figure 19. ATA Vibration isolation systems: Cold finger bumper, cold finger particle damper, wire rope isolators, and flexible thermal link

Prototype Detector Design

The ATA system is designed to support IR instrumentation. Often these electro-optical detectors are quite sensitive to imported vibration and jitter. In fact, pixel blur can have a severe impact on an optical instrument's sensitivity/accuracy. The ATA hopes to demonstrate that not only can the ATA system actively support a delicate IR instrument, but it can also do so without any negative impact on the performance or accuracy of that instrument. To this end, the ATA designed a custom-made dummy detector prototype to measure exported vibrations' potential impact. The detector is designed to replicate the mechanical profile of an integrated focal plane array with an optical cold stop.

The ATA detector prototype utilizes Kevlar string isolation system similar to the one used in the original SABER instrument. Kevlar wire is tensioned between a series of machine worm-gears. These gears act as a tensioning system for the detector block, which hangs suspended between them. The flexible thermal link forms a cold sink from the detector to the cryocooler. This design is ideal for thermal isolation because the detector is isolated from the surrounding structure except for a series of long, fine, insulative Kevlar threads. Because of the strength of Kevlar the string isolation can be tensioned to a high degree. This ensures that the detector assembly forms a mechanically stable and strong base for the dummy optical detector. Another benefit of this design is that the Kevlar threads can be adjusted in such a way as to change the orientation of the detector and fine-tune its position with respect to the mounted optical bench. In fact, with only slight modifications to the given design, a six-degree of freedom solution is quite possible.

The outer frame for the Kevlar support system is 3D DMLS printed from Stainless Steel with another prototype printed in PEEK. Both of these materials provide a strong, low thermal conductivity, support structure for the detector, and Kevlar Worm-Gear assembly. The dummy detector is fabricated from Aluminum 6061 and is designed to accommodate a dual-axis capacitive displacement sensor system. This system, coupled with the detector, will enable the ATA team to determine if the jitter threshold has been met for the prototyped detector assembly. Figure 20 shows the complete dummy detector assembly with Kevlar and Worm-Gear suspension technology.

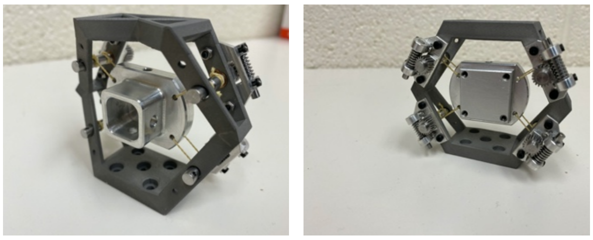


Figure 20. ATA Kevlar detector assembly

CURRENT PROGRESS

The ATA project has finalized the operational concepts and designs for the technologies being developed and has finished fabrication on a series of prototypes. The prototypes have been fully assembled and checked for fit and operation. The various static and dynamic O-ring seals have been checked for leaks via a pressurized and submerged water bath "Bubble" test. No seals have shown any leaks with 80 psi of static N_2 gas. In addition, the radiator deployment and tracking mechanism has been successfully demonstrated in a benchtop environment.

Finally, the test procedures for the full characterization of the system are finalized and the prototypes are instrumented and fitted with electronics and controls. Next, the ATA system will undergo a series of characterization tests in relevant ground based environments.

FUTURE WORK

The next step for the ATA system is to prepare for characterization of the prototype in a series of relevant tests.

1. The finalized prototype will be helium leak checked to quantize any small leak rates through the various static and dynamic seals.

2. The prototype and each key technology will be exercised through a standard CubeSat launch vibration test.

3. The Ricor K508N cryocooler, TCS MGD1000F micropump and the HX assembly will be characterized via a force dynamometer for exported vibration. A basic jitter source and vibration transfer model will be developed from that data. Next, the ATA vibration isolation and cancellation system will be tested, and the level of Jitter cancellation will be characterized.

4. Finally, the entire prototype will be tested in a cold shroud controlled TVAC chamber. The radiator will demonstrate cold deployment and tracking. Steady state hot, cold, and average temperature states will be the jitter level of the prototype detector will be continuously monitored via the capacitive displacement sensors.

Ultimately, the ATA system will be fully characterized for thermal and mechanical dynamic/vibration performance. The results will be analyzed and collated along with a comparison to the analytical models developed in the ACCS effort. A Thermal Desktop numerical model will also be created to accurately represent the ATA system. In addition to the primary work presented here the ATA team is working on a control and feedback algorithm with faculty at USU. This algorithm will enable the ATA system to automatically control and stabilize the steady state temperature environment of the ATA system with respect to the transient environmental inputs of a standard CubeSat orbit. Fabrisonics LLC will also be working with the ATA team to thermally characterize HX and radiator plates fabricated with different UAM processes.

The ATA team will be writing follow on grants to further advance the active thermal control technology prototyped by this work. In addition, another development effort is underway to mature SABER-Lite into a viable CubeSat instrument. Finally, the ATA team and JPL would like to provide the ATA system with a flight opportunity in the future as either a technology demonstration mission or a support technology to a high-powered CubeSat or an advanced IR instrument.

CONCLUSIONS

The ATA team has successfully developed a 1U fully operational ground-based prototype of a single-phase, two-stage active thermal control system for Small Satellites. This system is capable of supporting advanced IR electro-optical instrumentation in future Heliophysics and Earth-Sciene missions. The ATA system is also capable of thermal control for demanding high power CubeSat designs and is capable of managing the onboard thermal environment of a CubeSat. In addition, the ATA project has developed several unique and customized technologies such as: a dual axis fluid rotary union, a customized deployment and tracking mechanism for external radiators, a miniature passive vibration isolation and cancellation system, an advanced Kevlar-string and Worm-Gear detector isolation system, as well as a relevant ground based prototype of a 6U CubeSat.

The ATA project is on track to either meet or surpass the proposals original stated design requirements and objectives. Ultimately, the ATA team has made tremendous progress and plans on continued development of the ATA system as well as pursing future flight opportunities.

ACKNOWLEDGEMENTS

The ATA team would like to thank the NASA SSTP office for their continued support and funding as well as the Jet Propulsions Laboratory for their encouragement and guidance. In addition, the team would like to thank the following organizations for their contributions

- Koro Industries
- Vulcan Springs
- Micro-Epsilon
- Xometry Fabrication
- Ricor Cryogenics
- TCS Micro-Pumps
- Fabrisonics LLC

Finally, the ATA team would like to thank and acknowledge the wonderful student, faculty, and staff team at Utah State University. Without them none of this would be possible.

ACRONYMS

- ACCS Active CryoCubeSat
- AL Aluminum
- ATA Active Thermal Architecture
- CAD Computer Aided Design
- CONOPS Concept of Oporations
- COTS Common of the Shelf
- CNC Computer Numerical Control
- CSE Center for Space Engineering
- DMLS Direct Metal Laser Sintering
- EON-IR Earth Observing NanoSatellite
- FPA Focal Plane Array

- HX Heat Exchanger
- IR Infrared
- JPL Jet Propulsions Laboratory
- LWIR Long Wave IR
- MPFL Mechanically Pumped Fluid Loop
- MTBF Mean Time to Batch Failure
- MWIR Mid Wave IR
- NOAA National Oceonic and Atmospheric Administration
- N2 Nitrogen Gas
- PEEK Polyether Ether Ketone
- P&F Purge and Fill
- SABER Sounding of the Atmosphere in Broadband Emission Radiometry
- SSTP Small Satellite Technology Program
- TIMED Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics
- TRL Technology Readiness Level
- TVAC Thermal Vacuum
- U A CubeSat Standard Unit
- UAM Ultrasonic Additive Manufacturing
- USU Utah State University

REFERENCES

[1] Lucas S. Anderson "The Active CryoCubeSat Project: Design and Status" [Online] June 2017, https://digitalcommons.usu.edu/smallsat/2017/all2017/154/

[2] Anderson, L. S., "The Active CryoCubeSat Project: Testing and Preliminary Results" [Online] August 2018 https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4273&context=smallsat

[3] Proposal to the NASA Small Satellite Technology program. 2017. Active Thermal Architecture for Cryogenic Optical Instrumentation

[4] Mastropietro, A. J., Bhandari, Pradeep, Birur, Gajanana, et. al., "Summary and Status of 5 Mechanical Pumped Fluid Loop (MPFL) Projects Currently in Process at the Jet Propulsion Laboratory (JPL) for the Planned Europa Mission, Mars 2020, Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), Orbiting Carbon Observatory (OCO-3), and Cold Atom Lab (CAL)," Thermal and Fluids Analysis Workshop (TFAWS), Mountain View, CA, August 2016.

[5] Fabrisonics LLC [Online] June 2020, https://fabrisonic.com

[6] Fabrisonics LLC [Online] June 2020, https://fabrisonic.com/technology/

[7] Mastropietro, A. J., Pauken, Michael, Hofmann, Douglas, D'Agostino, Saverio, "Ultrasonic Additive Manufacturing (UAM) of Heat Rejection System (HRS) Heat Exchangers," Innovative Spontaneous Concept R&TD, Annual Report to JPL's R&TD Program Office, 2014.

[8] Maghsoudi, Elham, Mastropietro, A. J., Roberts, Scott, and Kinter, Bradley, "Experimental Thermal Performance Comparison of 3D Printed Aluminum Heat Exchangers vs Traditionally Manufactured Heat Exchangers," Spacecraft Thermal Control Workshop (STCW), El Segundo, CA, March 2017.

[9] Mastropietro, A. J., Roberts Scott, Hofmann Douglas, Maghsoudi, Elham, and Luong, Simon, "NASA Development of Complex Heat Exchangers Leveraging Additive Manufacturing," Propulsion Safety and Sustainment Conference, Phoenix, AZ, May 2017.

[10] Integral Rotary Integral Stirling 1/2W Micro Cooler K508N [Online] June 2017, http://www.ricor.com/products/integral-rotary/k508n/

[11] Johnson, D. L., "The Ricor K508N cryocooler operational experience on Mars". [Online] June 2020, https://aip.scitation.org/doi/10.1063/1.4860925

[12] TCS Micropumps-High Performance Miniature Pumps [Online] June 2017, http://www.micropumps.co.uk/

[13] Hawe AC-13 Accumulator [Online] June 2020, https://downloads.hawe.com/A/K_AC-en.pdf

[14] David Y. Kusnierkiewicz, "An Overview of the TIMED Spacecraft" [Online] September 2016, http://www.jhuapl.edu/techdigest/TD/td2402/Kusnierkiewicz1.pdf

[15] NASA TIMED Spacecraft: SABER [Online] June 2020, https://www.nasa.gov/timed

[16] TIMED Satellite Diagram [Online] June 2020, https://www.google.com/search?q=TIMED+satellite&client=safari&rls=en&sxsrf=ALeKk01t672REPzmSS7wetluwUYbOa_Uyw:1591605716183&source=lnms&tbm=isch&sa=X&ved=2ahUKEwjjmNeq6fHpAhXUG80KHcsIAdcQ_AUoAnoECBcQBA&biw=1439&bih=733#imgrc=MHfuaVR3sug5gM

[17] Proposal to NASA Small Satellite Technology Program. 2016, Sounding of the Atmosphere using Broadband Emission Radiometry CubeSat (SABER-Cube)

[18] NOAA EON-IR CubeSat Study for Operational InfraredSoundingshttps://digitalcommons.usu.edu/smallsat/2017/all2017/34/

[19] Blue Canyon Technologies [Online] June 2020, https://www.bluecanyontech.com