（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）

国外連携機関長期研修　報告書

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**Introduction**

High-energy astrophysical phenomena such as supernova explosions, pulsars, neutron stars, and active galactic nuclei continuously inject large amounts of energy into the universe. Many of these systems emit strong X-rays, making X-ray observations a powerful tool for probing their structure and underlying physical mechanisms. Supernova explosions are the primary sources of Galactic cosmic rays, and theoretical estimates indicate that approximately 5–10% of their kinetic energy is converted into cosmic-ray acceleration at shock fronts.

To probe this acceleration, the maximum synchrotron energy of electrons, which falls in the hard X-ray band above approximately 10 keV, provides a direct measure of efficiency. NuSTAR, the primary hard X-ray satellite, has an angular resolution of approximately 1 arcminute, insufficient to resolve supernova remnant fine structures. The SuperHERO project addresses this by targeting 5 arcsecond resolution using seven grazing-incidence mirror modules developed at NASA/MSFC paired with seven CdTe double-sided strip detectors (CdTe-DSDs), which offer high absorption efficiency above 10 keV and sub-pixel position reconstruction via inter-pixel charge sharing. I am currently developing a scalable DAQ system for SuperHERO built on SpaceWire and RMAP, capable of driving all seven detectors concurrently. SuperHERO is preparing for a balloon-borne experiment in autumn 2028 in Fort Sumner, New Mexico.

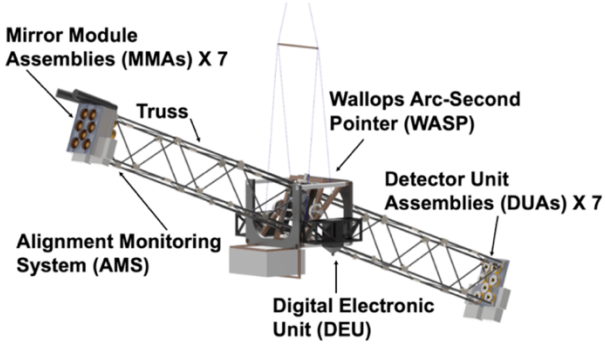



Figure 1. The *SuperHERO* observatory.[3] The Mirror Module Assemblies (MMAs) focus hard-X-rays onto their respective CdTe-DSD focal planes housed in the Detector Unit Assemblies (DUAs), with minor changes in their relative position being monitored by the AMS. The observatory's super-structure is Composite Carbon Fiber Truss and is pointed by the Wallops Arc Second Pointer (WASP).

(Thomas et al. 2025)

Beyond its primary astrophysical objectives, SuperHERO will also record atmospheric X-ray emission as background during the balloon mission. This signal, arising from cosmic-ray-induced ionization of atmospheric molecules, remains poorly measured at high altitude. Since cosmic-ray-induced ionization may influence cloud nucleation and climate, and current AI-based weather models do not incorporate cosmic-ray flux, this atmospheric data represents a valuable physics-grounded input for improving AI forecasting models.

**The Purpose of the Visit**

For the SuperHERO 2028 balloon mission, seven independent CdTe-DSDs will be deployed. While the overall telescope system is being developed at NASA/MSFC, the detectors are the responsibility of the University of Tokyo. All eight detectors (seven flight models and one backup) have been delivered to NASA/MSFC, where the detector housings and related hardware are currently being fabricated in preparation for the 2028 balloon mission.

In addition, I am the developer of the data acquisition (DAQ) system for these CdTe-DSDs. Since all seven detectors acquire data independently in an event-driven manner, efficiently collecting data from each detector and forwarding it to upstream software requires a purpose-built solution. Existing software could not be adapted to meet these requirements, and the DAQ system was therefore designed from scratch specifically for SuperHERO.

Considering the above, this visit had two primary objectives:

1. To calibrate all eight flight-model detectors using the beamline facility available at NASA/MSFC.
2. To operate the DAQ system I developed with the flight-model detectors, and to instruct NASA engineers on its usage and operation.

**Work Conducted**

We stayed at NASA/Marshall Space Flight Center (MSFC) for approximately one month beginning February 1, 2026, where we conducted calibration of the flight model detectors using the NASA/MSFC beamline facility. NASA/MSFC houses an X-ray generation facility spanning approximately 100 meters, capable of irradiating detectors uniformly and acquiring data across a range of energy bands by switching between multiple X-ray sources. The characteristic X-ray energy can be selected by changing the target metal used in the source. For example, tungsten produces X-rays near 59 keV, while rhodium (Rh) produces X-rays at 22 keV. During this visit, we used the Rh target to calibrate all 8 detectors over the course of one month.

As this was the first data acquisition campaign using the NASA/MSFC beamline, however, we encountered significant challenges in establishing the experimental setup. The CdTe double-sided strip detectors (CdTe-DSDs) are designed to operate at −10°C to achieve their full performance, and therefore energy calibration also needed to be carried out at that temperature. Accordingly, we began by building a setup to properly cool the detectors within the beamline environment. We successfully completed approximately 2 hours of data acquisition per detector for all 8 units using the Rh-target X-ray source. In addition, through this calibration campaign, we were able to establish an environment in which NASA/MSFC engineers can independently carry out energy calibration data acquisition in the future. In the final week of the visit, I ran the data acquisition system I had developed on the flight model detectors and confirmed that it operated correctly in practice.

**Outcomes**

This visit represented a major step forward for the SuperHERO program, as we successfully acquired beamline data for all 8 flight model detectors. The data obtained will be used to verify that the detection efficiency is sufficiently uniform across the pixels of each detector. Furthermore, the data acquisition system I developed operated correctly with the flight models, confirming that reliable data acquisition is achievable and substantially advancing the future development of SuperHERO.

The primary scientific objective of SuperHERO is the observation of hard X-rays from astrophysical sources such as supernova remnants. However, during the 2028 balloon mission at an altitude of about 40 km, the detectors will inevitably also record diffuse X-ray emission originating from the atmosphere itself, a signal that would conventionally be treated as background noise. Rather than discarding this data, we intend to exploit it as a scientific resource. This atmospheric X-ray emission arises from cosmic-ray-induced ionization, in which high-energy particles collide with atmospheric molecules and generate secondary radiation. Direct high-altitude measurements of this signal remain scarce, and the data acquired by SuperHERO will provide new quantitative constraints on the ionization state of the upper atmosphere.

This has direct implications for AI-based atmospheric modeling. Current machine-learning weather prediction systems, despite their impressive performance on large meteorological datasets, do not incorporate cosmic-ray flux as an input variable. Yet cosmic-ray-induced ionization is theorized to influence cloud nucleation and precipitation patterns. By providing high-quality observational data on atmospheric X-ray emission and ionization rates, SuperHERO can supply physics-grounded input that would allow AI forecasting models to better account for space weather effects on the atmosphere. In this sense, the precise detector calibration conducted during this visit is a foundational step not only for astrophysics, but for the broader goal of integrating cosmic-ray physics into AI-driven atmospheric science, directly contributing to the "air valorization" initiative.

Furthermore, through this visit to NASA, I gained valuable experience leading communications with NASA engineers as a core member of the experimental team. International collaboration and communication are critically important to advancing SuperHERO, and this visit allowed me to build that experience and further strengthen our international partnerships.



Figure 2. Saturn V rocket in Space & Rocket Center