Enabling the Next Generation of Advanced Small Satellites Through Active Thermal Control

Lucas Anderson [1, 2], Charles Swenson[1], Bruno Mattos[1], Chad Fish[2],

Miguel Nunes[3], Robert Wright[3]

[1] Utah State University, Center for Space Engineering, 4130 Old Main Hill, Logan, Utah, 84321, lucas.anderson@usu.edu
[2] Orion Space Solutions, an Arcfield Company, 282 Century Place, 1000, Louisville, CO, 80027 lucas.anderson@arcfield.com
[3] Hawaii Institute of Geophysics & Planetology, University of Hawaii at Manoa, Honolulu, HI, wright@higp.hawaii.edu

ABSTRACT

Within the last two decades, Small Satellites have taken the space industry by storm. Representing a natural shift towards a more agile and accessible platform for exploring our universe. Today, CubeSats and Small Satellites are valuable technology demonstrations and scientific testbeds. Hosting a variety of novel payloads, including high resolution, cryogenically cooled IR remote sensors, in-situ space weather probes, active sounding radars, and many others. In addition, constellations and Swarms of Small Satellites promise unprecedented coverage of our near-earth environment with deep-space CubeSats exploring the Cis-Lunar region and beyond. Fueling this progress are recent advances in satellite technology, such as energy-dense power generation and storage, high-performance onboard processing, fast telemetry links, and the miniaturization of cryogenic cryocoolers for Hyperspectral LWIR remote imaging. Modern 12U & 16U CubeSats can generate more than ~200 W of power in a form factor no larger than a shoe box. Ultimately, the promise of Small Satellites as a low-cost, fast-to-space solution for advanced scientific payloads comes at the price of ever-increasing power densities and a unique thermal challenge, which the next generation of thermal control technologies must face. This paper will focus on active thermal control as an integrated system and service and will introduce the Active Thermal Architecture MPFL technology as well as the upcoming ACMES mission.

1 INTRODUCTION

Thermal Engineering at its very core is the management, control, and balance of energy. And is a fundamental topic of space mission design. When applied to spacecraft, the goal is to maintain components within optimal thermal performance limits and to satisfy mission requirements and objectives. It encompasses the product life cycle from early concepts through operations, including design, modeling/analysis, implementation, characterization/testing, and validation/verification [1, 2, 3]. Spacecraft thermal control has a rich heritage dating back to the very earliest days of space exploration. The very first manmade satellite "Sputnik", which ushered in the space age, featured an active thermal control system, where the body of Sputnik, its electronics & radio transmitter enclosure, was sealed and pressurized with GN2 (~1.3 atm), a thermal switch would toggle a small fan that would circulate the Nitrogen and help to keep the electronics cool [4].

The space environment is incredibly challenging and varied, by all measures, extreme. Far from the insulating conditions we experience here on Earth, satellites experience enormous swings in temperature (thermal cycling) from hundreds of degrees below zero (^{o}C) to component melting levels above. In addition, satellites are required to operate throughout our solar system, from low earth orbit,

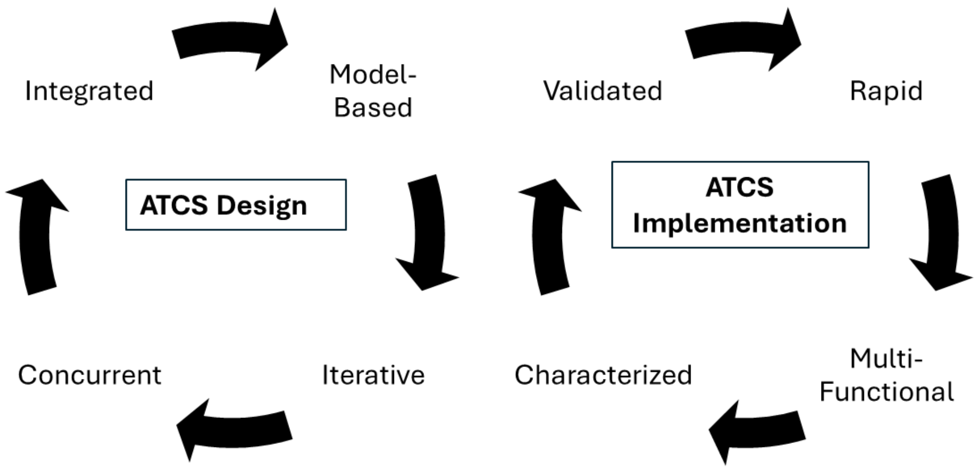


Figure 1. The basic design and implementation plan behind active thermal control technologies.

where solar flux, plasma, radiation, and the thermal signature of the earth dominate to the cold depths of deep space and even to touching the sun itself [5, 6, 7]. Without care and dedicated technology, a satellite can easily freeze or conversely turn into a lightbulb.

Traditionally, engineers have approached thermal design with a conservative attitude. Reducing risk and cost by utilizing passive techniques and relying on heritage technologies. This approach has been sufficient for the majority of the last ~70 years, with notable exceptions, because the overall ratio of spacecraft power to size (energy density) has remained small, often less than ~50 W per square meter (LEO: rad. efficiency~60%) [8, 9]. However, these traditional approaches have several major drawbacks. Including low ceilings on energy density, as mentioned previously, large thermal temperature gradients, inefficient thermal transfer coefficients, and operational temperature swings of tens of degrees. However, the largest disadvantage to the traditional thermal control approach is that each satellite requires a custom and unique thermal solution, which is often not considered until late in the development stage, which naturally drives change, cost, and ultimately risk [10]. This approach is becoming increasingly unviable for modern satellite design. The next generation of Satellites, SmallSats, and CubeSats will require standardized, high-power, high-performance, thermal control technologies that blend passive and active techniques in a holistic approach. Future satellites will be designed as standard platforms, sized in increments to match payload and bus power profiles and the challenging space environment. The satellites themselves will be insulated from the space environment and will rely on dedicated deployable radiators that can track, fold, and change their surface properties to match ever-changing mission requirements [11, 12]. Internal temperature control will be supported by active-&-passive single and dual-phase fluid loop heat exchangers, or similar ATCS, coupled to the dedicated radiators. Advanced 3D printing will be used to integrate these thermal control technologies with the satellite bus and structure, creating multi-functional technologies. These ATC systems will balance the generated, required, and incident power of the spacecraft and provide end-to-end feedback control of the bus and payload temperature environment. With the ultimate goal of creating a spacecraft that is not limited in its capability or simply hoping to survive or manage the space environment. Instead, they will rely on advanced technology and power to directly support their payloads and challenge the space environment itself. These satellites will usher in a new era of space exploration and will serve as the standardized foundation for low-cost, fast-to-orbit small satellites, constellations, and deep space explorer probes.

In this paper, we will explore the basics of active thermal control, with an eye toward upcoming technologies and what should be developed within the next decade. We will also introduce the Active Thermal Architecture as a novel fluid loop ATCS and discuss its role as a supportive technology on the upcoming Active Cooling for Multispectral Earth Sensors (ACMES) mission.

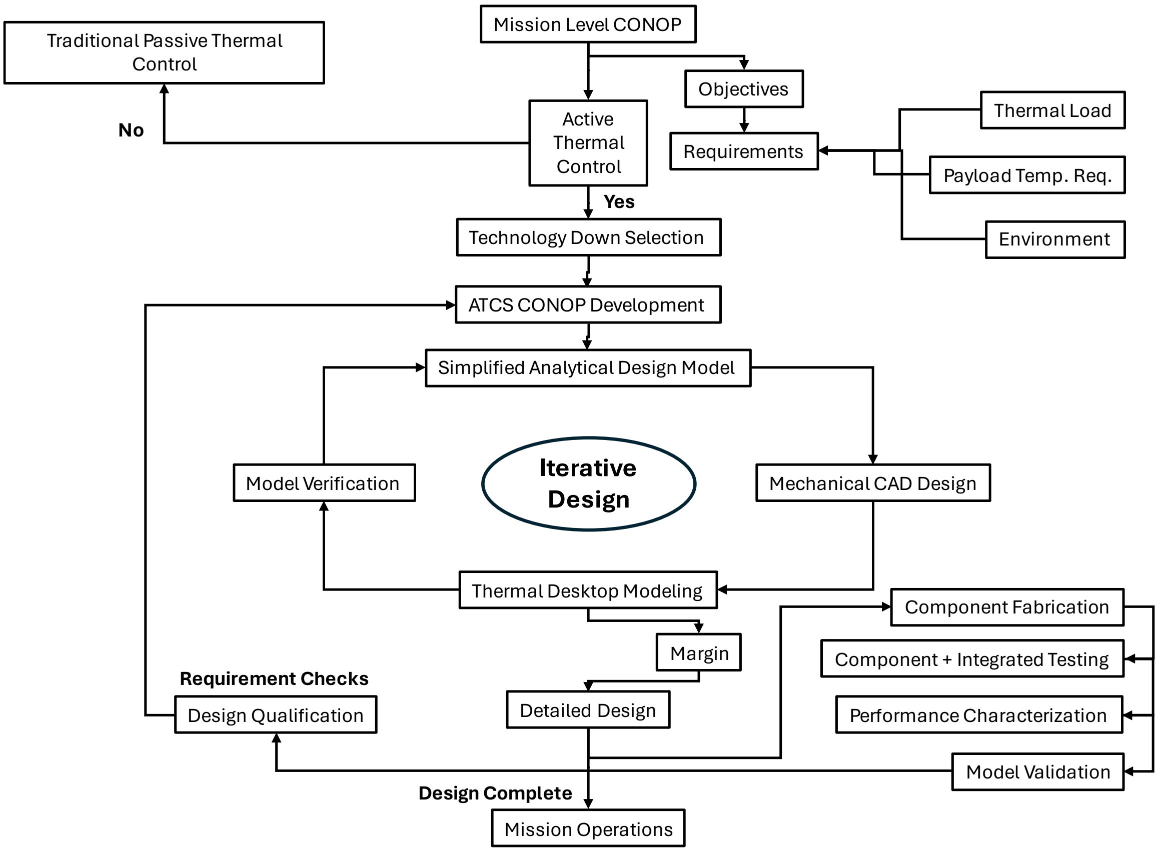


Figure 2. Space mission active thermal control design flowchart.

2 THERMAL CONTROL TECHNOLOGIES

Satellite thermal control technologies can be broken down into two broad categories: passive vs. active. Passive technologies include conductive links, insulators (ceramics, aerogels, etc.), interface materials/gap pads, Multi-Layer Insulation (MLI), and radiator surface materials such as coatings, paints, and tapes. Advanced passive technologies also include heat pipes, thermal switches, phase change materials, and radiator Louvers [13, 14, 15, 16]. It should be noted that this paper will focus on the benefits and need for active thermal control technologies, however, passive techniques should not be undervalued. They offer numerous benefits [17], the most notable of which are: simplicity, reliability, and the fact that they do not require power to operate. If a satellite or payload does not require active thermal control, it is advisable to implement passive techniques instead. Future engineers will utilize both active and passive thermal control strategies. The fundamental methods of heat transfer are: conduction, convection, radiation, and advection or mass transfer [18]. The key variables for each are listed below. To fully control a thermal system each of these variables must be considered.

- Conduction: *conductivity, area, and length*
- Convection: *convective "effective" conduction and area*
- Radiation: *area, view factor, emissivity, absorptivity, and efficiency*
- Advection*: simply transporting energy from one spot to another through ovement*

Active thermal control can be classified, as any technology that requires input power to reject thermal load or maintain setpoint temperatures. This includes heaters, certain types of Louvers, dynamic radiators, thermoelectric coolers, and fluid loops, which is a complex sub-category all on its own. NASA publishes the "State-of-the-art of Small Spacecraft Technology" [19] report, which catalogs the latest advancements in active thermal control. Of particular interest are smart radiators and fluid-based technologies. Smart radiators have control over one or more of the key variables given above.

Examples include radiators that can track points/angles in one or two dimensions, dynamically fold expand, or change their area, or modify their surface properties on demand. Currently, a few advanced radiators can deploy and track, while very few can retract their radiators (ISS EATCS). It should be noted, that currently none of these radiator technologies exist as COTS components for small satellites and CubeSats. There is ongoing research into materials that can change their emissivity and absorptivity on command. Two promising materials based on electrochromatics are SmartIR and Squid3 [20, 21]. The commercial company SmartIR has developed a graphene-based material that can dynamically vary the emissivity of a surface from 0.3 to 0.8 (approx.). While Squid3 has developed a variable absorptivity surface based on E-ink displays. Either of these technologies can be layered in a checkerboard pattern to actively control the radiative properties of a surface. Which would be a game-changing technology for active satellite control.

Fluid loop-based ATCS systems can be single-phase or two-phase and can have multiple stages to improve efficiency and temperature control. The simplest type of fluid loop is the single-phase Mechanically Pumped Fluid Loop (MPFL) [22]. A single-phase heat transfer fluid is pumped through a cold plate heat exchanger internal to the spacecraft and payload. Thermal energy is collected via convection and transported to an external body or deployed radiator. MPFLs offer many advantages, including variable effective conductance, near isothermal performance, coarse temperature control, and high input power to thermal rejection efficiency. Additional fluid loops, backup pumps, and thermal margins can be added to reduce risk. MPFLs can be improved by adding a regenerator, where the heat transfer fluid is re-circulated, through a valve control system. Regenerators improve the quality of the working fluid and protect against low-power cold cycles. By adding a second stage and breaking the MPFL into two separate loops, a warm internal and a cold external loop connected by a fluid heat exchanger MPFLs can be modified to provide degree-by-degree set point thermal control, while simultaneously protecting against hot & cold cycles. Finally, phase change materials (transient energy storage) can be added to further improve the dynamic performance of MPFLs. A far more capable and complex form of fluid heat transfer system is the two-phase vapor compression cycle aka the Vapor Compression Refrigeration Cycles (VCRC) and Cryocooler (CC). Vapor compression cycles allow the working thermal gradient to be reversed, such that energy can flow from cold to hot [18]. For a satellite, this could mean maintaining a cool, climate-controlled interior while rejecting large thermal loads to a small, hot, highly efficient radiator. VCRCs operate by extracting heat from the satellite system through a cold plate evaporator. Refrigerant is vaporized (latent vs. sensible heat) within the evaporator and compressed to a high temperature, high-pressure vapor. The liquid is re-condensed within the radiator, and the heat is released to the space environment. Conversely, cryocoolers often operate in a four-step process. A working fluid/gas, commonly Helium, is compressed, which increases its temperature. This compressed gas is forced through a regenerator, where some of the energy is dissipated. Next, the gas is expanded, cooling the gas and the surrounding materials (cold tip). The gas is pushed back through the regenerator warming the gas back up and the cycle is repeated creating a cooling effect. Recent advancements in micro-pumps and compressors have made both MPFL and VCRC fluid cycles possible. However, further research and technology development are required before they are available as COTS components. Additive manufacturing and 3D printing are both game-changing technologies for active thermal control technologies.

The primary goal of ATCS systems is to improve overall performance and efficiency. However, they add complexity, cost, and risk. Therefore, the benefits of an ATCS must outweigh the cons. In general, an active system should only be considered if the overall thermal load, on a Small Satellite or CubeSat, exceeds ~50 W (rule of thumb and varies widely) [11, 12], if the thermal environment demands it, or if a payload or component has narrow operational temperature limits. ATCS offer many benefits including setpoint temperature feedback and control, variable conductance, energy storage, isothermal operation, and balancing, controlling, and rejecting large thermal loads that would otherwise be impossible with traditional technologies.

2.1 ATCS Design Methodology

Figure 1 above shows the high-level methodologies for the design and implementation of an active thermal control system. Engineers must approach design with an integrated mindset [2, 14]. ATCS technologies will serve as dedicated support subsystems and must be developed at an early stage along with the bus and payload. Each ATCS will require a model-based development and analysis tool to predict behavior and performance [2]. This should include an analytical design tool and a numerical Thermal Desktop (TD) modeling tool. As the design develops in parallel (concurrent) with the rest of the spacecraft and mission, the ATCS will undergo an iterative process where design elements, margins, and performance are refined until the mission and payload requirements are satisfied. Implementation of the ATCS should focus on characterizing the performance of the thermal control system and validating the numerical performance models. Simple benchtop and laboratory testing can be used to confirm the accuracy of the models, which can then be trusted throughout the rest of the mission. Modern ATCS systems should be integrated directly into the satellite and payload, serving as multi-functional systems, improving performance and efficiency. A model of radiator temperature vs. area and thermal load is given in Figure 3. It is assumed that the flat plate radiator orbits at an altitude of ~550 km with one edge tracking the sun. The face of the radiator is tipped towards 45^{o} with one side tilted towards the earth and the other deep space. This graph can be used to quickly determine whether a traditional passive thermal control technology is sufficient or if a deployed radiator is required. For a 6U through 12U CubeSat, power levels above ~45 W will result in radiator temperatures exceeding 40 ^{o}C, which could exceed component operational limits when considering margin. Examples of deployable UAM radiators are also shown in Figure 3, the 6U ACCS and 4U ATA radiators.

The technical approach to designing and implementing an ATCS system is complex, however, some of the basic steps are outlined below and shown graphically in Figure 2. It should be noted, that this is not meant to be a definitive guide, but simply a roadmap similar to those provided by the SMAD handbook [2]. ATCS design should begin at the same time as the mission CONOP. A team X-style systems engineering design approach is recommended [14], where all of the major spacecraft systems are developed simultaneously and in parallel. The thermal requirements should be defined, with an eye toward feasibility and meeting the mission objectives. At this point, the necessity of an active thermal control system can be assessed. If traditional methods are acceptable, then refer to the SMAD handbook [2, 8, 13, 14]. If active thermal control is necessary then the specific type should be down-selected. It should be noted, that for complex missions, multiple types of thermal control might be necessary and that passive methods will always be coupled with active ones to provide ideal performance. Once a technology or series of technologies have been selected, then a thermal control operational concept can be developed and an analytical design tool built. This analytical design tool is critical and must focus on fundamental laws and equations. It should embody the 80:20 rule and will allow for rapid iterative design of the technology. It will also prevent designers and systems engineers from becoming mired in detail too early in the design process. This tool should allow individual parameters to be studied and high-level design trade-offs made quickly. In addition, by developing and using a fundamental modeling tool, the engineers will come to learn and understand the technology at a far deeper level than a pre-packaged numerical analysis code could ever provide. Overall, an analytical design tool will add a great deal of value to a program and allow engineers to rapidly and accurately produce 80% of the design. A simple CAD model should be generated from the results of the design tool, this model should only hope to capture the basic essence of the design. A numerical Thermal Desktop model can then be produced from this CAD, representing components as primitive shapes and focusing on the integrated design rather than detail. From this model, the requirements and performance of the ATCS should be verified. This iterative design loop should be cycled as quickly as possible with each refinement improving upon the design. Margin should be added per NASA and SMC-016 standards. Ultimately, the analytical tool and TD numerical model should agree and meet the thermal requirements given at the mission level (verification). Finally, the design can be refined with detailed CAD models and drawings being delivered to the SE team.

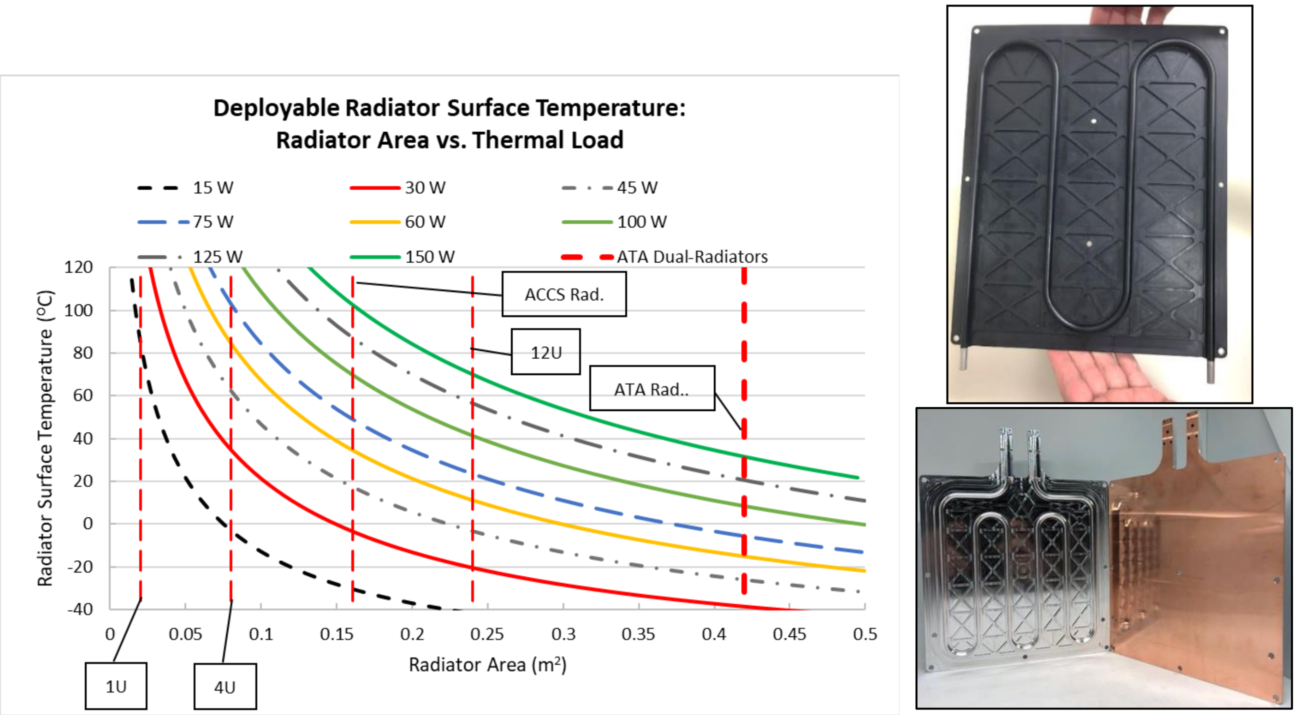


Figure 3. Left, radiator temperature as a function of power and area. Assumptions include a simplified orbiting plate and steady-state analysis. Surface properties are emissivity 0.85, and absorptivity 0.15, with a plate at 500 km altitude, edgewise tracking the sun and tilted 45 degrees viewing the earth. Right, 3D printed UAM radiators, 6U ACCS radiator (top), and 4U ATA radiator (bottom) with dual aluminum and copper layering.

At this point, the thermal control technology is ready for fabrication and testing. A special emphasis should be placed on characterizing the thermal performance in a relevant laboratory environment. This will help to raise the TRL of the technology, reduce risk, and allow the design models to be validated. Once validated, models can be used to accurately predict mission operations and future modifications to the technology, representing a significant savings in terms of effort and cost.

3 ACTIVE THERMAL ARCHITECTURE

The Active Thermal Architecture (ATA) is an advanced Active Thermal Control (ATC) technology based on a single-phase Mechanically Pumped Fluid Loop (MPFL) system [23, 24]. The ATA is a sub-1U technology designed for 6U CubeSat platforms that can easily scale to any reasonable thermal requirements. The ATA technology uses micro-pumps (low-power centrifugal pumps) to circulate a specialized heat transfer fluid in a closed circuit between an internal heat exchanger and a deployed tracking radiator. Ultrasonic Additive Manufacturing (UAM) [25], an advanced 3D printing process, is used to embed the ATC system directly into the satellite structure, forming miniaturized, simplified, multi-functional structures. By utilizing UAM, the ATA technology is intrinsically scalable without adversely impacting the payload or spacecraft structure. UAM also provides significant improvement to thermal performance, size, weight, and power (SWAP). The ATA system includes a deployed (double-folded) tracking radiator, multi-axis rotary fluid joints, and an integrated PID control system to throttle the working fluid and simultaneously provide bulk thermal management and dynamic zonal temperature control. The ATA system will serve as payload support to the HyTI 2.0 instrument, which generates >100 W of thermal load during operation and requires a stable interface temperature, ± ~5 °C, between 10 and 30 °C. Without the ATA system, the HyTI 2.0 instrument would quickly overheat and would not be able to reliably operate on a SmallSat platform. The operational concept for the ATA system is shown below in Figure 4. The ATA MPFL was developed under the Active CryoCubeSat program [26], a NASA USTIP-funded program at the Center for Space Engineering (CSE) at Utah State University. Through the efforts of the ACCS/ATA programs, the ATA system is currently at TRL ~6.

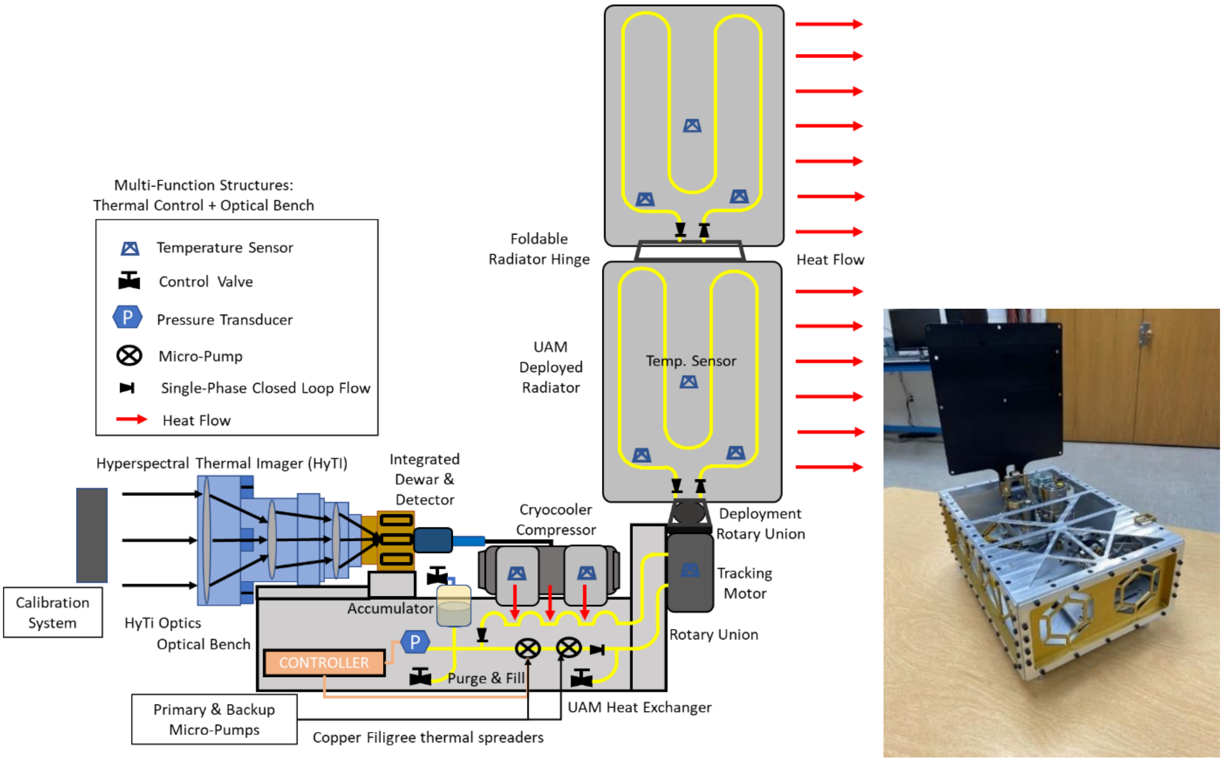


Figure 4. High-level operational concept for the Active Thermal Architecture technology. Single-phase working fluid is circulated between an internal heat exchanger and a deployed tracking radiator. The ATA system serves as the dedicated thermal control system for the HyTI 2.0 instrument, the optical bench for the telescope, and the outer wall of the spacecraft. The ATA system, 4U radiator, integrated with a 6U bus is shown on the right

4 ACTIVE COOLING FOR MULTISPECTRAL EARTH SCIENCE

The Active Cooling for Multispectral Earth Sensors (ACMES) mission is an upcoming technology demonstration mission funded by the Earth Science Technology Office (ESTO) through a NASA 2021 In-Space Validation of Earth Science (InVEST) grant [27]. ACMES is a +16U CubeSat that will be launched to a 550 km near sun-synchronous, high-inclination orbit, >85º in late 2025. The ACMES mission will consist of a 1-year technology demonstration, followed by up to 3 years of scientific operations. ACMES objectives include:

- *Enable the operation of cryogenic optical instruments on CubeSats*
- *Provide LWIR observations of the Earth's surface*
- *Create unique opportunities for a diverse set of students to contribute to NASA's work in exploration and science*

The ACMES spacecraft will be one of the most technologically advanced CubeSats ever launched. It will feature high-powered tracking solar arrays (~230 W BOL), onboard edge-data real-time processing, 400 Wh of protected Lithium batteries, integrated cold gas propulsion, and a next-generation S & X band telemetry system capable of downlinking >189 Gb/day via a DVSB2.0 link to KSAT ground stations in Troll and Svalbard. ACMES will feature four unique payloads: the second generation Hyperspectral Thermal Imager (HyTI 2.0), The ATA technology, which will be used to manage the high-powered and cryogenic thermal environment of HyTI, allowing continuous operations over land. And two student lead payloads. ACMES hopes to serve as an educational platform for the next generation of aerospace engineers and scientists. To this end, the ACMES spacecraft will host The Filter Incidence Narrow-band Infrared Spectrometer (FINIS) a tilted filter SWIR daytime Methane detector, and the Planer Langmuir/Impedance Diagnostic (PLAID) a novel, low-impact suite of ionospheric instruments. Figure 5, below shows CAD renderings of the ACMES spacecraft with key payloads and components labeled.

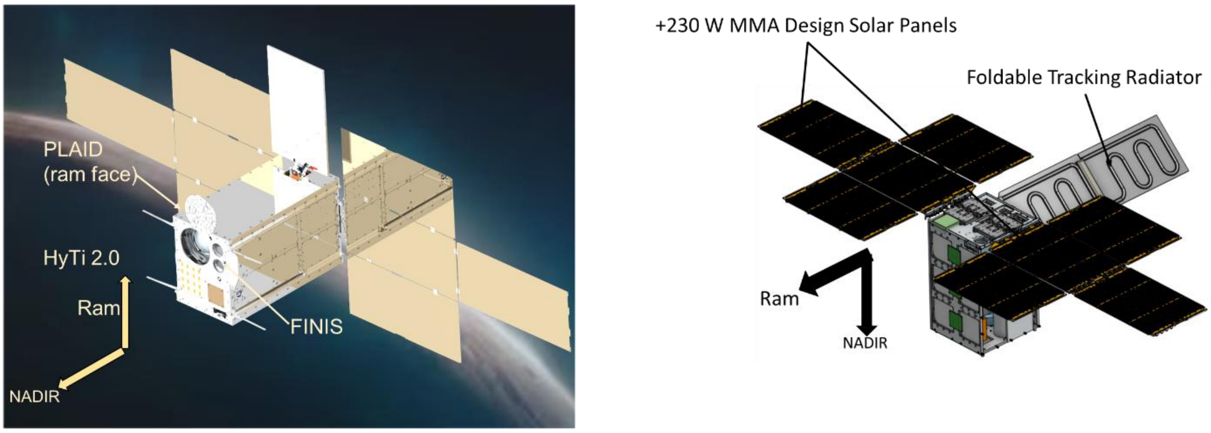


Figure 5. Left, a photo-realistic design of the 16U ACMES satellite. Right, a conceptual CAD diagram showing the high-powered MMA solar arrays and a dual folding MPFL ATA radiator.

4.1 Hyperspectral Thermal Imager 2.0

The second-generation Hyperspectral Thermal Imager (HyTI 2.0) is an advanced hyperspectral (25-bands) LWIR (7.5-12.5 µm) remote Fabry-Perot interferometer [28]. HyTI 2.0 will produce push broom spectro-radiometrically calibrated image cubes with a ground track swath width of 1.47° or 14.1 km and a pixel-by-pixel resolution of better than 45 meters. The HyTI telescope is coupled to a high-resolution JPL Hot-Barrier Infrared Detector (BIRD) focal plane array (1280 x 512-pixel 12 µm pitch). The HyTI focal plane requires cryogenic cooling to ~65 K and features an integrated dewar-cooler assembly produced by AIRS. The integrated cryocooler is the AIM SF-100, a high-capacity, long-life, flight-qualified Stirling-based cryocooler. The HyTI 2.0 instrument produces terabytes of data and requires extensive onboard computing. To support this data processing, HyTI will leverage the UniBAP IX-10 flight computer. The HyTI instrument will also feature an onboard radiometric and dark-current calibration system. When combined, the SF-100, IX10, and AIRS camera boards produce >100 W of continuous thermal load, which is the primary driver for the inclusion of the ATA technology. In addition, the HyTI telescope is sensitive to thermal variations of more than ±1 °C, and the SF-100 expander will experience thermal runaway at rejection temperatures above ~40 °C. The HyTI 2.0 instrument is an important milestone in CubeSat technology. HyTI hopes to produce LandSAT equivalent ground mapping data from a low-cost CubeSat platform. The scientific applications for the HyTI 2.0 instruments include mapping the chemistry and distribution of exposed rocks and minerals, land-mass temperature surveys, soil hydration/evapotranspiration, and quantifying volcanic gas and ash emissions in the lower atmosphere. The HyTI 2.0 instrument is being developed by the Hawaii Space Flight Laboratory and the University of Hawaii Manoa. The first generation HyTI 1.0 instrument was launched on a 6U CubeSat as part of a separate ESTO-InVEST-funded mission in April 2024. A preliminary CAD model of the HyTI 2.0 instrument is shown below in Figure 6.

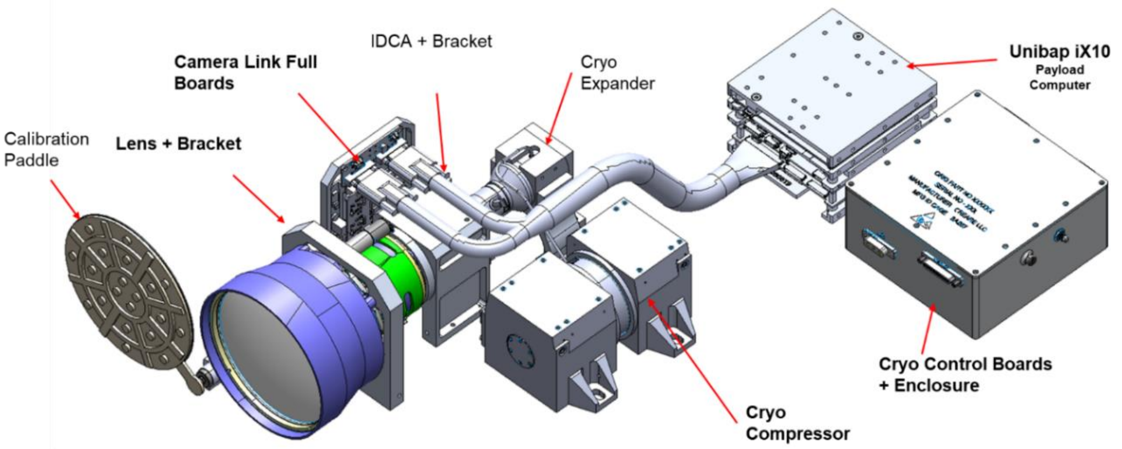
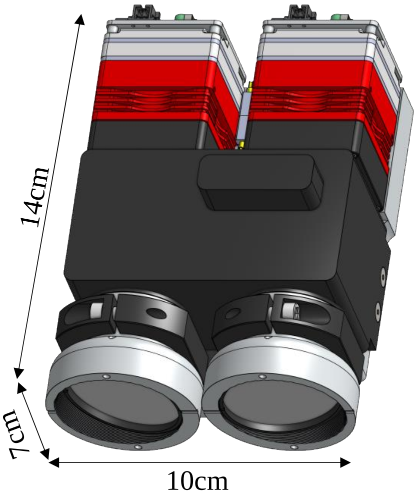


Figure 6. CAD design and component layout of the HyTI 2.0 hyperspectral instrument.

4.2 Filter Incidence Narrow Band Infrared Spectrometer (FINIS)

FINIS is a compact, low-power infrared spectrometer for measuring the total concentration of Methane, CH_4, within an atmospheric column [29]. FINIS operates by measuring both the absorption and emission of Methane (1.660 to 1.666 µm) through a tilted spectrometer design, fixed narrow-band filters spread the incoming light (transmission & absorption) across the detector with a resolution of 2 nm (FWHM). The density of CH4 is calculated from the logarithmic difference in intensity between a signal captured by an absorption pixel and a transmission pixel. Because FINIS operates as a push broom scanner, the same point on the ground is measured at both wavelengths. FINIS is a daytime instrument with, a solar zenith angle requirement of <60^{o} and a ground swath width of ~88 km (ground pixel size ~140 m). The FINIS camera is composed of custom optics and a FLIR Tau series SWIR detector. An internal calibrator mounted to a solenoid actuator provides on-orbit calibration of the instrument, both dark current and pixel gain leveling. FINIS primarily hopes to detect and locate small Methane leaks, which contribute over 90% to the total global Methane. The concentration of Methane in our atmosphere is critical to our understanding of global warming and space-based remote instruments capable of detecting point-source leaks are critical to the future well-being of our planet. The FINIS instrument is shown below in Figure 7.



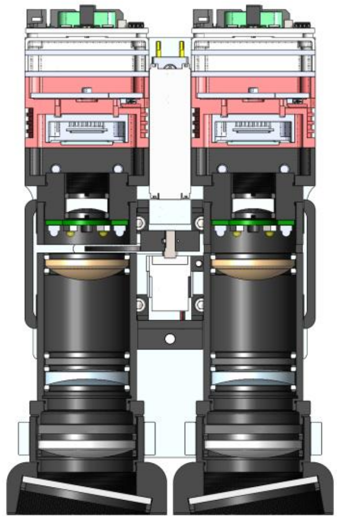


Figure 7. Left, CAD design of the FINIS instrument. Right, a cutaway view showing the camera, dual Tau detectors, and integrated calibration system.

4.3 Planer Langmuir/Impedance Diagnostic Probe

The Planer Langmuir/Impedance Diagnostic (PLAID) instrument is a set of planar-style space weather probes designed to study the ionosphere’s plasma environment. PLAID will directly measure, the in situ, density of the plasma environment (electron density & temperature) as well as the charging of the ACMES satellite, as an E-potential with respect to the ambient plasma. PLAID features a Langmuir probe, an RF-impedance probe, and a floating potential probe. Traditionally, space weather probes require complex, deployed booms. If successful, PLAID will represent a great improvement and reduce the complexity and SWAP of these instruments. PLAID will be mounted on the RAM surface of the spacecraft so that the planar antenna surfaces are directly exposed to the ionospheric plasma.

5 CONCLUSIONS

The next generation of advanced Small Satellites is facing a bottleneck. Power generation and energy storage technologies have matured to such an extent that traditional thermal control approaches are struggling to keep up. The space community needs an infusion of innovative thermal control technologies, with a particular focus on high-performance active thermal control systems. The future of satellite thermal control will revolve around dedicated and integrated, concurrent systems, which will serve as an enabling technology and provide end-to-end spacecraft thermal control. Examples of these technologies include variable conductance mechanisms, long-life coatings and surface materials, phase change systems, fluid loops, and smart radiators. In the future, satellites will rely on power and advanced technologies to shrug off the challenges of the space environment and support advanced payloads in Earth Science, Heliophysics, and deep space exploration.

The ATA is an example of just such a technology. Based on a closed loop single-phase MPFL, the ATA will serve as a payload support system to the HyTI 2.0 instrument on the upcoming ACMES mission. The ACMES mission is currently being developed by the Center for Space Engineering (CSE) at Utah State University (USU), Orion Space Solutions (OSS), and the Hawaii Space Flight Laboratory (HSFL) with a planned launch date of late 2025.

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