STOP model implementation for the PICTURE-C exoplanetary imaging balloon mission, progress report I: thermal modeling and comparison with flight data

Thaddeus Potter, Christopher Mendillo, Kuravi Hewawasam, Jason Martel, Timothy Cook, Supriya Chakrabarti
University of Massachusetts, Lowell

PICTURE-C

The Planetary Imaging Concept Testbed Using Recoverable Experiment-Coronagraph (PICTURE-C) telescope is a coronagraphic imaging mission for multi-spectral imaging of exozodiacal dust around nearby stars. Mounted on the Wallops Arc-Second Pointer (WASP) and flown on a high-altitude balloon (~38km), PICTURE features a sophisticated wavefront control system and a Vector Vortex Coronagraph, capable of creating contrasts of approximately 1×10^{-7} at working angles of 2-10 λ/d.

Because of the tight tolerances needed to achieve these targets, alignment errors caused by thermal expansion of the supporting structure could significantly impact the final performance of the instrument. As such, a model which takes these factors into account is necessary.

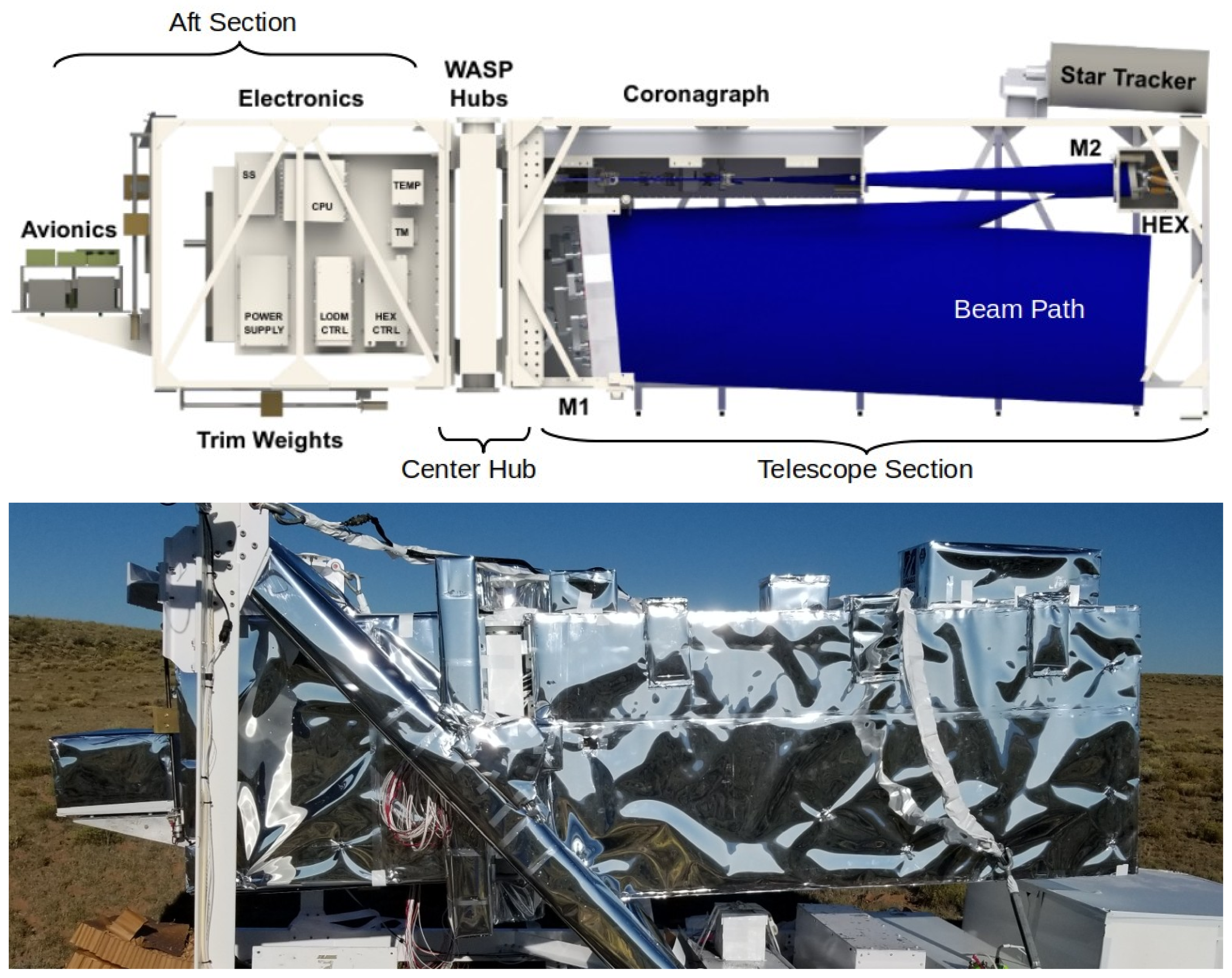


Fig. 1: The PICTURE-C Observatory. **Top:** Labeled Mechanical Design, Flight 1 configuration. **Bottom:** Photograph taken after recovery of Flight 1.

PICTURE-C Thermal Model

Thermal Model of PICTURE-C was implemented using COMSOL Multiphysics®, a software suite capable of solving a wide range of physics problems with a single interface.

This will allow future studies which include mechanical loads to be performed on the same model, and with minimal overhead.

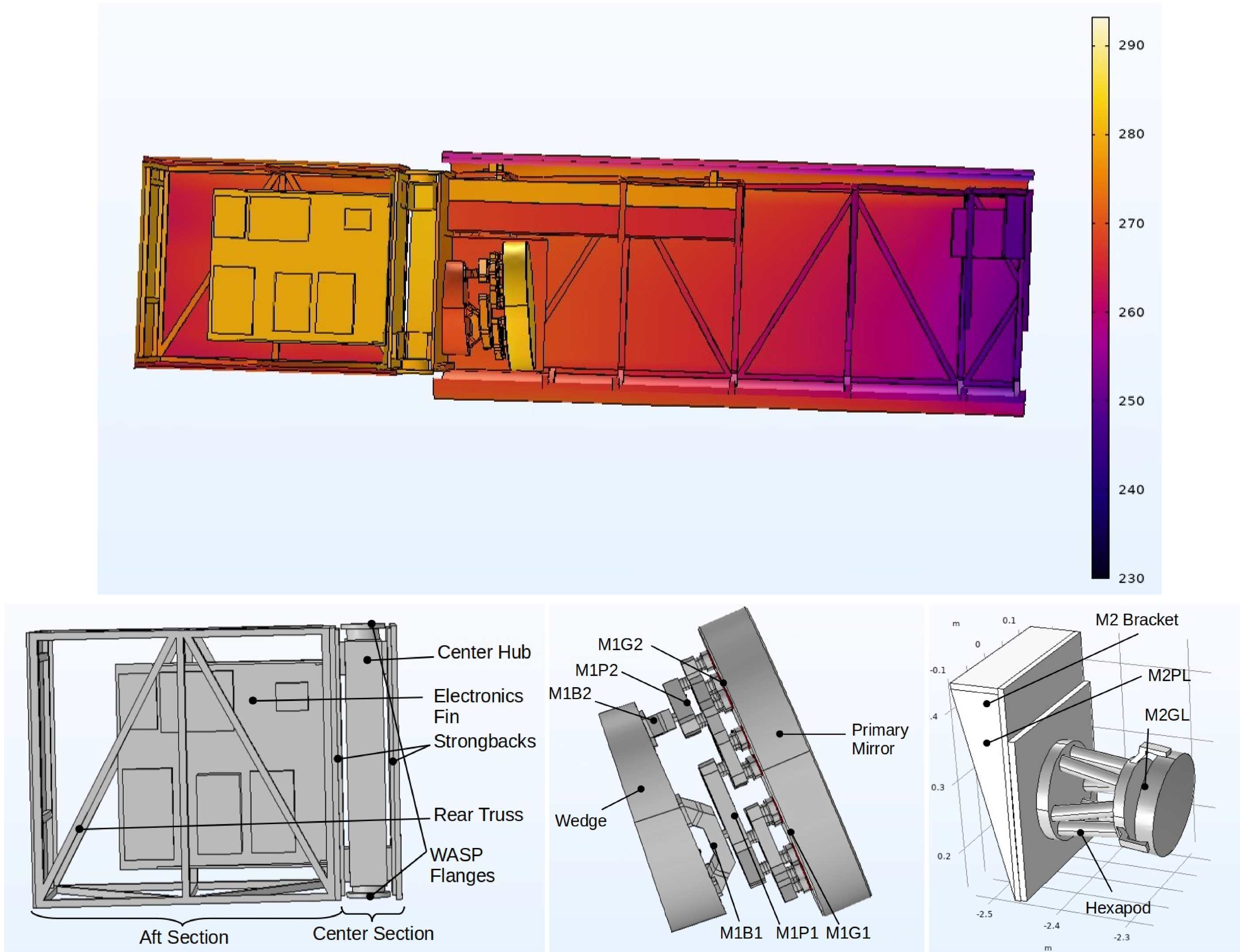


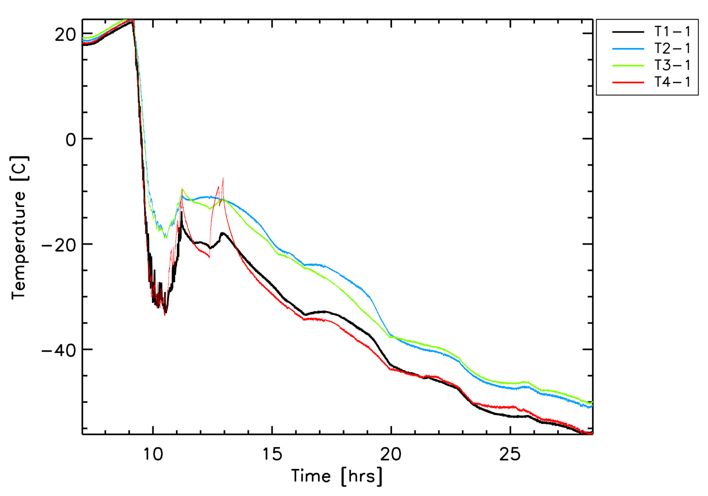
Fig. 2: PICTURE-C as Implemented in COMSOL. **Top:** Full modeled structure, showing initial model temperatures. **Left:** Center and Aft Sections. **Center:** Primary Mirror Assembly. **Right:** Secondary Mirror Assembly.

Defeaturing was performed using COMSOL's inbuilt geometry functions. The aft section along with the primary and secondary mirror assemblies, shown above, required the most significant changes. The structure is insulated by 2.5 cm Polystyrene boards, which is wrapped in Aluminized Mylar. The observatory contains 80 temperature sensors, 37 of which were used to calibrate the thermal properties of the model system.

Flight Environment and Boundary Conditions

The balloon flight environment is challenging, requiring effective temperature control for widely varying conditions: low air temperature and convective cooling in the troposphere, and high solar irradiation and lack of convective cooling in the upper stratosphere (~38km).

Fig. 3: Temperature evolution of the front end of truss structure during flight 1. Ascent from approximately 09:30 to 12:00.



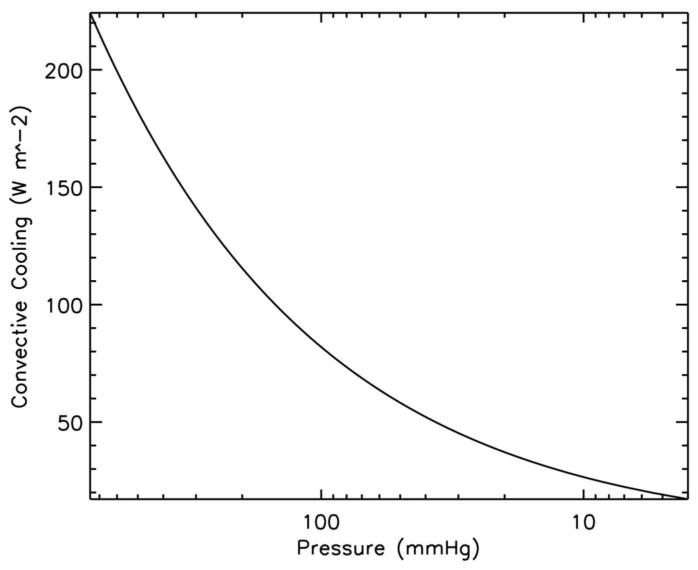


Fig. 4: Convective Cooling Falloff with Pressure. Maximum: 345 W m^{-2} at 760 mmHg. Minimum: 16.3 W m^{-2} at 4 mmHg.

As such, temperature evolution of the payload is dictated by the radiation environment, alongside the insulation and surface properties of the payload.

Table 1 outlines the radiation environment experienced at float altitude, and Table 2 shows the surface and coating properties use in the payload.

Table 1: Radiative Sources in PICTURE-C Thermal Model

Source	Power ($W\,m^{-2}$)	Source Direction
Direct Solar	1366	Varies by Time
Earth Albedo	819	-z Half-Sphere
Earth Emission	175	-z Half-Sphere

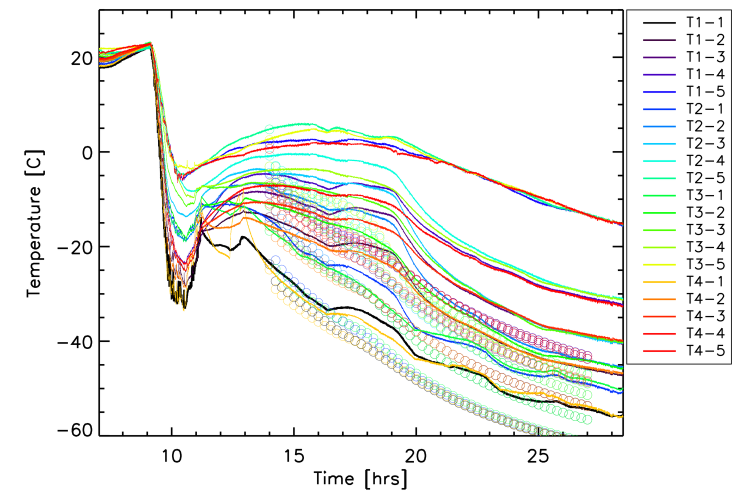
Table 2: Surfaces and coatings used in the PICTURE-C mission

Material	Solar Absorptivity (α)	Infrared Emissivity (ϵ)	α/ϵ
Aluminized Mylar	0.17	0.760	0.223
Lord Aeroglaze® A276	0.26	0.88	0.261
Aluminum*	0.08	0.02	4.00
Stainless Steel*	0.47	0.14	3.36
ULE Glass	0.9	0.75	1.20
Mirror, Protected Aluminum	0.03	0.03	1

* Machined, Unpolished

Results / Discussion

Overall heat balance of the telescope in the model does not yet match data taken during flight 1. Discrepancy between model and flight data is strongest for the center and aft section, a massive and shielded portion of the payload.



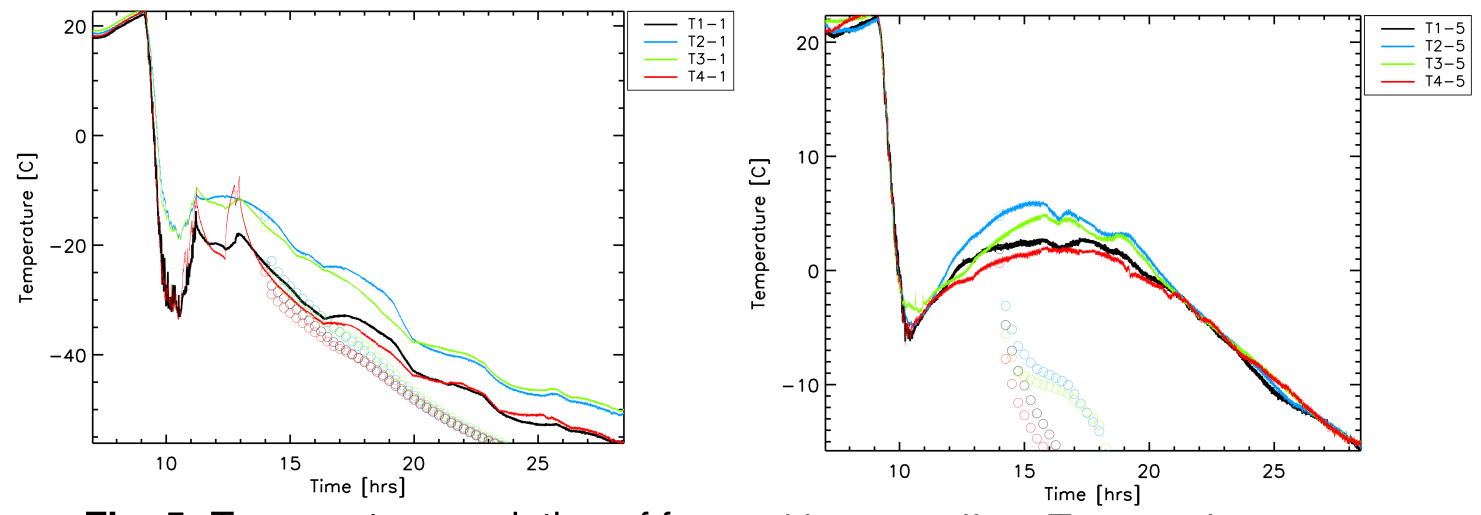
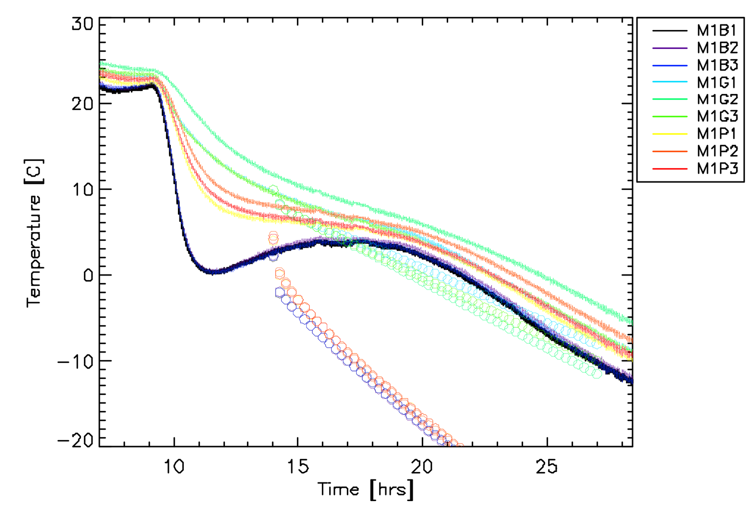


Fig. 5: Temperature evolution of forward truss section. Temperature sensors laid out such that the first digit corresponds to the beam it is placed on, and the second where it is located, with 1 furthest forward, and 5 towards the aft section. **Top:** Full truss structure. **Left:** Forward Temperature Sensors. **Right:** Aft Temperature Sensors. Lower sensors (T1,T4) cool faster due to lower exposure to ambient radiation. Rear end cools more slowly due to coupling to center section.

Fig 7: Temperature evolution of primary mirror assembly. M1Bx - Base (Closest to Strongback), M1Px - Plate (Center of Assembly), M1Gx - Glass (Primary mirror). Base and plate sensors cool more quickly due to thermal coupling to center section.



There are two potential solutions that we are currently investigating: (1) the discretization of radiation, and (2) the inclusion of the gondola and pointing system.

(1) In order to accurately model the reflective properties of the insulation and mirror surfaces, radiation must be treated using rays. This is computationally expensive and leads to lower resolution of reflection and emission. This lower resolution may change how much radiation escapes from the payload.

(2) Though thermal conductance between the gondola and the payload was thought to be small, it is possible that conductive coupling to the gondola provides a significant amount of heat to the payload, and would contribute to the thermal inertia to the center section of the payload.

Conclusions / Future Work

This study represents the first steps in developing a high fidelity, end-to-end model of the PICTURE-C observatory. Though current results do not accurately reflect the temperature evolution observed during Flight 1, progress has been made on the implementation of the thermal model, and further study will be performed in order to more accurately simulate the heat balance of the payload.

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