VIRTUAL APERTURE MULTISPECTRAL IMAGING FOR ATMOSPHERIC REENTRY STUDIES

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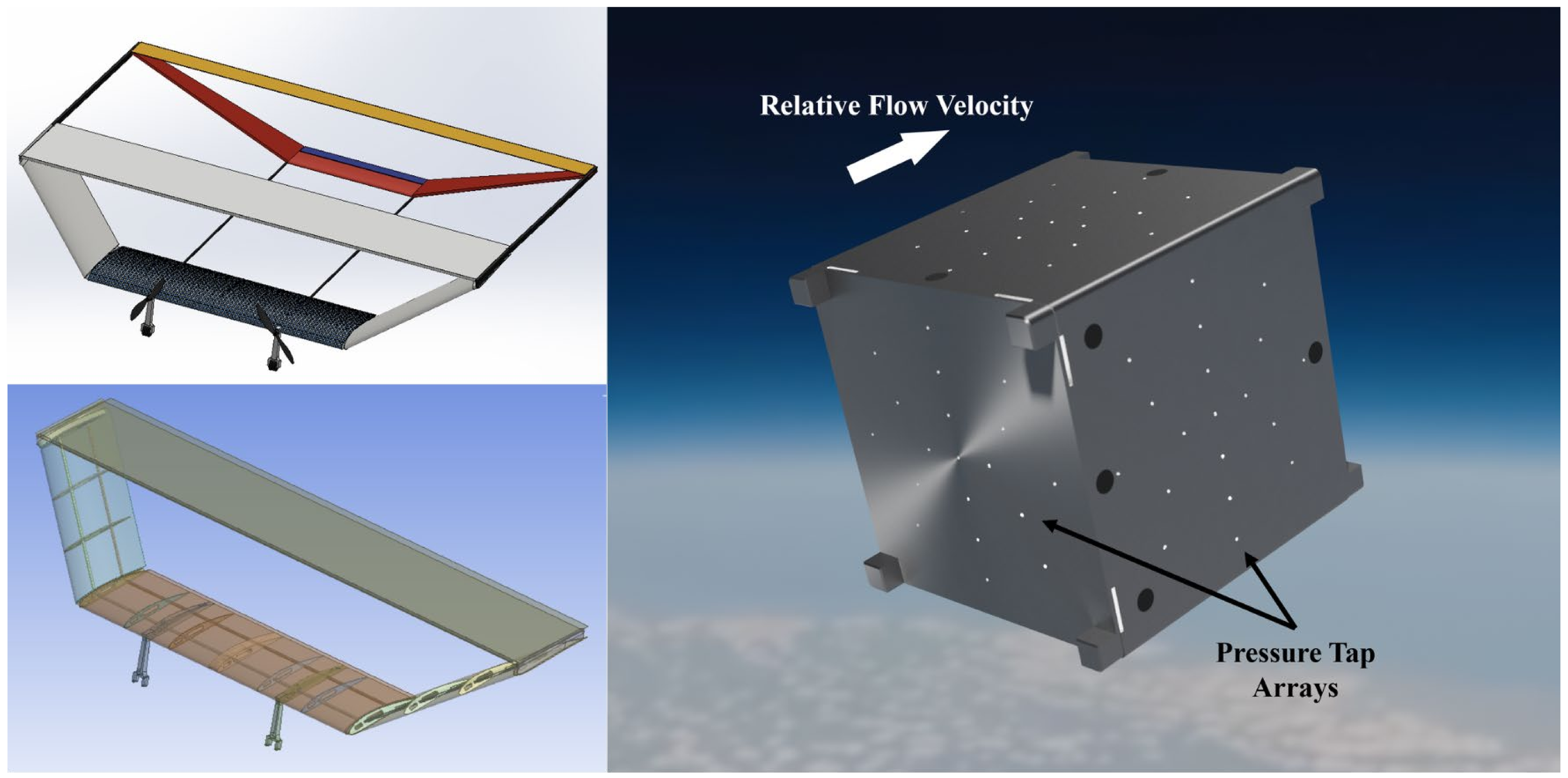

Left: *We propose utilizing the high-altitude long endurance (HALE) flying leaf shown here as a base for a synthetic aperture optical system array that will capture data on hypersonic reentry conditions (thermal imaging) for orbital debris (including defunct satellites) while fulfilling the primary mission objectives of Glitter Belt proposed by [1]. One such reentry object could be a 1U CubeSat outfitted with pressure sensors for a full suite of reentry aerodynamics research. Image credit: [1]*
Right: *1U CubeSat with pressure sensors flush mounted to outer surface for aerodynamic data collection during atmospheric reentry. Image credit: Nathan Eller, from [7]*

TWO METHODS TO PERFORM NOVEL HYPERSONIC RESEARCH

USING IR INTERFEROMETRY AND ONBOARD SENSORS

The need for implementing sustainable, cost efficient, and powerful imaging systems for atmospheric reentry objects is of increasing interest, and even more so as the number of satellites and launch vehicle parts expected to reenter the Earth's atmosphere is projected to increase in the near future. [2-3]. One application of swarms of large slow-moving reflectors at high altitudes is to perform imaging looking up into space. Our initial interest is in Low Earth Orbit (LEO) and vehicle surfaces at the start of re-entry, where signal to noise ratio can be quite high. Later, as positional accuracy of the reflectors is improved, we project application to study space weather phenomena, and perhaps even deep space imaging, using the clear, thin atmosphere and steady flight of the arrays to achieve satisfactory signal to noise ratio. This research represents an early concept-level study of a high-altitude interferometric optical system that utilizes synthetic aperture to create high-resolution thermal imagery (infrared wavelengths) to study hypersonic flow characteristics in reentry bodies. The study addressed the increasing need for orbital debris and reentry object tracking, management, visualization, and study using novel high-altitude optical assets.

Additionally, this research focuses on exploring the viability of small spacecraft for obtaining aerodynamic characterization using direct load measurements. The study proposes the use of an array of micro-electromechanical pressure sensors to directly measure unsteady aerodynamic forces from bodies of arbitrary shapes and flight attitudes during atmospheric reentry. Such a measurement system integrated into small spacecraft would provide better insights into dynamically evolving flow characteristics than the integrated forces deduced from inertial measurement systems. The scope is limited to the integration of a pressure sensor array using open-source embedded systems, followed by assessing system performance and limitations (see [7]).

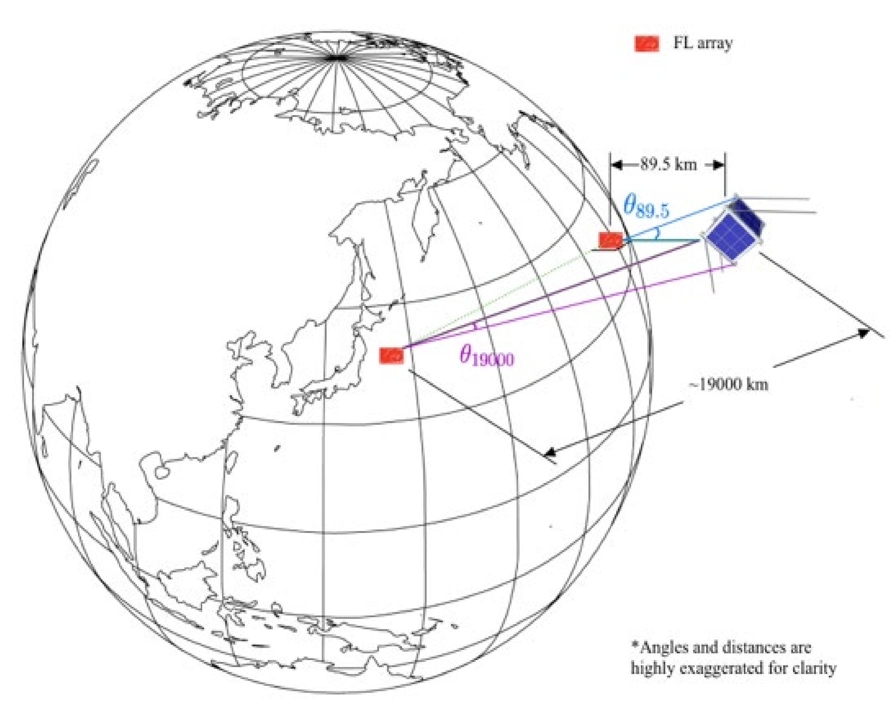

Figure 1. With an FLT array off the coasts of Japan and the U.S. (each held at 30.5 km (about 19 mi) altitude), we determined the angular resolution required to resolve a CubeSat beginning its reentry at 120 km (about 75 mi). At maximum, for an altitude of 30.5 km, the maximum distance between flying leaflets is about 2140 km (limited by the horizon) which corresponds to angular resolution $\theta = 5.3 \times 10^{-3}$ *degrees or* ≈ 19 *arcseconds.*

WHY SYNTHETIC APERTURE?

To create high-resolution thermal imagery, it is required to have impractically large apertures for radio telescopes to capture the infrared wavelengths. The demand for such large apertures is subverted by having several dish antennas of practical sizes. These regularly spaced antennas collectively form an equivalent of an exceptionally large aperture telescope. This concept of using discretely spaced interferometers is commonly known as synthetic aperture. This system exploits the phase differences of at least two sources to create a combined, more detailed image as described in [4] and others. The complications of performing infrared interferometry from widely separated moving platforms are numerous and future studies will examine the technical feasibility of such a system.

ACQUISITION AND POSITIONING CHALLENGES

Satellite ground track data is useful for predicting reentry events, but there are still many uncertainties associated with time and position predictions that will make imaging challenging. The most accurate models consider solar radiation pressure, spacecraft attitude, atmospheric drag, Earth's gravitational and magnetic field effects, three or more body effects, and other orbital perturbations. The constantly changing solar cycle swells and shrinks the atmosphere, further complicating reentry predictions. Targeted reentry vehicles, especially large ones, will be the easiest to image.

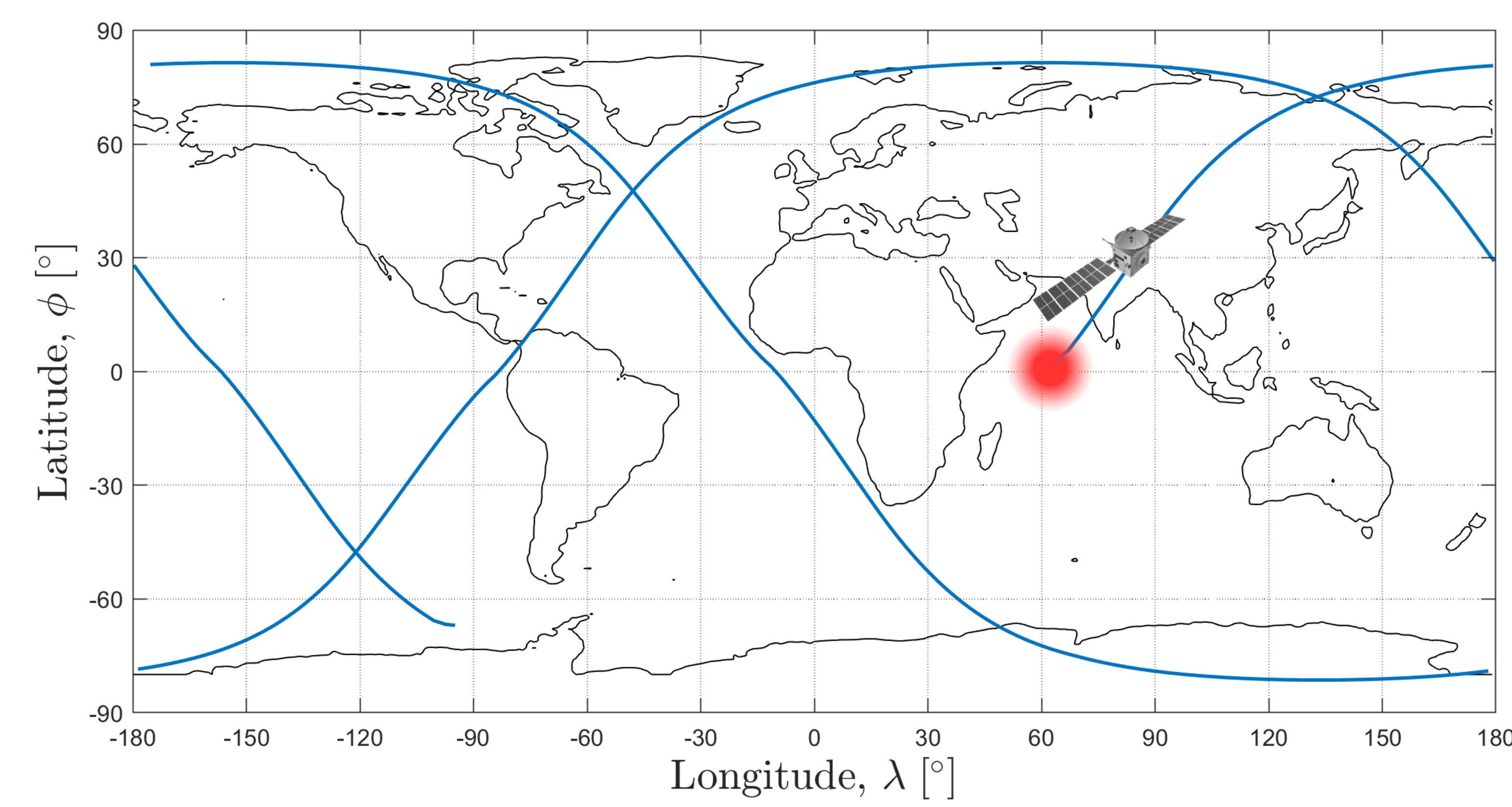

Figure 2. Our code takes published two-line elements and plots ground tracks for user-specified time intervals. This plot shows the AAU (Aalborg University, Denmark) CubeSat (Catalog ID# 27846) if it were to perform a controlled reentry in the Indian Ocean. Our system aims to capture high-resolution imagery of the hypersonic flow field surrounding the deorbiting object during reentry. All plots were created using MATLAB (`groundtrack` function courtesy of Tamas Kis: https://tamaskis.github.io

REENTRY FLIGHT ENVELOPE

We strengthened our model by considering a range of drag coefficient, C_D, corresponding to a 3σ maximum limit Gaussian distribution. This data will help in determining flight reentry path profile for the CubeSat and is essential for defining mission parameters for the FLTs. Figure 2 shows Mach number and velocity as functions of altitude during reentry.

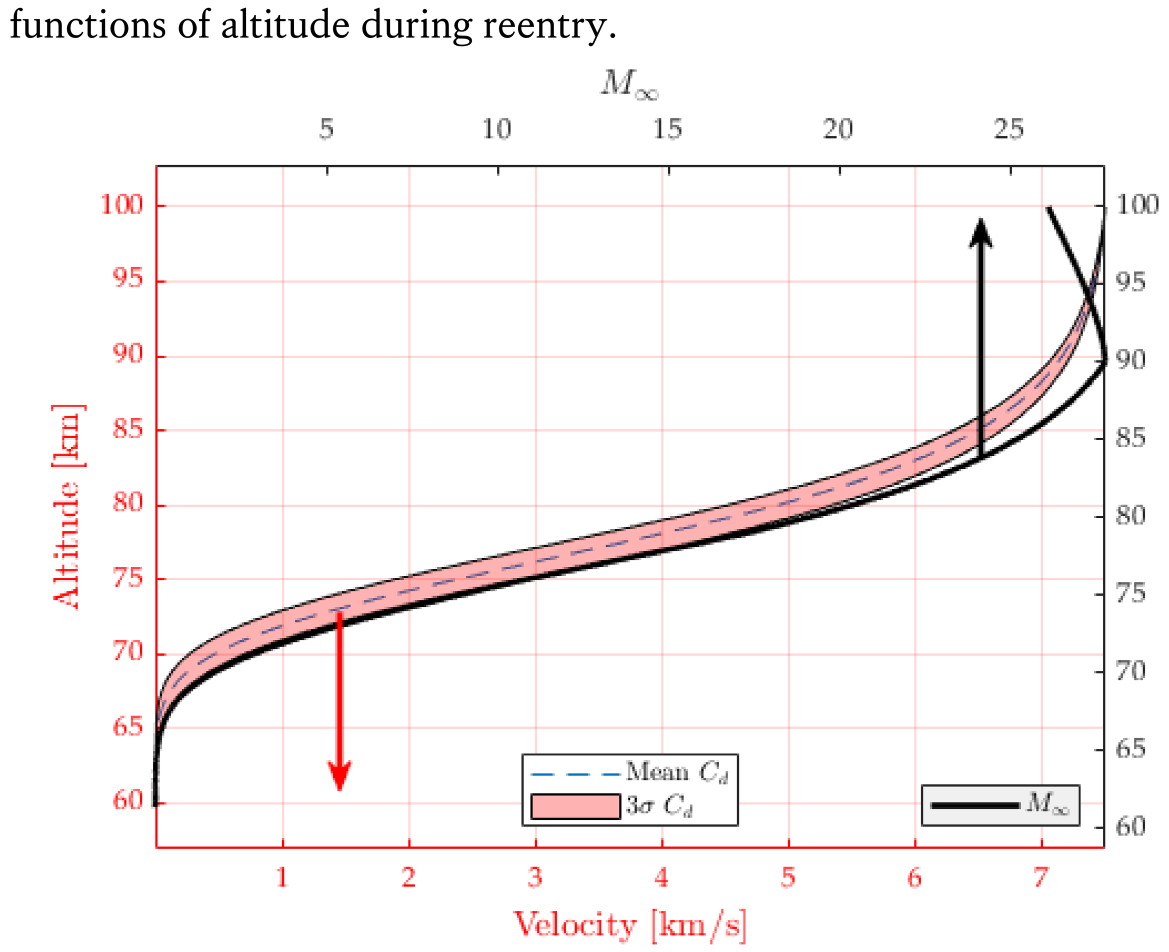

Figure 2. Velocity and freestream Mach number for a 1U CubeSat during atmospheric reentry. The C_d *values were produced by assuming a Gaussian distribution to simulate tumbling. Shown here are the mean (dashed) and 3-σ drag coefficient region (shaded). The vehicle becomes sonic around 70 km and by this altitude the object has burned up. Arrows indicate associated plot axes. Plots like this and Figure 3 will help with both optical and pressure sensor system design.*

HOW BRIGHT DOES IT GET?

Simulating the amount of light received per square meter at all altitudes during the reentry event will help our team to determine maximum incident photons for the sensors and will aid in optical system design. The deorbiting CubeSat shines brightest between ~80 km and 50 km. The maximum brightness is associated with a fireball at roughly 2,800 Kelvin (4,580 degrees F).

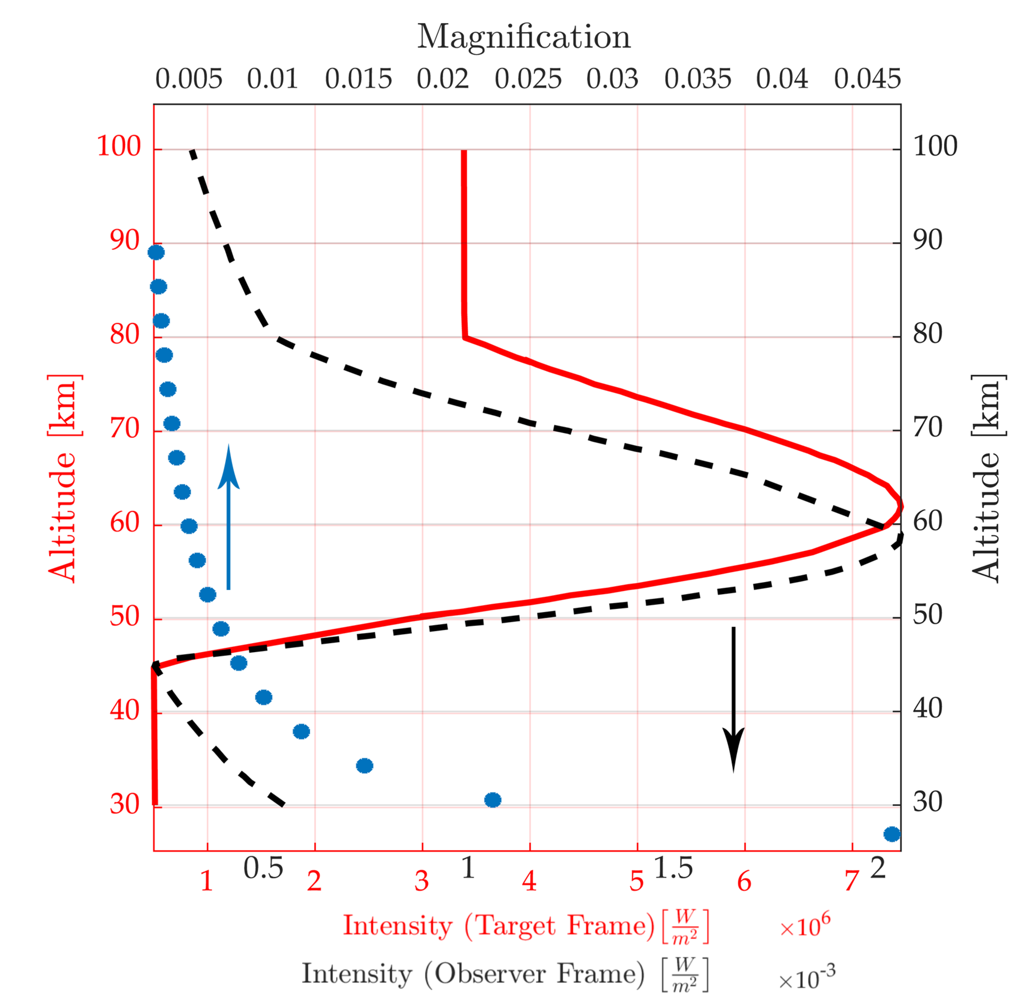

Figure 3. (a) Lower x-axes. Thermal energy per unit area (Intensity) emitted by the reentry object (the Target) during atmospheric reentry from both the Target (solid; lowermost values on the x-axis) and Observer (dashed; arrow points to the uppermost values of the bottom x-axis), of the proposed high-altitude synthetic aperture optical system. Expected photon intensity values for the system will drive sensor and system architecture design. Note that the intensities sensed by the FLT array (the Observer) are on the order of mW/m2. (b) Upper x-axis. Magnification (dotted; arrow points to x-axis) of the Target image seen from the Observer frame, treating the trailing sheets as spherical reflectors.

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