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Active Thermal Control for the Multispectral Earth Sensors (ACMES) Mission

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ABSTRACT

The Active Thermal Architecture (ATA) is a sub 1U active thermal control system providing payload thermal support and setpoint thermal control for the Active Cooling for Multispectral Earth Sensors (ACMES) mission. Based on a single-phase fluid loop heat exchanger, the ATA features a micro centrifugal pump, an innovative working fluid, and a two-axis flexible rotary fluid joint coupled to a deployable tracking radiator. The ATA system leverages advanced Ultrasonic Additive Manufacturing (UAM) techniques to directly integrate the ATA system within the payload and CubeSat structure. NASA's Science Mission Directorate has selected the ATA system to fly on the ACMES mission. A 12U CubeSat technology demonstration funded by the In-space Validation of Earth Science Technologies (InVEST) program. The ATA will serve as payload support to the Hyperspectral Thermal Imaging instrument (HyTi). A high spectral/spatial density long-wave infrared (8-10.7 µm) instrument. HyTi also features advanced, onboard high-performance computing. The ATA will thermally support HyTi allowing for continuous operations. ACMES will also feature two student-led instrument development projects. A highly sensitive methane detector FINIS and a planar Langmuir/Impedance probe PLAID. ACMES will be a joint development effort between Orion Space, the University of Hawaii, and Utah State University.

INTRODUCTION

The Active Cooling for Multispectral Earth Sensors (ACMES) mission[1] is a technology demonstration flight featuring four unique payloads. The primary of which is the Active Thermal Architecture (ATA). The ATA is an advanced active thermal control technology for high-power payloads, advanced CubeSats, and Small Satellite missions. The second payload is the next-generation Hyper-Spectral Thermal Imager (HyTi) instrument. HyTi is a high spectral/spatial density, long-wave infrared imager providing data similar to the current LandSat constellation. The ATA serves as payload support for the relatively high-powered HyTi instrument and enables near-continuous operations, providing valuable scientific data for the Earth Science community. Students will develop the last two payloads at Utah State University with support from Orion Space Solutions. FINIS is a high-precision methane imager, and PLAID is a planar RF impedance probe for in situ space environment observations. Funded by NASA's Earth Science Technology Office (ESTO) under an In-Space Validation of Earth Science Technologies (InVEST) grant, ACMES collaborates with Utah State University, Orion Space Solutions, and the Hawaii Space Flight Center.

The mission concept for ACMES is a one-year technology demonstration followed by up to three years of scientific research. ACMES will launch in late 2024 to 2025 to a ~550 km sun-synchronous orbit with an ascending node between 10:00 AM and 12:00 PM, ensuring at least four years of operation above 400 km with an ascending node drift of less than ~2 hours. The spacecraft will be a 12U bus developed by OSS with single-axis articulating solar arrays capable of generating over ~120 W of instantaneous power (orbit average > ~60 W). The ACMES spacecraft concept and mission operation are shown below in figure 1. Mission objectives are outlined below in Table 1.

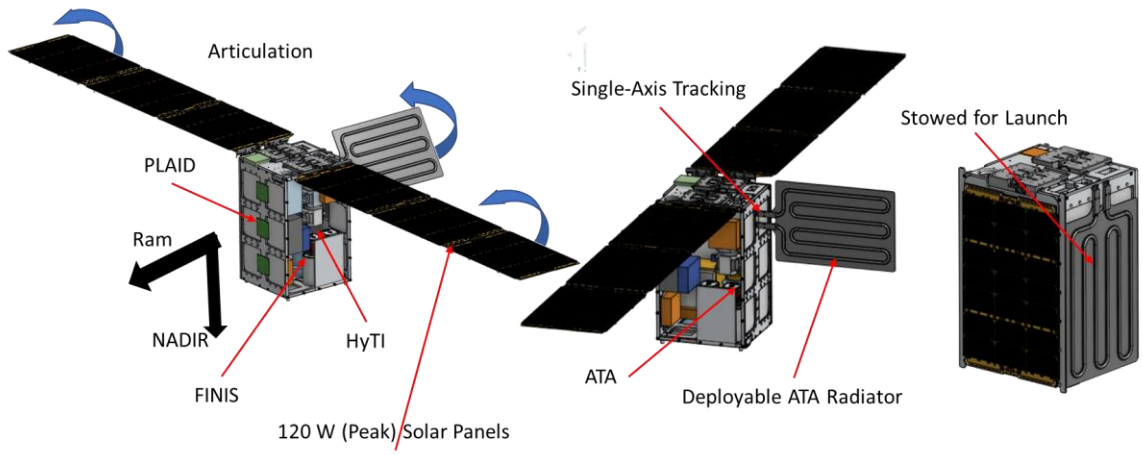

Figure 1: ACMES 12U CubeSat Design and Operational Mission Concept

Traditional CubeSat thermal control primarily relies on passive techniques and a hot case (cold survival) design methodology. Passive thermal control technologies include body-mounted radiators, radiative surface coatings, conductive flow paths, and, in some cases, integrated heat pipes[2]. These passive thermal control methods are sufficient for low-powered payloads. However, passive control methodologies often result in wide temperature swings and non-ideal hot/cold operating environments for the spacecraft, adversely affecting payload or bus components such as batteries.

Active thermal control technologies require input power to reject thermal loads. These include single-phase mechanically pumped fluid loops, two-phase refrigeration cycles, cryocoolers, thermoelectric coolers, etc. Active thermal control has the following advantages[2,3]:

- Efficient high-power rejection
    - High heat flux
- Dynamic thermal control
    - Variable effective conductance
    - Setpoint PID control
- Accept & reject thermal loads at multiple locations
- Enable deployable radiators
- Near isothermal operation
- Flexible & adaptive design

With current improvements in satellite power generation, high-efficiency solar panels, high-density batteries, and miniaturized cryocoolers, the need for advanced thermal control is already apparent. Current missions that would benefit from active thermal control include the first generation HyTi instrument, JPL's CubeSat Infrared Atmospheric Sounder[4] (CIRAS), NOAA EON-IR[5], and the proposed Sounding of the Atmosphere in Broadband Emission Radiometry (SABER-CUBE) mission.

Table 1: ACMES Mission Objectives

Objectives
Primary Goal: Demonstrate the ATA technology on a CubeSat • Demonstrate the ATA in a space environment. Raise the TRL to ~7. • Thermally support the HyTi instrument and enable continuous operations. • Demonstrate on-orbit the thermal control of a high-power CubeSat.
Secondary Goal: Provide LWIR observations of the Earth's surface. • Operate the HyTi multispectral instrument as a scientific mission to observe the landmasses of the Earth for one year (up to 4 years). • Demonstrate the effectiveness of non-mechanical scanning multispectral sensor technology. • Demonstrate onboard computing to reduce high-data rates
Tertiary Goal: Create opportunities for students to contribute to NASA's work in Exploration and Science. • Provide work and research experiences that enable students to contribute to the ACMES mission. • Inspire students to contribute to NASA's work in exploration and discovery.

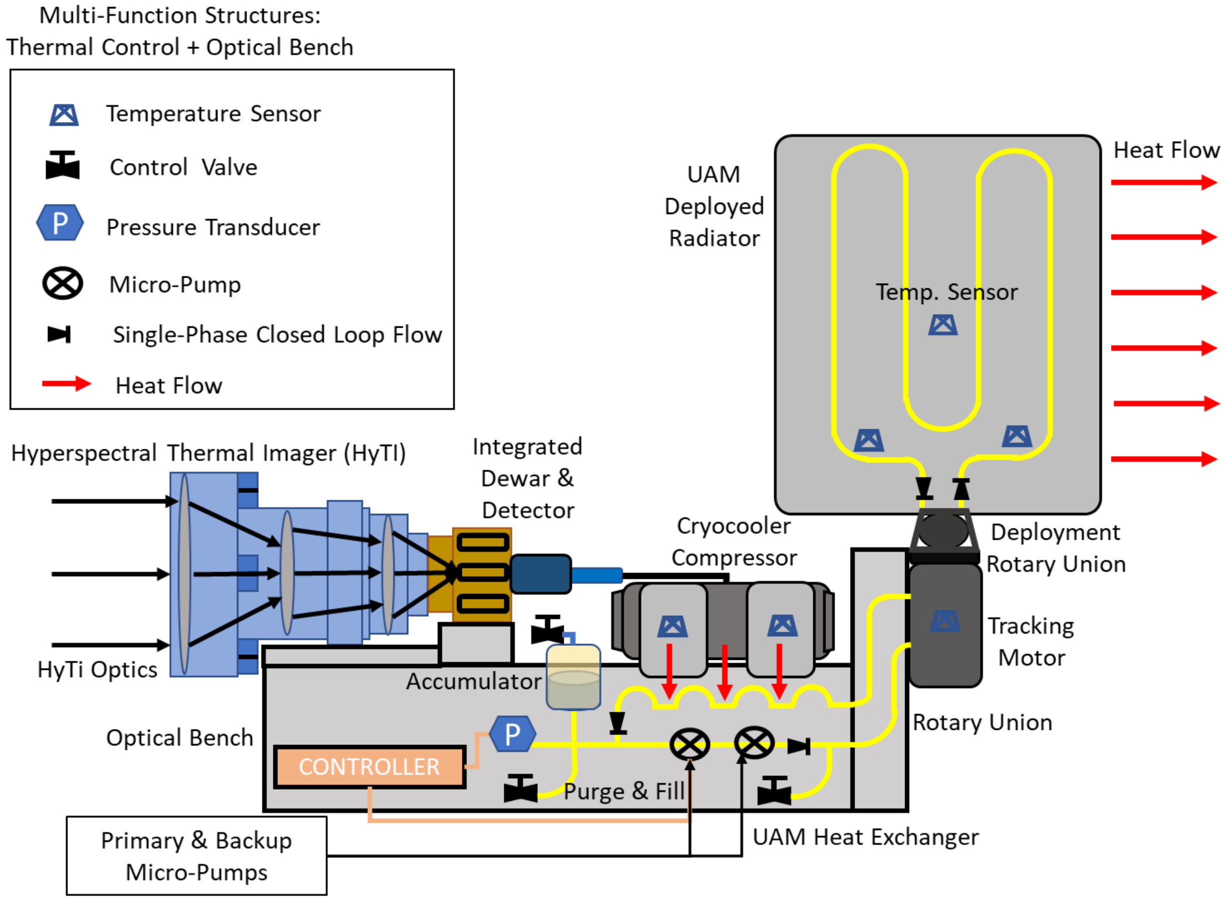

Figure 2: The Operational Concept for the Active Thermal Architecture System

ACTIVE THERMAL ARCHITECTURE

The ATA is an advanced active thermal control technology based on a miniaturized mechanically pumped fluid loop (MPFL) heat exchanger (HX)[6,7,8,9]. Thermal energy is absorbed internally by the multi-function HX and transported, in a closed-loop, to a deployed tracking radiator by a single-phase working fluid. A two-axis articulating rotary fluid joint allows the working fluid to pass between the spacecraft and the deployable radiator. A micro-centrifugal pump drives the MPFL system. The ATA leverages advanced 3D fabrication techniques such as Ultrasonic Additive Manufacturing to directly embed the working fluid channels into the payload/spacecraft structure. The ATA's operational concept (CONOP) is shown in figure 2, while several realistic ground prototypes are shown in figure 3. ATA is a follow-on project to the ACCS project[10,11]. The ATA is a novel active thermal control technology for advanced CubeSat and Small Satellite missions in helio-physics, earth science, and deep space.

Figure 3: Realistic 6U Prototypes of the ATA System

Ultrasonic Additive Manufacturing

Ultrasonic Additive Manufacturing (UAM) is an advanced 3D printing technology that combines traditional subtractive machining techniques with modern additive printing. UAM structures are formed from thin sequential layers of metallic tape. An ultrasonic weld head scrubs each metallic layer to the base material. Ultrasonic vibrations cause shearing at the interface, resulting in plastic deformation, interface diffusion, and recrystallization of the metallic layers, forming an atomic bond[12]. Subtractive machining is then used to refine and finish the structure. This process is low-temperature and uniquely suited to mixing metal types, creating internal voids and embedding fluid channels directly into metal media.

UAM is crucial for the ATA system and allows the fluid path to be miniaturized, simplified, and directly integrated with the payload and spacecraft bus. UAM also offers several key advantages, including improved thermal performance (reducing interface resistances), rapid design & fabrication, and the development of unique designs that would otherwise be impossible with traditional methods. The ATA's 4U mixed metal radiators are shown in figure 4.

Mechanically Pumped Fluid Loop

The TCS M510 &/or M450 micro-pump forms the heart of the ATA MPFL. TCS micro-pumps are lightweight, efficient, and capable of high flow rates >1200 mL/min and differential pressures >11 PSID. Nominally, these pumps are operated below 3 W with flow rates between 100 and 400 mL/min. TCS micro-pumps can be mounted directly (manifold) to the UAM HX structures, making them ideal for CubeSat operations. In addition, the TCS M510 and M450 are "canned" designs, which means that they have no dynamic seals. This dramatically improves the vacuum compatibility of the pump, reduces overall wear, and increases the pump's lifespan to at least 20,000 hours with optional 100,000-hour variants available[13]. The flow rate of the micro-pump governs the ATA's setpoint thermal control. By throttling the pump from laminar to turbulent and from on to off, the operating temperature and overall thermal load can be dynamically varied as the mission profile changes. TCS micro-pumps, including the M510, M450, and MGD1000, are shown in figure 5. Figure 6 shows a CAD model of the 1U integrated ATA system. Key components are labeled.

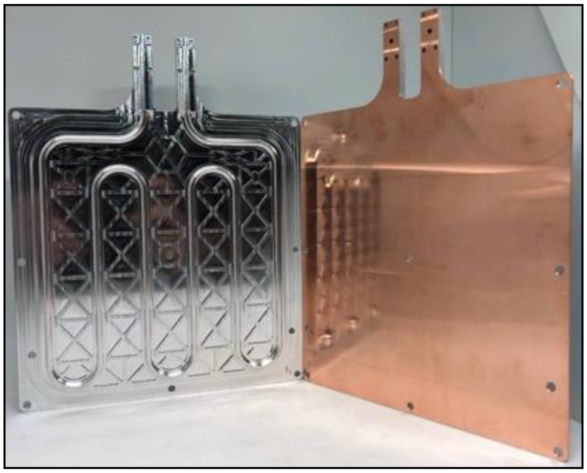

Figure 4: UAM radiators (4U) showing mixed metallurgy[12]

Figure 5: TCS Micro-Pumps

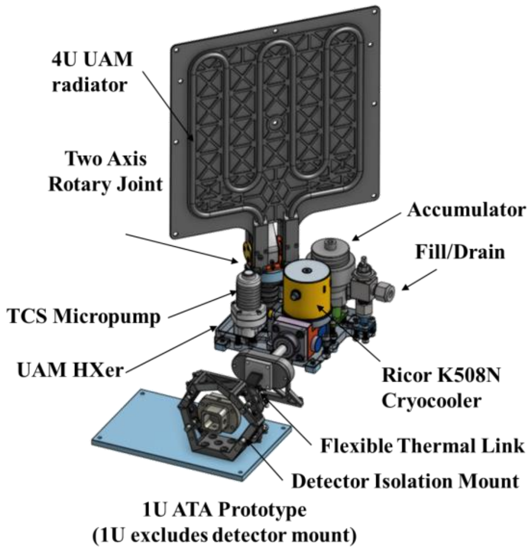

Figure 6: Integrated "labeled" ATA system

The ATA uses an advanced single-phase working fluid called Novec 7000 (7200 optional). Produced by 3M, Novec is a low temperature, low viscosity heat transfer fluid. Novec is thermally stable, non-toxic, dielectric, and exhibits a low GWP, making it ideal for Small Satellite MPFLs[14].

The deployable tracking radiator is made possible through a custom dual-axis fluid hinge. The initial one-time deployment of the radiator is accomplished by a horizontally mounted, to the spacecraft body, dual-channel rotary union driven by a Contorque deployment hinge. This mechanism allows the deployment torque of the radiator to be tuned by simply adding or subtracting springs. The continuous single-axis rotation of the deployed radiator is driven by a geared micro-motor coupled to a second rotary union, perpendicular to the first. This dual rotary union design can be mixed and matched to form a variety of dynamic systems, including two-axis tracking radiators, foldable radiators, and door-hinged designs. The ATA dual-axis rotary fluid hinge is shown in figures 7 & 8. The ATA working fluid is circulated to the deployed articulating radiator through a dynamic rotary union joint. The radiator can be tracked edge onto the sun to optimize thermal rejection or angled face onto the sun/earth for additional thermal input from the environment. By allowing the radiator to track, a second line of thermal control is added to the ATA system.

As an MPFL, the ATA system requires an integrated gas/fluid accumulator to compensate for changes in the static charge pressure caused by the thermal expansion/contraction of the working fluid. In addition, the fluid accumulator serves as a fluid reservoir to compensate for small leaks within the system[15]. The ATA fluid accumulator is a custom-made piston design that can easily be scaled to match any required fluid volume. The gas side is charged, to ~75 PSIG, through a micro-valve, and the exact compression ratio of the gas is measured by determining the position of the accumulator piston with a Hall-Effect magnetic sensor. The ATA prototype accumulators are shown in figure 9. Guard patch-heaters are installed on the ATA HX to compensate for full-system shutdowns and extreme cold cycles.

The ATA utilizes both static and dynamic soft O-ring seals. Great care has been taken to minimize the number of seals & reduce the leak potential of the system. Dynamic joints are double sealed to reduce potential leaks further. EPDM O-rings provide chemical compatibility and the required operating temperature range of the ATA system.

Figure 7: ATA custom rotary fluid joint

Figure 8: ATA 4U UAM radiator and dual-axis rotary fluid union

Figure 9: ATA piston fluid accumulators

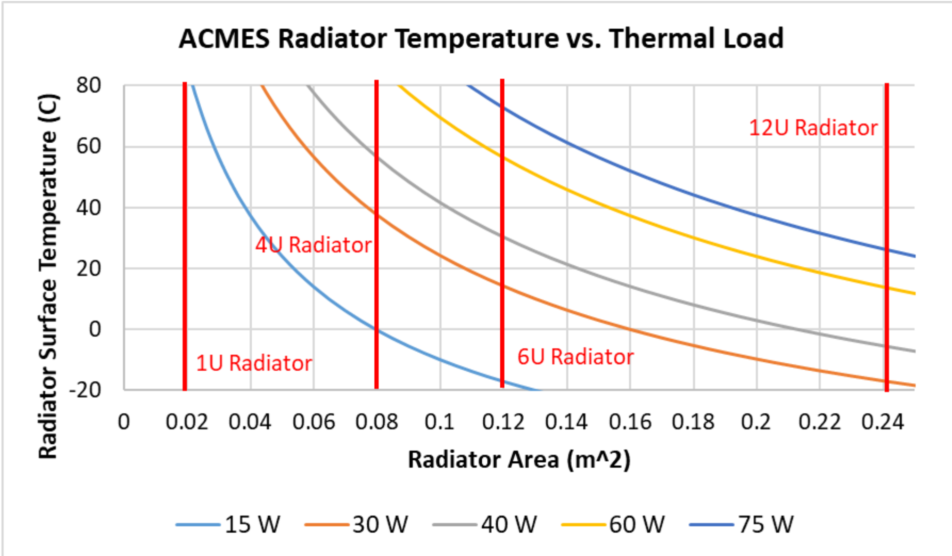

Figure 10: ACMES radiator temperature vs. thermal loading as a function of the area

The ATA radiator is sized to 6U (~0.12 m^2) to manage the operating thermal load of the HyTi instrument, nominally between 30 and 40 W, while maintaining the heat exchanger rejection temperature at 25 ºC. The space environment adds to the overall thermal load of the system. The MPFL is directly integrated with the ACMES spacecraft bus and the HyTi payload. The flow channel profile ensures that the heat transfer fluid is in direct contact with the thermal rejection regions of the HyTi instrument and distributes the thermal waste load near isothermally across the radiator. The hydraulic diameters are maintained at approximately ~0.15" throughout the fluid loop. The operating temperature of the ATA system is ideally between -20 ºC and 60 ºC (with an average below ~30 ºC) with a low-end survival temperature of -40 ºC. Figure 10 represents the various ACMES radiator temperatures as a function of thermal load and radiator area. Figure 11 compares the original +6U ACCS radiator, the 4U ATA radiator, and the proposed 6U ACMES radiator.

The ATA system has undergone complete General Environmental Verification & Specification testing to an approximate TRL level of 6. This testing included exported vibration characterization, launch load testing (NanoRacks soft stow & NASA GEVS), and two separate TVAC cycles, including one held at JPL's Environmental Testing Laboratory (ETL)[16,17]. In addition, the ATA MPFL has been helium leak qualified to a leak rate of better than e^{-9} atm cc/sec. The ACMES MPFL will be an updated and customized variation of the ATA system.

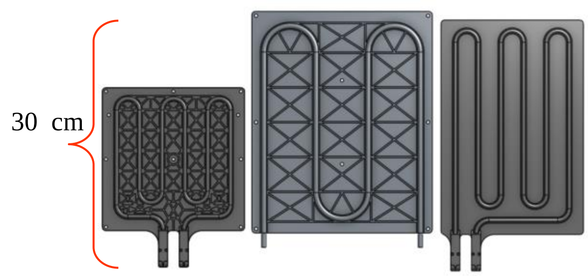

Figure 11: Radiator size comparison. From left to right: ATA, ACCS, ACMES

HYPERSPECTRAL THERMAL IMAGING

The Hyperspectral Thermal Imaging Instrument (HyTi) is an advanced high spatial, high spectral LWIR hyperspectral imager for LandSat-like observations of the Earth. The second generation of HyTi (HyTi 2.0) will fly with the ACMES mission as one of the two primary payloads[18,19].

HyTi utilizes a no-moving parts design. The LWIR hyperspectral scene is imaged by a static refractive lens, through an air-gapped, sloped Germanium Fabry-Perot interferometer to an Integrated Dewar Cooler Assembly (IDCA) containing the focal array. The interferogram of the image is constructed by the push broom motion of the satellite's ground track as a stacking of interference patterns. Fourier Transforms are used to create a spectrally & radiometrically calibrated image cube of the co-registered images. HyTi 2.0 will image the continental landmass of the Earth with a goal of 100% coverage.

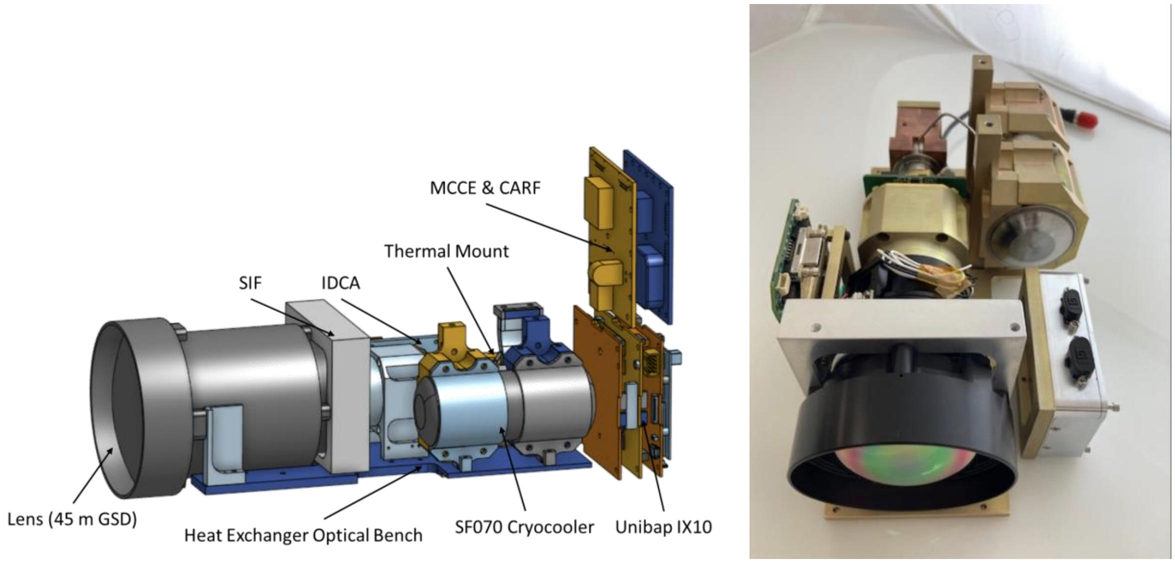

Figure 12: The HyTi instrument. Labeled CAD design on the left and first generation HyTi on the right[20]

HyTi features JPL's innovative Barrier Infra-Red (Hot Bird) focal plane array (FPA) technology. The Hot-Bird FPA is a low-cost, high-yield, high-performance focal plane with excellent pixel density, a sensitivity between 8-10.7 µm (separated into 25 separate bands) and an element density of between 640 X 512 &/or 1280 X 1024 pixels. The spatial ground sampling distance is 60 meters for HyTi and <45 m for HyTi 2.0. To reduce dark currents, the HyTi IDCA will be cooled to between 68 & 72 K by an integrated AIM-SF070 cryocooler, which requires 15 W orbit average power. The next generation HyTi instrument will likely require an upgraded AIM-SF100 cryocooler generating 35 W orbit average. The continuous support of this high-power cryocooler is the primary mission for the ATA system, which will be directly integrated with HyTi 2.0 through multi-purpose UAM thermal support structures. The HyTi instrument is shown in figures 12. A processed HyTi LWIR image of Ohau is shown in figure 13.

The HyTi instrument imaging rate is oversampled to greater than 139 Hz. This results in a data rate of several Terabytes per day, requiring onboard processing of the raw data from L0 to L2, through image co-registration, FFT analysis, image calibration, and partial least squares regression. HyTi incorporates the Unibap Deep Delphi iX5 (iX10 for 2.0) heterogeneous high-performance computer platform (featuring CPU, GPU and FPGA capabilities). Onboard processing reduces the HyTi data rate by a factor of 10x, which is further reduced by 3:1 lossless compression. This still results in a large data rate and an advanced X-band telemetry link.

Figure 13: Lo Image of Oahu capured by a plane mounted prototype of the HyTi instrument[20]

The first generation HyTi mission, funded by DARPA/NASA through an InVEST grant, is currently scheduled to launch late 2022 on a 6U spacecraft as a separate technology demonstration. HyTi 2.0 is a advanced next generation LWIR ground imaging instrument and an ideal application for active thermal support and the ATA subsystem[20].

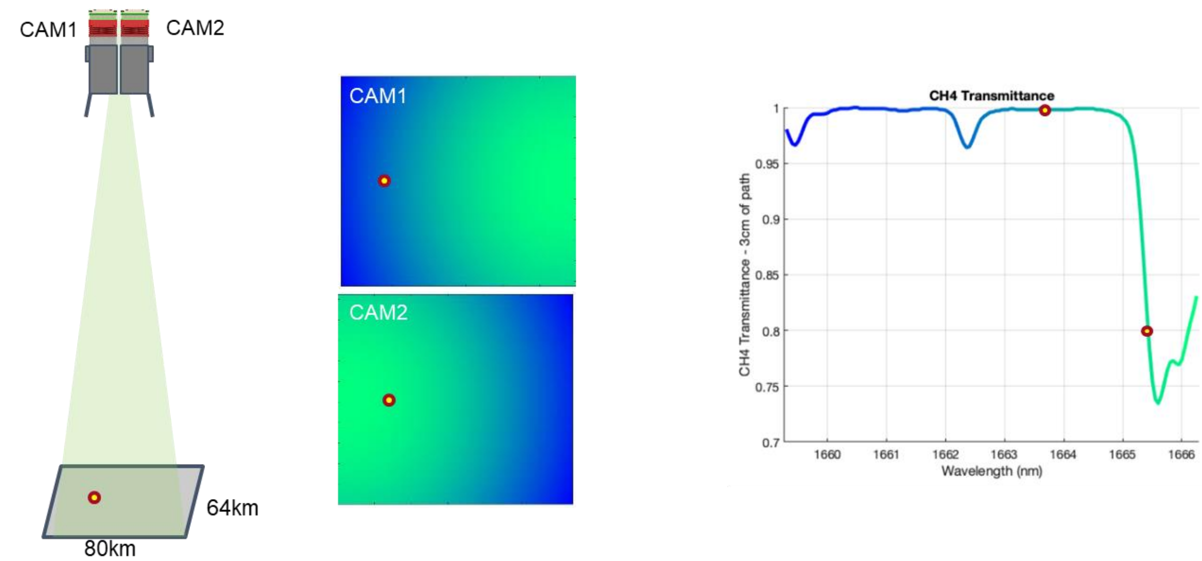

Figure 14: FINIS concept of operation

FINIS INSTRUMENT

The Filter Incidence Narrow-band Infrared Spectrometer (FINIS) instrument detects daytime Methane CH_4 as a solar illuminated scene. The operational concept of FINIS is shown in figure 14. FINIS observes Methane between the transmission and absorption wavelengths of 1.660 to 1.666 µm with a strong Methane absorption feature at 1.666 µm. These spectral bands are produced by a tilted interference filter that monotonically distributes the de-tuned wavelength across the focal plane array. Combined with the viewing angle of the instrument, FINIS effectively scans in wavelength along the Methane absorption spectrum as the incident angle of light changes. FINIS utilizes dual FLIR SWIR cameras tilted in reverse (towards each other) along the satellite's ground track. Allowing FINIS to simultaneously image the same scene at absorbing and non-absorbing wavelengths. The atmospheric concentration of Methane within the viewing column is extracted by comparing the relative brightness ratio/differences of the imaged scene by the two cameras[21]. Transmission to absorption. FINIS will require on-the-ground absolute radiometric calibration and on-orbit flat fielding of the array. As FINIS operates, ground location images overlap and are sampled multiple times with varying signal-to-noise ratios. The final Methane concentration value is determined from the SNR weighted average of this overlapping data. FINIS is a compact, affordable, hyperspectral methane imager with no moving parts, making it an attractive sensor for CubeSat applications. The dual-camera design of FINIS for ACMES is shown in figure 15, while the single-camera ground prototype is shown in figure 16.

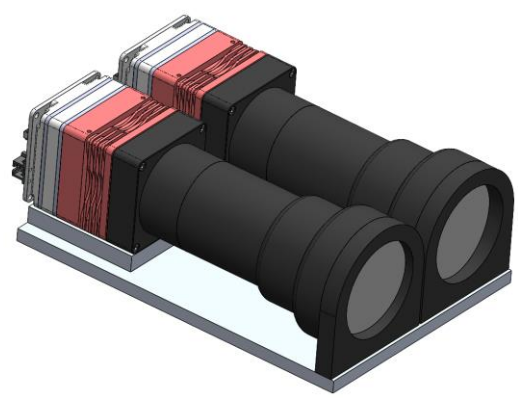

Figure 15: ACMES FINIS instrument

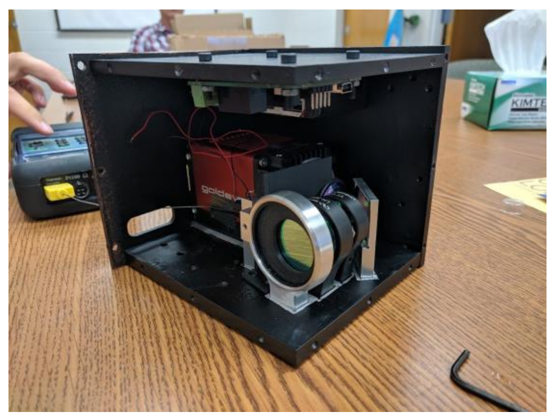

Figure 16: Ground-based prototype of the FINIS instrument

PLAID INSTRUMENT

The Planar Langmuir Impedance Diagnostic (PLAID) instrument is a novel planar-style RF impedance probe capable of observing the charging of the spacecraft and the space environment. Specifically, the electron temperature, density, and electric potential of the space environment plasma. As a static patch instrument on the RAM surface of the spacecraft, the impact of PLAID is minimal compared to traditional deployable rigid-boom style Langmuir probes. Langmuir RF impedance antennas are commonly formed from dipoles or monopoles that are short compared to the free space electromagnetic wavelength at the instrument driving frequencies[22]. PLAID will be the first planar-style probe employed for Small Satellites. PLAID effectively becomes a capacitor with the ionospheric plasma acting as the dielectric. The current flowing through PLAID will have resonant signals, both magnitude & phase, with respect to impedance vs. frequency. PLAID will be fabricated as a series of flat plates. The front face of PLAID will be exposed to the RAM ionospheric plasma. The fringing electric field will extend into the plasma and change the impedance of PLAID as a function of plasma density. The DC potential of the PLAID will be swept to explore the characteristics of the sensor under various plasma sheath conditions. PLAID will be insulated so that capacitance shunting to the spacecraft will not occur.

ACMES DEVELOPMENT & OPERATION

Orion Space Solutions of Colorado will lead the primary development of the ACMES spacecraft. Including the design and fabrication of the 12U bus and avionics. OSS offers experience, facilities, and heritage for spacecraft and payload development. In addition, the ATA payload will be built by OSS. The ACMES ATA payload will be an improved second-generation design over the ground-based prototypes and will be customized to integrate with the OSS bus and support the HyTi instrument. The 2nd gen. ATA will leverage UAM parts from Fabrisonics LLC, micro-pumps from TCS, and a heat transfer fluid from 3M. OSS will fabricate all additional components. Student teams at Utah State University will design both FINIS and PLAID. The FINIS mechanical/electrical build will be done by OSS, while PLAID will be fabricated entirely at Utah State University. The Hawaii Space Flight Institute will develop the 2nd generation HyTi instrument with support from OSS.

The ACMES spacecraft will be launched to the required orbit by a CLSI launch and operated through the KSATlite ground network by OSS. Science operations centers will be located at Utah State University and the University of Hawaii at Manoa.

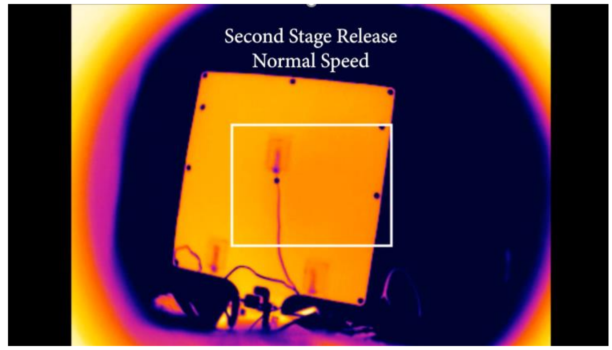

Figure 17: Thermal view of the ATA radiator during TVAC GEVS characterization

Figure 18: Orion Space Solutions' large TVAC testing facilities

ACMES GEVS QUALIFICATION

The ACMES satellite will be fully qualified and characterized for LEO operations by OSS. Including benchtop checkouts at the component level, system integration/testing, avionics, deployment testing, launch load qualification, and TVAC characterization. The OSS team will also perform comprehensive simulations & modeling of "a day in the life" of the ACMES satellite. The HyTi and FINIS instruments will be calibrated on the ground for absolute radiometric signal and flat fielding of the focal array. An infrared radiometric image of the deployed, tracking ATA radiator is shown in figure 17. The large vacuum chamber testing facilities at OSS are shown in figure 18.

The ATA is designed by a series of custom analytical models used for the rapid iterative development of single-phase active thermal control systems. Detailed Thermal Desktop and Star CCM flow profile numerical models will also be developed as the project progresses.

These models will help to predict the performance and behavior of the ATA system, HyTi, and the ACMES satellite. The ATA payload will undergo detailed ground-based characterization and qualification. This analysis will begin with the semi-custom TCS micro-pumps. The flow vs. power performance will be measured along with the overall pressure drop within the ACMES ATA system (compared to 2k-pressure drop modeling). The pumps will also undergo stress & lifetime testing to determine failure mechanisms. The ATA fluid accumulators' reaction to the expected mission temperature profile will be recorded, and the predicted system static pressure will be defined as a function of temperature. Due to the ATA being a pressurized system, each component will be burst tested to a safety factor of 15 (1500 PSIA) and qualified for an additional 2000 PSIA. Helium leak detection will be used to demonstrate that the ATA soft O-ring seals do not leak above a rate of $10^{\wedge-8}$ atm cc/sec. The ATA subsystem will be shaken at a component level to demonstrate the failure-proof operation of the O-ring seals, the radiator deployment hinge, the tracking radiator, and the micro-pumps. Finally, the ATA will undergo a separate thermal TVAC test to characterize its performance and behavior. This data will be used to tune the PID control algorithm[23].

The ATA system will be integrated with HyTi and the spacecraft bus by OSS. The ACMES spacecraft will be benchtop tested for operation and qualified for launch loads per the CLSI and launch provider requirements. Post-launch deployment of the solar panels, lens cover, and radiator will demonstrate post-launch operations. A final TVAC thermal cycle will qualify the ACMES mission for space operations. The ACMES spacecraft will be delivered to the launch provider in late 2024 to 2025.

CONCLUSIONS

The Active Cooling for Multispectral Earth Sensors (ACMES) mission is an advanced technology demonstration mission for the in-space validation of the Active Thermal Architecture (ATA) and second-generation Hyperspectral Thermal Imager (HyTi) payloads. Additional payloads will include the high-performance Methane detector FINIS and the Planar Langmuir probe PLAID. ACMES is funded by NASA's Earth Science Technologies office through an InVEST grant. The ACMES project is a joint development venture between Orion Space Solutions, The Hawaii Space Flight Center, and Utah State University. ACMES will be a 12U spacecraft, developed by OSS, and launched into a sun synchronous 10:00 AM to 12:00 PM orbit late in 2024 to 2025.

The ATA is an active thermal control technology for thermal management and control of high-power payloads on CubeSats and Small Satellites. Based on a single-phase closed loop MPFL heat exchanger system, the ATA represents a critical advancement in thermal control technology. The ATA can easily be scaled/customized to accommodate a wide variety of spacecraft and payloads, enabling the next generation of advanced SmallSat missions.

The HyTi instrument is a groundbreaking hyperspectral LWIR thermal imager and has the potential to replace larger traditional thermal ground-mapping satellites with an affordable CubeSat alternative. HyTi is also pioneering high-performance onboard processing and CubeSat machine learning. The ATA instrument will be used thermally support the high-powered HyTi instrument and enable continuous operation of the HyTi and ACMES missions.

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