

Dual-Mode Experiment on Bow-Shock Interactions (DEBI)

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INTRODUCTION

Current and planned ground-based ballistic missile defense systems rely on optical seekers with a hit-to-kill (HTK) strategy or blast fragmentation warhead to impact the incoming warhead. For this, the kinetic kill vehicle (KKV) must sense and track the target candidate and carry out the maneuvers required for the HTK intercept. For endo-atmospheric interceptors flying at hypersonic velocities, the aerodynamic heating loads will significantly increase temperatures on external surfaces, including optical windows. Further, thermal excitation of atmospheric species occurs in the flow field around the KKV. Given that the seekers operate in the infrared spectrum, emissions from hot optics and/or excited constituents in the sensor's field of regard could lead to sensor blinding in some regions of the spectrum. The Dual-mode Experiment on Bow-shock Interactions (DEBI) program was designed to further the understanding of chemistry associated with hypersonic flight in interceptor applications within the Earth's atmosphere. The DEBI measurements were carefully designed to examine atmospheric emissions in the shock-heated air and not aperture window emissions. Dual-mode sensing, both ultraviolet (UV) and infrared (IR), was employed, and the data obtained in the flight test will be used to improve and/or validate state-of-art aerothermochemistry models. Reference [1] describes the operational context for a two-color mid-wave IR (MWIR)-UV wavelength seeker. Ultimately, the program should provide the Missile Defense Agency (MDA) the predictive capability necessary to design sensor systems that will be effective under real flight conditions.

MISSION OPERATIONS

The DEBI experiment duration was approximately 40 seconds of flight, meeting primary objectives. The experiment delivery began from the launch site at the National Aeronautics and Space Administration's (NASA's) Wallops Island Flight facility (NASA/WFF). The experimental vehicle design reference requirement was to reach an upward velocity of 3.5 km/s at altitude of 40 km. In-flight data were actually acquired as the payload ascended and commenced at 34.8 km with a velocity of 3.4 km/s following payload nose cone separation and continued through the

ABSTRACT

The Dual-mode Experiment on Bow-shock Interactions (DEBI) project was designed to contribute further understanding toward the aerothermochemistry associated with hypersonic flight for interceptor applications within the Earth's atmosphere. Such detailed understanding is required to accurately model the optical radiation from high-temperature flows around hypersonic vehicles for missile defense missions. The flight experiment was successful. Therefore, this paper summarizes the flight experiment, the innovative solutions, and our "lessons learned" during the design and development of the DEBI instrumentation suite.

experiment's over-the-horizon departure. A Terrier-Malemute launch vehicle with MK-12 Terrier motor was determined to provide sufficient delta V to meet the experiment requirements on ascent. Figure 1 depicts the typical mission operations for the DEBI flight on the NASA/WFF range.

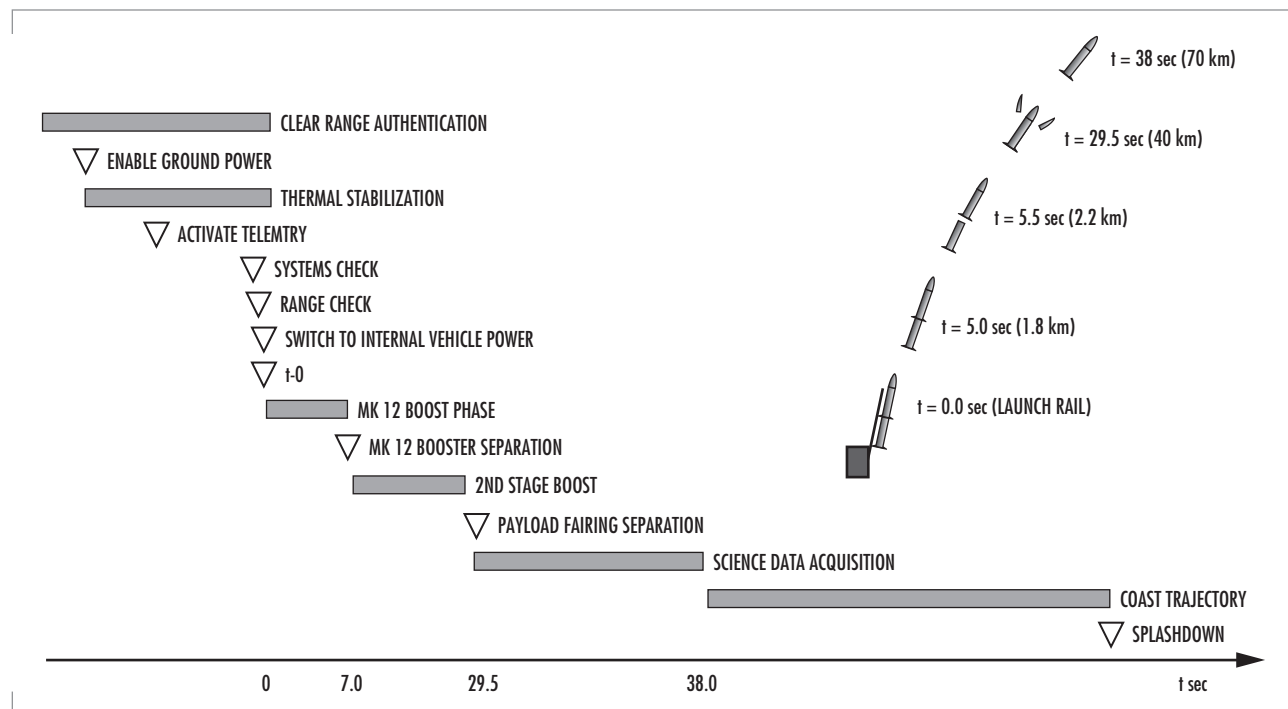


FIGURE 1. DEBI mission operations are concluded within first 40 seconds of flight.

SCIENCE OBJECTIVES

The major goal of the DEBI flight was to characterize the outboard optical environment associated with the flight of a hypersonic interceptor in the atmospheric phase of flight. Interceptor window and sensor environments have not been spectrally characterized at higher speeds in controlled flight conditions. The DEBI flight provided this opportunity for far longer times than could be acquired in shock tubes and with realistic boundary conditions as found in free flight. DEBI was the third in a series of sounding rocket flights. The first two missions, Bow-shock I and Bow-shock II, focused on the UV region of the spectrum and successfully provided data needed to improve predictive capabilities in UV wavelengths by four orders of magnitude. DEBI focused on the IR region of the spectrum and employed a suite of instruments that provided data on flow-field chemistry from the mid- to near-IR in the altitude range of interest (approximately 40 to 70 km) and at a representative nominal hypervelocity of 3.5 km/s. These data will then be used to refine the aerothermochemical models. UV instruments will also be used to obtain anchoring data for comparison with previous flights.

The use of both UV and IR instruments also fulfilled the secondary objective of demonstrating a dual-mode system as a possible solution to potential sensor blinding issues. Analysis of the flight data will provide compelling evidence to demonstrate whether a UV seeker onboard a

slender-bodied vehicle will experience any shocklayer interference or window heating problems. Unlike the IR, it was anticipated from pre-flight calculations that the window will remain transmissive in the UV and the shocklayer radiance will be below the detectivity limits of a UV instrument. The forebody design for the experiment was similar to that currently used in MDA's Atmospheric Interceptor Technology (AIT) program. The similarity ensured that the flight data were obtained in a relevant configuration. Figure 2 shows the pre-flight predicted intensities for molecular spectra excited by the bow-shock at 3.5 km/s speed and 40 km altitude. We expect the flight data to verify both the magnitudes and spectral features shown. Based on our experience with earlier flight experiments, we expect there could be important differences in both predicted signal levels as well as radiating species. The species presently modeled are idealistic in that they represent IR-emitting species formed by reactions of shock-heated air (N_2 , O_2 , O , NO , NO_2 , CO_2 , H_2O , OH) only. Detectors covering a wide spectrum of measurements are described in the instrumentation section. Full details about the predictions can be found in reference [2].

INSTRUMENTATION

The instruments were designed as three separate instrument packages for the DEBI experimental flight. The instrument packages consist of detectors imbedded within a radiometer, a spectrometer, and two UV photometers. The detectors were interconnected to apertures via lens system and fiber-optic bundles. The apertures were positioned at the vehicle stagnation point and two symmetrically aft-stationed points downstream of the vehicle nose. Data to be acquired were collected from 16 scanning spectrometer channels: 2 UV channels, 6 short-wave IR (SWIR) channels, 8 MWIR channels, and an array of temperature sensors. Two additional data channels in the IR radiometer were dedicated to determining the MWIR detector background and the payload system noise levels. The UV detectors provided legacy data to past Bow-shock I and II experimental flights.

The payload nose tip for the DEBI vehicle is shown in Figure 3, and is representative of the AIT interceptor. Each measurement location on the nose cone tip was fitted with a recessed sapphire lens connected to a fiber-optic bundle that routed the signal to the appropriate detector within the spectrometer or radiometer. DEBI UV detectors provided legacy data because they overlap with the Bow-shock I and Bow-shock II experimental flights. However, the IR fiber-optic bundles provided a challenge to the design and fabrication of the DEBI payload. The primary technical problem was in selecting the appropriate fiber-optics materials that met our link budgets

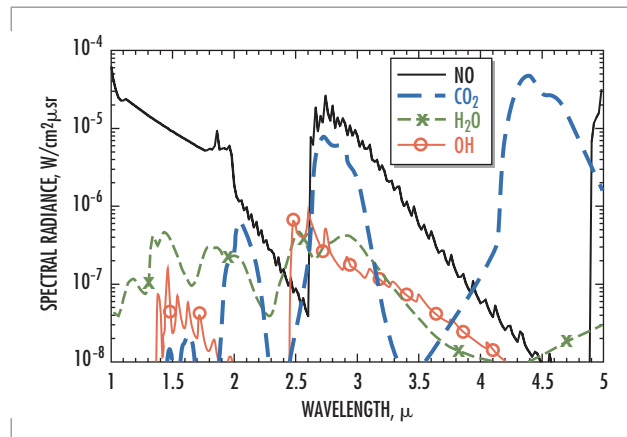


FIGURE 2. Aerothermochemistry model predicted response intensities for measurable species at 40 km altitude from induced bow-shock excitation at 3.5 km/s.

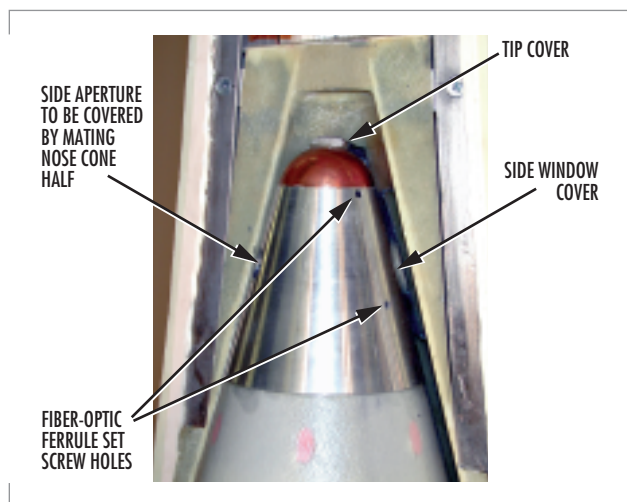


FIGURE 3. DEBI nose tip showing half of the ejection cover and aperture covers.

and could also survive the environments induced from the flight and detector thermal requirements. The DEBI team planned for two severe environmental factors. The first environmental threat was thermal cycling during ground segment integration and checkout. During chill-down cycles there was high likelihood for direct liquid nitrogen (LN_2) coolant contact with some instrumentation components and the fiber bundles. The second environmental concern was the acoustic-vibration flight environment. We selected fluoride glass fibers to meet our IR requirements and used UV-grade quartz fibers for the UV data channels. There was a tradeoff in the selection of the fluoride glass fiber material, as it was more brittle than the fiber-optic materials used in Bow-shock I and II. Consequently, the fluoride fiber material did not have a tight bend radius, which created major design constraints with regard to the positions and orientations of the instrument packages.

The MWIR and SWIR radiometers had InGaAs and HgCdTe photodiode detectors coupled to windows with IR fluoride glass fibers. The scanning IR spectrometer had a fast $f/0.5$ relay lens system at the exit slit and a stepper motor-driven diffraction grating with InGaAs photodiode detectors for short wavelength regions, extended InGaAs photodiode detectors for the intermediate wavelength regions, and photovoltaic short wavelength HgCdTe detectors for the longest wavelength regions. One key element used to get an acceptable signal-to-noise ratio for the MWIR was the implementation of chalcogenide glass for a lens material. The chalcogenide material has a high index of refraction (~ 2.5), and was easily machined by skilled lens makers. Consequently, the chalcogenide glass made it possible to get an appreciable amount of light on the MWIR detectors to meet acceptable expected signal-to-noise ratios for the detector material. All detectors were cooled below 193°K before flight and provided with sufficient thermal inertia to maintain acceptable temperature limits for the in-flight 40-second duration. The thermal stability design worked better than the DEBI team expected.

PAYLOAD

Payload elements, including structures, thermal control, power, telemetry, command and data handling, and the payload fairing, are shown in Figure 4. The payload subsystem is built to the requirement that instruments survive the stressful flight experience sufficiently long to satisfy the science objectives to collect data over as large an altitude range as possible. The integration of instruments into a payload needed to provide a cold environment for the IR instruments, fiber optics, and nose tip, and an even colder environment for the detectors themselves, while providing a warm environment for all the rest of the payload electronics. It needed to protect this internal environment from the extremely severe aeroheating in the dense atmosphere to the point at 40 km when

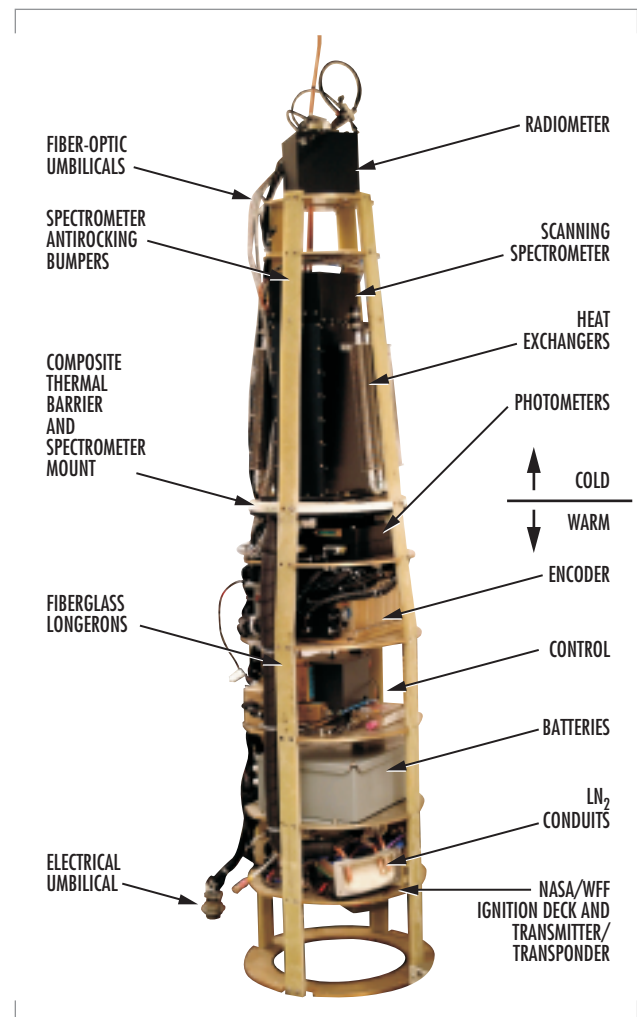


FIGURE 4. DEBI payload.

the rocket motor burns to completion and the velocity is 3.5 km/s. The measurement nose tip was designed to prevent blackbody radiation from the tip itself from entering the fiber optics until the payload reaches an altitude of approximately 70 km. An entire section of the payload including the nose tip was isolated from the rest of the payload and the outside environment and kept at a temperature of approximately -60° C. An ejection clamshell-styled nose cone provided protection for the cold section from the extreme ascent aeroheating.

We expected the measurement surface to be quickly heated after the nose was ejected. It should be noted that copper was used for the forward hemispherical surface to absorb the strong heat flux without getting so hot that its blackbody radiation will mask the atmospheric radiation to be measured. Another key to preventing this interference was to use a cold sapphire lens to image the end of the fiber bundle to a location outside of the nose tip. The fiber bundle and lenses were recessed within the nose tip to slow heating. The aperture through which the fiber optics view is kept outside of the optical field of view. This helped to prevent scatter sources that would allow contaminating blackbody radiation to enter the measurement system.

CONCLUSION

The DEBI experiment was launched on a Terrier-Malemute launch vehicle from NASA/WFF 10 June 2003. Both operational and scientific objectives motivated the collection of MWIR and UV data for a slender body travelling at hypersonic speeds. It was assumed that present aerothermochemical models are able to predict shocklayer radiance from idealized chemically reacting flows. However, even this assumption has never been confirmed by any flight data. It is likely that DEBI data will uncover unanticipated deficiencies in the aerothermochemical models or in validating radiance models. Design and materials selection solutions for many of the issues have been identified. In addition to the scientific data, an important outcome of this flight will be the validation of our engineering solutions for small, affordable rocket flight experiments. Subsequent publications will cover data analysis.

ACKNOWLEDGMENTS

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