

Cryogen-Free Common-Aperture VIS/SWIR/MWIR Spaceborne Imager via Adiabatic Frequency Conversion

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ABSTRACT

Spaceborne remote sensing systems typically operate in either visible (VIS, 0.4-0.7 μm) or infrared bands, each providing complementary information. VIS imaging enables high-resolution reflectance-based observations, while short-wave infrared (SWIR, 1-2.5 μm) provides material-sensitive contrast under challenging illumination, and mid-wave infrared (MWIR, 3-5 μm) provides access to thermal emission signatures. However, integrating these modalities within a single spaceborne payload remains a significant challenge, limiting the ability to capture co-registered multi-band data for dynamic and time-sensitive scenes, even when fusion is performed in post-processing.

In this work, we present a prototype of a cryogen-free, common-aperture imaging architecture enabling simultaneous VIS, SWIR, and MWIR acquisition within a single optical system. The approach is based on Adiabatic Frequency Conversion (AFC), a nonlinear optical process that efficiently up-converts SWIR and MWIR radiation into the visible domain, allowing detection using standard, uncooled sCMOS sensors. By eliminating the need for cryogenic infrared detectors, the proposed architecture significantly reduces system complexity, mass, cost, and associated reliability risks, while leveraging the maturity and performance of visible-band detector technology.

The system operates in a multi-mode configuration, where a shared telescope and optical train support direct VIS imaging alongside SWIR and MWIR channels implemented through an AFC stage. This single-aperture design enables fully simultaneous, inherently co-aligned acquisition across all spectral bands. Such band co-registration at the point of acquisition is particularly advantageous for dynamic scenes and cannot be replicated through the fusion of independently acquired datasets.

A central enabler of this architecture is the use of adiabatically poled nonlinear crystals in the frequency-conversion stage. Unlike conventional phase-matched nonlinear processes, which are inherently narrowband, adiabatic frequency conversion supports efficient broadband conversion of incoherent SWIR and MWIR radiation across a wide spectral and angular range. This enables single-shot, wide-field SWIR and MWIR imaging without spectral scanning or angular restriction, overcoming a fundamental limitation of prior up-conversion imaging approaches. In parallel, the broadband optical design supports visible-band imaging within the same shared telescope architecture.

Preliminary laboratory experiments conducted using a space-qualified Ritchey-Chrétien telescope demonstrate the feasibility of the proposed architecture and validate its imaging performance. The presented approach enables a new class of compact, cost-effective, and cryogen-free spaceborne payloads providing co-registered VIS/SWIR/MWIR sensing within a unified system. This capability opens new opportunities for Earth observation and environmental monitoring missions requiring high-fidelity multi-band situational awareness with reduced Size, Weight and Power (SWaP) and improved mission economics.

Keywords: Infrared imaging, space imaging, MWIR, Adiabatic Frequency Conversion

1. INTRODUCTION

Spaceborne imaging systems increasingly rely on multispectral observations to extract physical information that cannot be obtained from visible imagery alone. While visible (VIS) imaging provides high spatial resolution and excellent scene

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interpretation, infrared observations reveal complementary information associated with material composition, moisture content, and thermal emission. In particular, short-wave infrared (SWIR) imaging enables improved material discrimination and imaging under challenging illumination conditions, whereas mid-wave infrared (MWIR) observations provide direct measurements of thermal signatures that are essential for applications including wildfire detection, industrial activity monitoring, maritime surveillance, environmental monitoring, and defense.

Despite the clear benefits of multispectral imaging, most spaceborne systems continue to acquire visible and infrared imagery using independent optical channels or separate payloads. This approach introduces additional mass, volume, power consumption, and system complexity while making accurate spatial and temporal registration between spectral bands increasingly difficult, particularly for dynamic scenes. Furthermore, the widespread use of MWIR imaging remains constrained by the reliance on cryogenically cooled infrared focal-plane arrays (FPAs), which are associated with higher cost, lower detector resolution, increased calibration requirements, and significant engineering complexity compared with mature silicon detector technology.

These limitations motivate the development of imaging architectures that can simultaneously acquire visible and infrared imagery while minimizing payload complexity. An attractive solution is the use of a common-aperture [1] optical system capable of supporting multiple spectral bands through a shared telescope, thereby providing intrinsic geometric alignment between all imaging channels while reducing SWaP [2].

In this work, we investigate such architecture by integrating broadband Adiabatic Frequency Conversion (AFC) imaging module into a representative spaceborne telescope. Using this technology, broadband SWIR and MWIR radiation can be converted into the visible spectral range, allowing infrared images to be recorded using mature silicon image sensors instead of conventional cryogenically cooled infrared detectors. AFC, originally introduced as a robust approach for broadband nonlinear optical frequency conversion [3,4], has recently emerged as a promising alternative for infrared imaging [5,6]. By efficiently upconverting broadband, incoherent SWIR or MWIR radiation into the visible domain, AFC enables infrared images to be acquired using high-performance, uncooled CMOS image sensors, eliminating the need for cryogenic infrared FPAs. This approach has the potential to substantially reduce payload size, weight, power consumption, cost, and reliability risks while leveraging the maturity, resolution, and performance of visible-band detector technology.

The objective of this work is not only to demonstrate the feasibility of AFC for spaceborne MWIR imaging, but also to explore a new payload architecture in which VIS, SWIR, and MWIR observations are acquired through a common optical system. Such architecture provides the foundation for intrinsically co-registered multispectral imaging and opens the possibility of advanced computational fusion techniques in which the high spatial resolution of visible imagery can be directly exploited to enhance simultaneously acquired infrared observations.

2. MWIR REMOTE SENSING

Limitations of Conventional MWIR Imaging

Although MWIR remote sensing provides unique thermal information, implementing high-performance MWIR imaging payloads remains challenging. State-of-the-art MWIR focal-plane arrays (FPAs), including InSb, MCT, XBN, and Hot Full Midwave (HFM) technologies, typically require cryogenic cooling to temperatures between approximately 80 and 150 K to achieve acceptable dark-current performance. Compared with mature silicon detectors, these FPAs generally offer lower pixel counts, higher cost, increased power consumption, and more demanding calibration requirements.

Typical commercial MWIR detectors provide resolutions of approximately 1280 X 1024 pixels and exhibit read noise on the order of 100 electrons per pixel. Achieving high image quality therefore relies on large full-well capacities and careful optimization of the optical system. In addition, pixel-to-pixel non-uniformity requires periodic radiometric calibration using multiple uniform blackbody references over the operational temperature range. While these challenges have been successfully addressed in numerous space missions through cryogenic cooling systems and onboard calibration assemblies, they significantly increase payload complexity, mass, power consumption, cost, and development effort.

AFC imaging technology

To address these limitations, we have integrated the AFC imaging concept, developed by Spiral Photonics, into a space-grade optical telescope based on a corrected Ritchey-Chrétien design. The broad spectral and angular acceptance of AFC is particularly well suited to imaging extended, spatially incoherent infrared scenes. With the broad and robust upconversion, it enables single-shot imaging on a silicon-based camera without the spectral scanning or precise angular alignment typically required by conventional nonlinear upconversion systems while preserving the spatial information carried by the incoming radiation [6].

In the current implementation (SPIRAL1.0 camera, TRL5), a Q-switched 1064 nm laser serves as the pump source for the nonlinear frequency-conversion process. The system is designed to convert infrared radiation spanning 1.9-5 μm , covering the extended SWIR and MWIR spectral regions. The resulting upconverted wavelengths (approximately 680-880 nm) fall within the sensitivity range of conventional silicon image sensors, enabling the use of commercially available high-resolution cameras. In the present demonstration (Fig. 1), a PCO sCMOS camera with 4.2Mpixel resolution was utilized.

For spaceborne applications, the combination of broadband AFC, mature silicon detector technology, and a common-aperture optical architecture offers a practical path toward compact cryogen-free VIS/SWIR/MWIR payloads. By replacing cryogenic infrared FPAs with silicon imaging technology while preserving inherent spectral co-registration, the proposed architecture has the potential to reduce payload SWaP, improve reliability, and simplify future multispectral Earth-observation missions.

3. DEMONSTRATION USING A SPACE-QUALIFIED TELESCOPE

Experimental Set-Up

To experimentally validate the proposed imaging architecture, we performed laboratory measurements using a space-qualified telescope originally developed for the RUNNER satellite [7]. The telescope is a 35 cm aperture Ritchey-Chrétien design with an $f/10$ focal ratio and a secondary mirror assembly producing a 32% central obscuration. For the present experiments, the field-flattening lens assembly was removed, leaving the native two-mirror RC optical configuration to simplify integration with the AFC imaging system.

The primary objective of these experiments was to verify that the telescope's central obscuration does not adversely affect the nonlinear up-conversion process or the resulting image quality. The complete system was evaluated using a laboratory collimator illuminated by a blackbody source maintained at 1000 $^{\circ}\text{C}$. An MTF target positioned at the collimator focal plane served as the imaging scene for quantitative performance assessment.

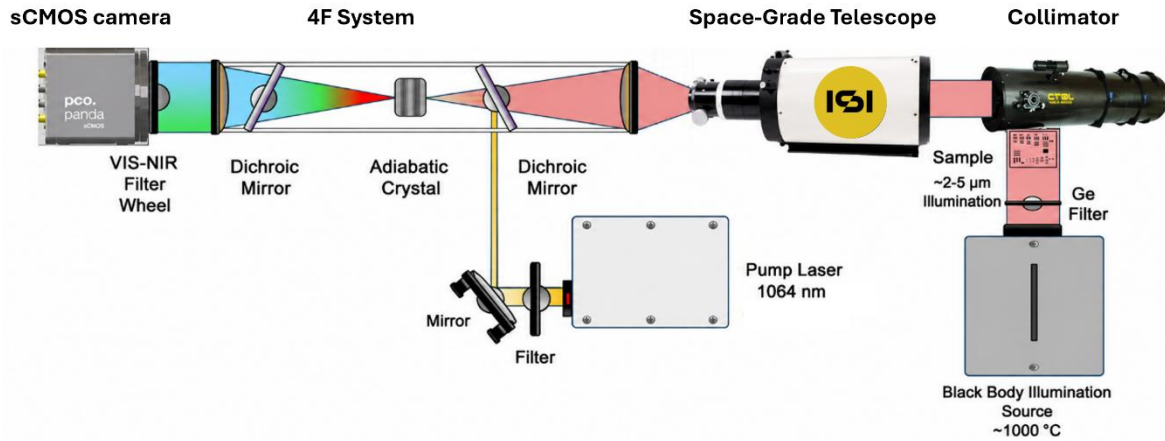


Figure 1. **Experimental setup schematics.** A blackbody source maintained at approximately 1000 $^{\circ}\text{C}$ illuminates an MTF target through a germanium (Ge) filter, producing broadband infrared radiation centered in the 2-5 μm spectral region. The scene is collimated and imaged by a 35 cm aperture space-qualified Ritchey-Chrétien telescope. The telescope output is relayed through a 4F optical system incorporating an adiabatically poled nonlinear crystal. A pulsed 1064 nm pump laser is combined with the infrared image using dichroic mirrors, enabling adiabatic frequency conversion of the infrared scene into

the visible/near-infrared spectral range. The upconverted image is recorded by a commercial sCMOS camera equipped with a VIS-NIR filter wheel, while the residual pump radiation is removed using spectral filters. The experiment demonstrates the compatibility of a representative spaceborne reflective telescope with broadband AFC imaging.

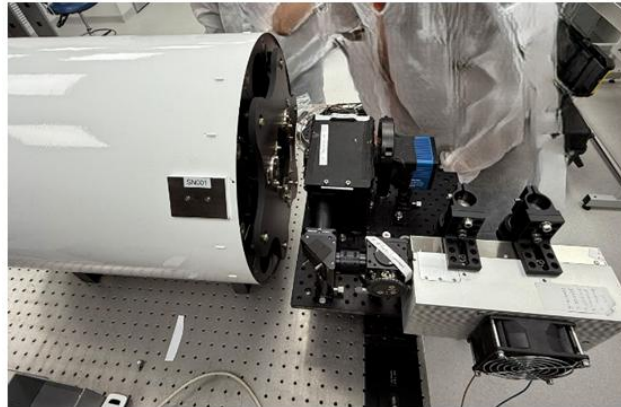


Figure 2. **Laboratory integration setup.** A view of the space-grade telescope back end showing the AFC module with a 4.2 MPixel sCMOS camera mounted behind the telescope focal plane, demonstrating its integration with a representative spaceborne optical architecture.

Results

Representative images acquired with the proposed imaging system are shown in **Fig. 3**. Since the MTF target was illuminated exclusively by filtered blackbody radiation in the 2-5 μm spectral range, no visible illumination was present in the optical path. Consequently, the image recorded by the sCMOS detector originates entirely from infrared radiation that was frequency upconverted through the AFC process. The successful recovery of the MTF target therefore provides direct experimental evidence of broadband infrared-to-visible image conversion.

Beyond demonstrating the upconversion process itself, the results confirm that the spatial information contained in the original infrared scene is preserved throughout the complete optical chain. The individual elements of the MTF target remain clearly distinguishable after propagation through the space-qualified Ritchey–Chrétien telescope, the AFC module, and the silicon imaging detector, indicating that the nonlinear frequency-conversion process maintains sufficient image fidelity for spatially resolved infrared imaging.

An additional objective of this study was to evaluate the compatibility of AFC with representative spaceborne telescope architectures. The successful imaging performance obtained using a Ritchey–Chrétien telescope featuring a 32% central obscuration demonstrates that neither the reflective telescope geometry nor the secondary-mirror obscuration introduces observable degradation that prevents effective broadband image upconversion. This result is particularly significant because central obscuration is a common characteristic of compact space telescopes and therefore represents a realistic operational configuration.

Although the present experiments were intended primarily as a proof of concept, they provide the first experimental validation that broadband AFC can be successfully integrated with a representative spaceborne optical system while maintaining the spatial information required for imaging. Quantitative characterization of parameters such as modulation transfer function (MTF), conversion efficiency, signal-to-noise ratio (SNR), radiometric accuracy, and overall end-to-end imaging performance will be the subject of future work.

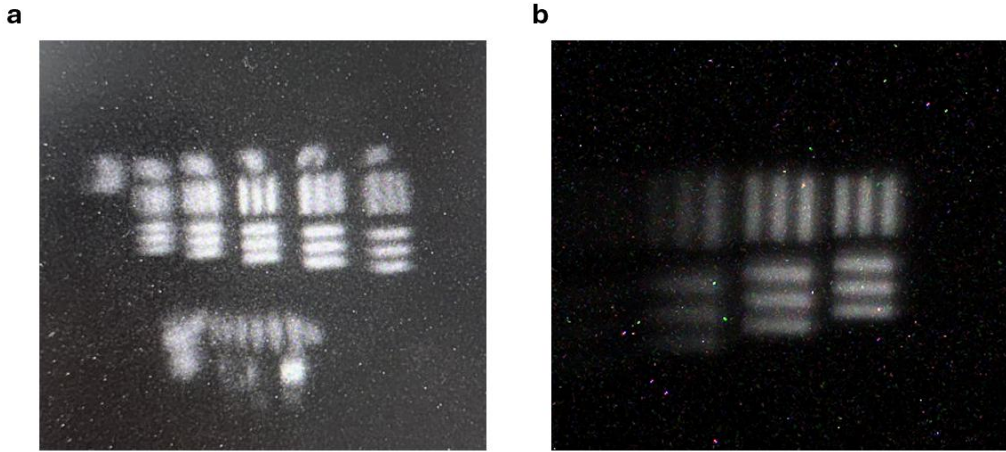


Figure 3. **Experimental MWIR upconversion imaging results.** Images of the MTF bar target acquired with the silicon sCMOS camera following AFC upconversion of the incident MWIR radiation. **(a)** Large-field-of-view configuration, demonstrating image formation over an extended field, with degradation toward the field edges attributed to the finite angular acceptance and non-optimized optical configuration of the present laboratory AFC system. **(b)** Reduced-field-of-view configuration, showing improved spatial uniformity and clearer resolution of the MTF bar patterns. The target was illuminated exclusively by filtered blackbody radiation; therefore, the detected images originate from frequency-upconverted infrared radiation. The resolved bar patterns demonstrate that spatial information is preserved through the complete telescope, AFC and sCMOS imaging chain.

4. SYSTEM DESIGN FOR COMMON-APERTURE VIS/SWIR/MWIR

A key advantage of the proposed architecture is the ability to employ a single telescope for both VIS and infrared (SWIR/MWIR) imaging. Since reflective telescope optics exhibit inherently broad spectral bandwidth, the entrance aperture and primary imaging optics can be shared by all spectral channels. Broadband reflective coatings, such as enhanced aluminum, provide high reflectivity from the visible through the MWIR, allowing the telescope front end to operate efficiently over the entire spectral range while eliminating the need for separate optical payloads.

The principal design challenge arises in the telescope back end, where the VIS and infrared channels impose different optical requirements. Visible imaging typically benefits from smaller detector pixels, larger focal-plane formats, and field-flattening optics optimized for silicon image sensors. In contrast, the infrared channel incorporates the AFC module, which imposes different optical constraints and requires efficient transmission throughout the SWIR and MWIR spectral bands. Furthermore, refractive corrector elements commonly employed in Ritchey-Chrétien telescopes are generally optimized for visible wavelengths and often exhibit poor transmission beyond the near infrared.

The simplest implementation therefore separates the spectral channels immediately after the shared telescope using a dichroic beam splitter. The VIS channel employs conventional correction optics together with a high-resolution CMOS or sCMOS detector, while the SWIR/MWIR channel is routed to optics compatible with broadband infrared transmission before entering the AFC imaging module. This architecture preserves the primary advantage of a common entrance aperture while allowing each channel to be independently optimized for its respective wavelength range.

A higher level of integration can be achieved by designing the complete optical train for broadband VIS-to-MWIR operation. In this configuration, both channels share not only the telescope mirrors but also the correction optics, reducing the number of optical assemblies and potentially improving SWaP. Such an approach requires optical materials that maintain high transmission across the full spectral range, including zinc sulfide (ZnS) or suitable chalcogenide glasses.

An even more elegant solution is the adoption of an entirely reflective optical system. Three-mirror anastigmat (TMA) architectures, for example, provide excellent aberration correction without introducing chromatic aberration and are therefore naturally compatible with broadband multispectral imaging. Although TMAs are generally more demanding to manufacture and align than conventional two-mirror RC telescopes, they eliminate the need for broadband transmissive correction optics and provide a particularly attractive platform for future common-aperture VIS/SWIR/MWIR payloads.

In all three architectures, the shared telescope aperture inherently preserves a common boresight and optical geometry, enabling precise pixel-level co-registration between the visible and infrared channels. This intrinsic alignment is

particularly valuable for dynamic scenes, where independent optical payloads may introduce spatial or temporal registration errors. Consequently, AFC enables the integration of broadband SWIR/MWIR imaging into a unified multispectral payload while fully retaining the performance and maturity of conventional visible imaging systems.

The significance of the proposed architecture extends beyond the replacement of the infrared detector. By combining broadband frequency upconversion with mature silicon imaging technology, the proposed system simultaneously addresses several long-standing limitations of conventional MWIR payloads while enabling capabilities that are not readily achievable using existing architectures. Table 1 provides a qualitative comparison between conventional cryogenically cooled MWIR imaging systems and the proposed AFC-based common-aperture payload.

Table 1. Comparison of traditional MWIR and proposed AFC Payloads.

Conventional MWIR Payload	Proposed AFC Payload
Specialized MWIR sensor	CMOS/sCMOS
Cryogenic MWIR FPA	Ambient detector
Independent VIS and MWIR channels	Hardware-level co-registration
Detector resolution limited by FPA	High-resolution silicon detector available
Radiation hardening required	Utilization of rad-hard CMOS sensor

5. CONCLUSIONS

This work demonstrated the fundamental feasibility of a cryogen-free common-aperture VIS/SWIR/MWIR imaging architecture based on Adiabatic Frequency Conversion. Laboratory experiments using a space-qualified Ritchey Chrétien telescope merged with AFC module confirmed that broadband infrared radiation can be successfully upconverted and imaged using a conventional silicon sCMOS camera while preserving the spatial information required for imaging. These results establish the compatibility of AFC with representative spaceborne optical systems and provide an important experimental step toward practical space implementation.

The significance of the proposed architecture extends well beyond the replacement of conventional cryogenic infrared detectors. By enabling the visible, SWIR, and MWIR channels to share a common optical system, the proposed payload inherently acquires perfectly co-registered multispectral imagery. This intrinsic spatial and temporal alignment provides a unique capability that is difficult to achieve with conventional multi-aperture payloads and creates an ideal foundation for advanced multispectral data fusion.

In particular, the proposed architecture enables the direct fusion of high-resolution visible imagery with simultaneously acquired SWIR and MWIR data. Since all spectral bands are acquired through the same telescope and optical path, visible imagery can potentially be used to enhance the effective spatial resolution of the infrared channels without the registration errors associated with independently acquired datasets. Such VIS-guided infrared sharpening [7] represents a promising new approach for overcoming one of the principal limitations of current SWIR and MWIR imaging systems while preserving their unique spectral and thermal information.

Although the present work establishes the fundamental feasibility of the proposed concept, further development is required before operational deployment. Future work will focus on quantitative characterization of conversion efficiency, signal-to-noise ratio, radiometric performance, optical throughput, calibration, long-term stability, and overall end-to-end imaging performance under representative space conditions.

Taken together, these results suggest that AFC may enable a new generation of compact, cryogen-free multispectral Earth-observation payloads. By combining mature silicon imaging technology with inherently co-registered VIS, SWIR, and MWIR sensing, the proposed architecture offers a practical path toward reducing payload complexity while enabling new computational imaging capabilities that exploit hardware-level spectral co-registration to produce higher-quality infrared imagery than is achievable with conventional architectures.

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