Imaging Hypersonic Plasma Signatures Using a Programmable Telescope and Video-Rate SWIR Multispectral Camera

Sarvesh Garimella
MyRadar
Douglas Franz
MyRadar
Scott Ferguson
Astronomy Live

ABSTRACT SUMMARY

This study demonstrates a novel system for observing hypersonic vehicles by combining a commercial-grade, programmable tracking telescope with a high-speed multispectral shortwave infrared (SWIR) camera. The telescope, guided by precision tracking algorithms and orbital telemetry, follows re-entering rocket stages and other fast-moving bodies, while the SWIR camera (900–1700 nm range, >60 Hz) captures real-time plasma emissions not visible in traditional optical wavelengths. This enables identification of key plasma constituents such as atomic oxygen, hydroxyl radicals, and excited nitrogen, providing insights into shock-layer physics, boundary-layer interactions, and radiative heat transfer. Preliminary results show millisecond-resolution imaging of spatiotemporal plasma variations, offering valuable data for heat shield design, atmospheric entry modeling, and propulsion diagnostics. By leveraging accessible, commercial-grade technologies, the approach lowers barriers to advanced hypersonic research, with future efforts aimed at improving spectral processing, enhancing tracking accuracy, and expanding to additional wavelength bands for more comprehensive plasma characterization.

1. INTRODUCTION

The observation and characterization of hypersonic vehicles, such as re-entering rocket stages or high-speed maneuvering bodies, require advanced optical techniques capable of capturing transient plasma emissions. These emissions result from high-temperature interactions between the vehicle and the surrounding atmosphere, forming complex, rapidly evolving spectral signatures across multiple wavelengths [1,2]. In this study, we employ a commercial-grade, programmable tracking telescope coupled with a high-speed, video-framerate multispectral shortwave infrared (SWIR) camera to capture and analyze plasma characteristics in real time [3,4].

Our system consists of a high-aperture, motorized telescope equipped with precision tracking algorithms to follow the rapid motion of hypersonic vehicles across the sky. The telescope is paired with a multispectral SWIR imaging system capable of recording spectral emissions at frame rates exceeding 60 Hz, allowing for detailed temporal and spatial resolution of plasma behavior. The SWIR camera's spectral range, spanning approximately 900–1700 nm, provides insight into molecular species, radiative heat transfer, and ionization effects that are not readily visible in traditional visible-wavelength imaging [3].

The experimental methodology involves capturing hypersonic flight events, including controlled rocket stage re-entries and other high-speed atmospheric maneuvers. We leverage real-time tracking data from orbital predictions and telemetry feeds to direct the telescope, ensuring optimal data acquisition during critical flight phases [3]. The multispectral imaging approach allows for the potential differentiation of plasma constituents, including atomic oxygen, hydroxyl radicals, and excited nitrogen species, enabling a deeper understanding of the vehicle's shock-layer physics and boundary-layer interactions [2,5].

Preliminary results demonstrate the feasibility of resolving high-speed plasma dynamics with millisecond temporal resolution, revealing spatiotemporal variations in emission intensity and spectral composition [5,6]. These findings have significant implications for aerospace applications, including vehicle heat shield design, atmospheric entry modeling, and hypersonic propulsion diagnostics [4]. Furthermore, the use of commercially available, programmable tracking telescopes and video-rate SWIR imaging enhances the accessibility of such observations,

opening new opportunities for remote sensing of hypersonic phenomena [4,6]. This work represents a novel application of emerging optical tracking and multispectral imaging technologies for hypersonic research. Future efforts will focus on refining spectral processing techniques, improving tracking accuracy for maneuvering targets, and extending observations to other spectral bands for a more comprehensive plasma characterization.

2. METHODS

The Starlink 10-26 rocket launch was tracked using in-house software on a motorized telescope with optical and SWIR sensors mounted in the line-of-sight vector of the telescope. The SWIR sensor is the imec SNAPSHOT SWIR 9-band. The collection software is HSI Mosaic 1.9.1.1 which processed de-mosaiced and aligned 168 x 211 x 9 data cubes at a framerate of ~25 Hz. The temperature of the sensor at time of collect was 25.0 C.

The tracking of the Starlink 10-26 rocket launch involved modifying an optical setup for imaging hypersonic plasma signatures using a programmable telescope and a video-rate SWIR multispectral camera. The launch was observed from a 528 viewing site, approximately 11.64 miles from SLC-40, on Saturday, July 26, 2025, at 09:00 UTC. This observation was part of a broader effort to characterize optical and SWIR signatures from rockets and re-entering objects, utilizing in-house software and specialized sensors.

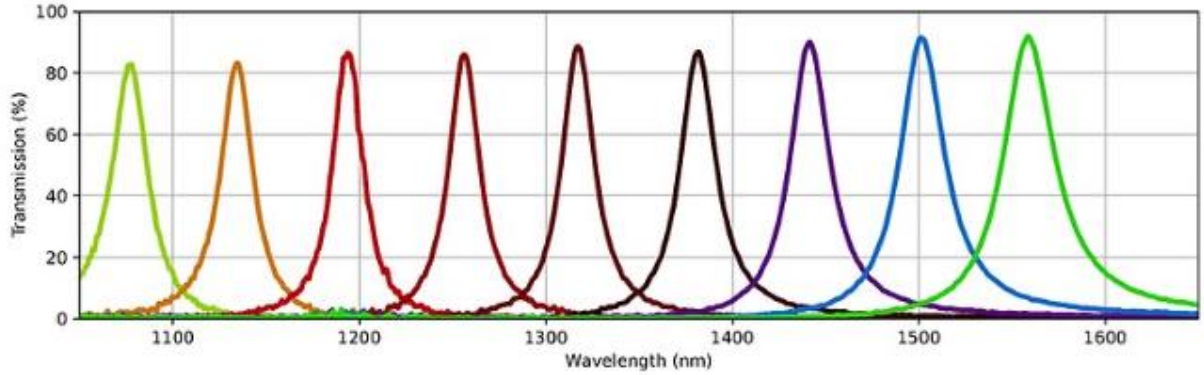

Fig. 1. Spectral coverage for the 9 Cicada SWIR bands

The primary instrumentation for this capture included a motorized telescope equipped with both optical and SWIR sensors mounted in the line-of-sight vector. For the Starlink 10-26 rocket launch, the specific SWIR sensor used was the imec SNAPSHOT SWIR 9-band camera, which captured still frames across its nine distinct bands, with center wavelengths including 1122 nm, 1140 nm, 1162 nm, 1193 nm, 1211 nm, 1298 nm, 1383 nm, 1466 nm, and 1654 nm. For other launches, the Silios Cicada SWIR sensor was tested for comparison, and its bands are illustrated in Fig. 1. The collection software responsible for processing the imec data was HSI Mosaic 1.9.1.1, which efficiently de-mosaiced and aligned 168 x 211 x 9 data cubes at a framerate of approximately 25 Hz. Custom python code was developed for the processing of the Cicada data. During the capture, both sensors maintained a stable operating temperature of 20-30ºC.

The data collected from the Starlink 10-26 launch included various captures, such as an optical tracker camera image showing the rocket with a marked target, as well as multiple still frames from each of the imec SWIR camera's 9 bands. Analysis of this data also involved examining pixel intensities across the SWIR spectrum, providing insights into the spectral characteristics of the launch plume. Such detailed spectral data are crucial for understanding how hypersonic phenomena evolve, particularly in relation to plasma signatures, and helps to characterize the optical properties of rocket plumes.

Fig. 2. Telescope and software table setup for image capture and tracking controller.

3. RESULTS

The detailed observation of the Starlink 10-26 mission serves as an initial demonstration of research aimed at imaging hypersonic plasma signatures through advanced optical and SWIR sensor technologies. The launch, which took place from SLC-40 at Cape Canaveral Space Force Station on Saturday, July 26, 2025, at 09:00 UTC, was successfully observed from a viewing site approximately 11.64 miles away. This particular mission's data, captured during its early launch phases, provides critical insights into the spectral characteristics of rocket plumes, which are further elucidated through a series of illustrative figures.

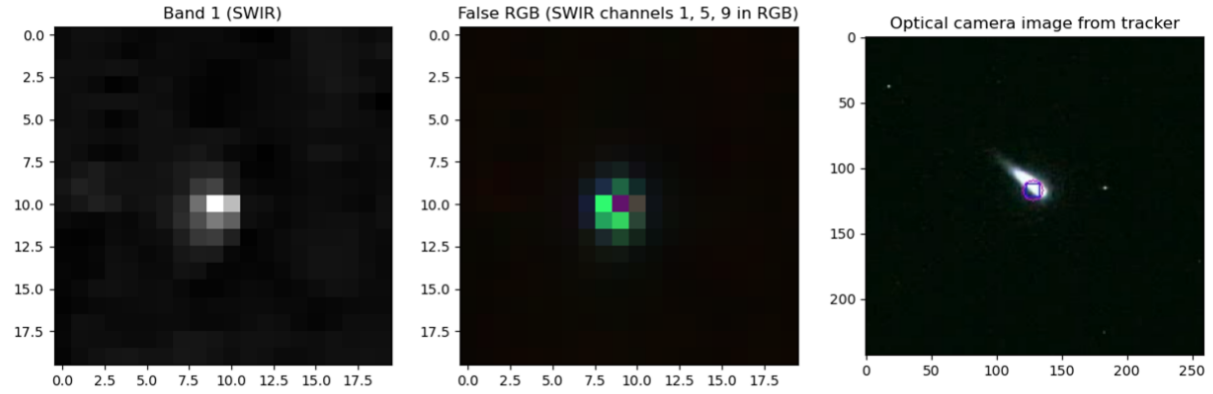

Fig. 3. Starlink 10-26 still frames of interest with imec SWIR camera (left), false RGB of SWIR (center), and optical tracking camera (right).

Key results from the Starlink 10-26 launch are presented through several visual captures. As described, still frames of interest from the imec SWIR camera, a false RGB composite of SWIR bands, and an optical tracking camera image are shown. The false RGB image specifically utilizes SWIR channels 1, 5, and 9 as its red, blue, and green components, corresponding to center wavelengths of 1122 nm, 1210 nm, and 1654 nm, respectively. Crucially, the pixel intensities across the SWIR spectrum for pixels 0 through 6 within the SWIR Band 1 image were analyzed, revealing unique spectral signatures. These pixels, situated in the front of the launch vehicle or near the center of the emission spot, exhibit a noticeable peak in the 1450-1650 nm region. Conversely, pixels located more rearward or facing the wake of the vehicle generally show a flat exhaust, lacking this characteristic dip. Additionally, individual

still frames from all nine bands of the imec SWIR camera were captured, providing a comprehensive spectral view of the launch event across its designated wavelengths.

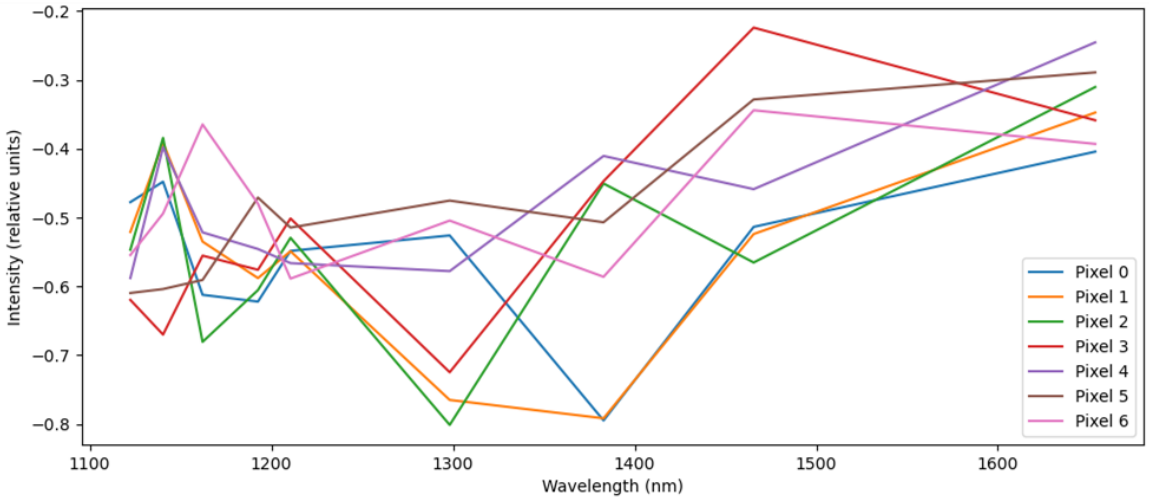

Fig. 4. Pixel intensities across SWIR spectrum for imec capture of Starlink 10-26 launch.

These results collectively contribute to a more nuanced understanding of the differences in SWIR channel pixel intensities observed in various directions of flight, which were chosen to be within the 5-6 MACH range. The data from both the imec camera for Starlink 10-26 and the Cicada camera for CRS-33 are vital for studying pixel-level plume data and characterizing how hypersonic phenomena evolve. This ongoing work, which aims to collect more tracking data and expand the analysis to include various launch vehicles, is fundamental for advancing research into the optical and SWIR signatures of rockets and re-entering objects.

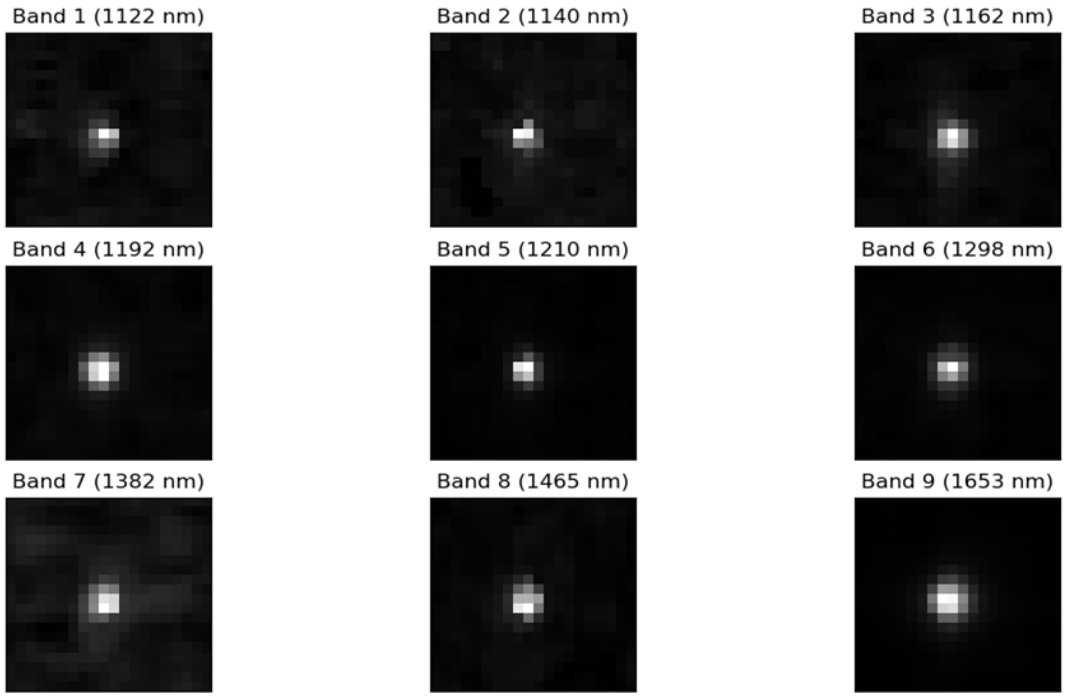

Fig. 5. Still frames of Starlink 10-26 capture in each of all 9 bands of the imec SWIR camera.

Beyond the Starlink 10-26 mission, similar observations were made for other launches, providing comparison data. For the CRS-33 launch, observed on August 24, 2025, at 06:45 UTC from the same 528 viewing site, a Cicada SWIR camera was employed. This capture included a full interleaved image of all 9 bands from the Cicada SWIR camera, whose bands range from approximately 1077 nm to 1572 nm (Fig. 1). The Cicada SWIR capture allowed for the analysis of analogous pixel spectrums from the front, between front and center, center, and rearward regions of the plume, demonstrating how pixel intensities vary across the SWIR spectrum, with leading-edge pixels often showing higher intensities at the spectral edges. Furthermore, the Crew-11 launch, occurring on August 1, 2025, at 15:00 UTC, was tracked optically, with captures illustrating the rocket's path after exiting a cloud plume. These diverse datasets are critical for characterizing optical and SWIR signatures and understanding the complex properties of hypersonic plasma plumes.

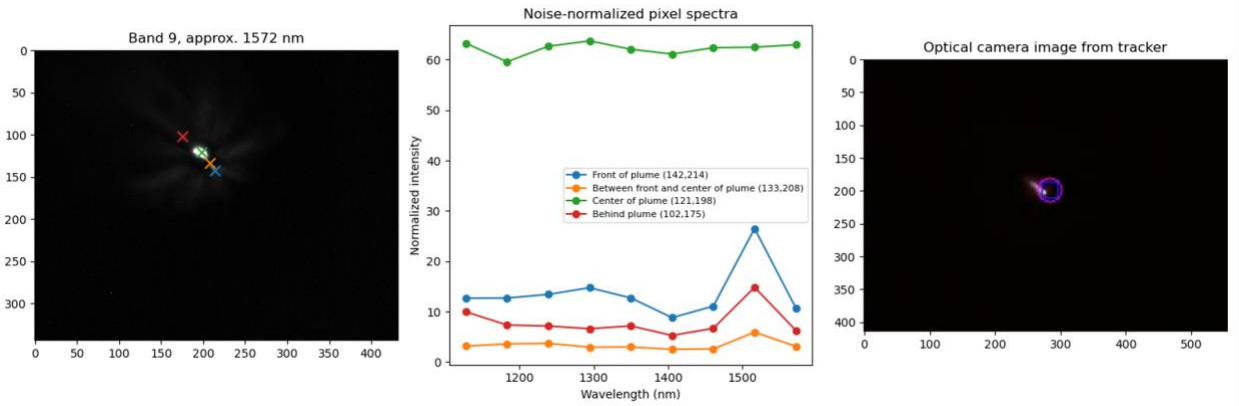

Fig. 6. Frame of Cicada camera capture from the CRS-33 launch (left) with selected pixel spectra (center) and optical tracking frame (right).

4. DISCUSSION AND FUTURE WORK

The preliminary results from this study demonstrate that commercially available optical tracking and multispectral SWIR imaging systems can provide valuable insights into hypersonic plasma phenomena. The successful resolution of spatiotemporal emission dynamics at millisecond scales highlights the potential of this approach for capturing transient events that are often missed by traditional long-exposure or visible-wavelength imaging. By extending the observation window into the SWIR region (900–1700 nm), the system was able to resolve plasma signatures from key molecular and atomic species, enabling a richer understanding of radiative transfer and ionization processes within the shock layer. This finding reinforces the promise of relatively low-cost, modular instruments as effective diagnostic tools in aerospace research.

One of the key implications of this work is its potential application to vehicle design and atmospheric entry modeling. Hypersonic vehicles face extreme thermal and chemical loads during re-entry, where the accurate characterization of boundary-layer interactions and radiative heating is critical for validating computational fluid dynamics (CFD) models and designing reliable thermal protection systems [2]. Remote SWIR-based plasma diagnostics could provide non-intrusive datasets for benchmarking such simulations, offering insights that laboratory-based wind tunnels or expansion tubes cannot always reproduce at full flight scale [4]. Furthermore, the demonstrated ability to capture rapid variations in plasma composition may aid in refining models of shock-layer instabilities and energy transfer mechanisms that govern vehicle survivability in hypersonic regimes.

Fig. 7. Optical tracking camera capture for the Crew-11 launch before passing through a cloud.

Future work will focus on expanding the spectral and temporal resolution of the system. While the current setup covers the SWIR band effectively, extending coverage into the mid-wave (MWIR) and long-wave infrared (LWIR) could provide complementary information about vibrational-rotational transitions, blackbody radiation from heated surfaces, and more complete spectral energy distributions [3]. Intercomparison and validation methods, including radiometric and spectral cross-checks against laboratory and wind tunnel plasmas, will be essential for translating raw emission data into quantitative measurements of plasma temperature, density, and species concentration. Additionally, integrating high-frame-rate imaging with advanced computational techniques such as machine learning could help automate the detection of spectral features and extract physics-informed parameters in real time, enabling rapid feedback for both experiments and operational decision-making.

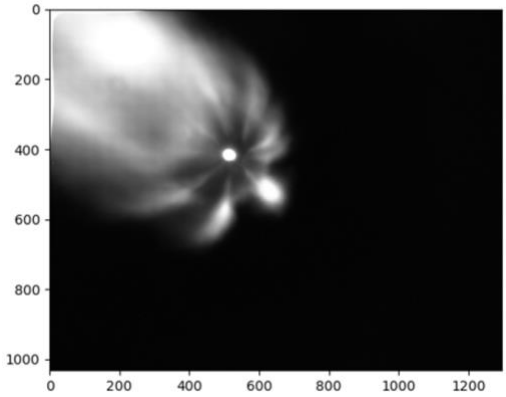

Fig. 8. Characteristic SWIR capture (all bands, mosaiced) with the Cicada SWIR camera of CRS-33 launch, highlighting detail and variability.

Another area of development involves enhancing tracking and targeting accuracy for maneuvering hypersonic vehicles. While orbital predictions and telemetry were sufficient for controlled re-entry events, future studies will need to address scenarios where vehicles execute unpredictable maneuvers or operate without telemetry support [6]. Incorporating multi-sensor fusion—combining optical tracking with radar or lidar inputs—may improve pointing precision and resilience to atmospheric turbulence. Ultimately, the continued refinement of these multispectral observation platforms, together with coordinated efforts between experimentalists and modelers, will create new opportunities for hypersonic diagnostics. By bridging the gap between laboratory testing and real-world flight observations, such systems could play a pivotal role in the next generation of hypersonic vehicle design, validation, and operational safety.

5. REFERENCES

[1] Gillman, E. et al., "Review of Leading Approaches for Mitigating Hypersonic Vehicle Communications Blackout and a Method of Ceramic Particulate Injection Via Cathode Spot Arcs for Blackout Mitigation," NASA Technical Report, 2010.

[2] Wen, S. et al., "Plasma evolution mechanism and distribution characteristics of hypersonic vehicles," AIP Physics of Plasmas, 2024.

[3] Horvath, T. et al., "Shuttle Entry Imaging Using Infrared Thermography," 39th AIAA Thermophysics Conference, 2007.

[4] Van Wie, D., "Hypersonics: Past, Present, and Potential Future," Johns Hopkins APL Technical Digest, 2021.

[5] Urzay, J., "The physical characteristics of hypersonic flows," Stanford University, 2020.

[6] Yi, S. et al., "Research progress on aero-optical effects of hypersonic optical window with film cooling," Light Science & Applications, 2024.