Thermal Design of ASTHROS

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The Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths (ASTHROS), is a 2.5-m balloon-borne observatory that will make the first spectrally-resolved high spatial resolution 3D map of ionized gas in Galactic and extra-galactic star forming regions via the THz fine structure lines of ionized nitrogen and other nearby spectral lines. Building on the Stratospheric THz Observatory (STO-2) and Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO) missions, ASTHROS, launching in 2023 will, over its 21-day Antarctic mission, map two template Galactic star forming regions and the entire disk of the M83 barred spiral galaxy at high angular resolution. The Applied Physics Laboratory (APL) will build the ASTHROS gondola and thermal control system. The latter will use a fluid loop and radiator very similar to that used by APL on GUSTO. This paper will present an overview of the thermal design of the ASTHROS gondola and telescope.

Nomenclature

ALMA = Atacama Large Millimeter/Submillimeter Array
ASTHROS = Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths
ASU = Arizona State University
BOPPS = Balloon Obseravation Platform for Planetary Science
CBE = current best estimate
CSBF = Columbia Scientific Balloon Facility
EG = ethylene glycol
GUSTO = Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory
IMU = Internal Measurement Unit
ISM = Interstellar Medium
JHU = Johns Hopkins University
JPL = Jet Propulsion Laboratory
LMT = Large Millimeter Telescope
LPM = liters per minute
MLI = multi-layer insulation
MTU = momentum transfer unit
PET = polyester tape
PTR = Pulse Tube Refrigerator
SEA = sun elevation angle

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SIP = support instrument package
SOFIA = Stratospheric Observatory for FIR Astronomy
SPV = South Polar Vortex
STO = Stratospheric THz Observatory
ULDB = Ultra-Long Duration Balloon

I. Introduction

THIS paper introduces the thermal design for the Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths (ASTHROS), a 2.5-m balloon-borne observatory that, in order to explore feedback mechanisms from massive stars on the Interstellar Medium (ISM), will make the first spectrally-resolved high spatial resolution 3D map of ionized gas in Galactic and extra-galactic star forming regions. ASTHROS, managed by the Jet Propulsion Laboratory (JPL), will observe the THz fine structure lines of ionized nitrogen and other nearby spectral lines that have low atmospheric transmission and are thus challenging to observe from the ground or even from airborne observatories such as the Stratospheric Observatory for FIR Astronomy (SOFIA). Building on the experiences gleaned from the Balloon-Borne Large Aperture Submillimeter Telescope (BLAST), Balloon Obseravation Platform for Planetary Science (BOPPS), Stratospheric THz Observatory (STO-2), and Galactic/Extragalactic Ultra-Long Duration Balloon (ULDB) Spectroscopic Terahertz Observatory (GUSTO) ballon missions, ASTHROS, launching in 2023 will, over its 21-day Antarctic mission, map two template Galactic star forming regions and the entire disk of the M83 barred spiral galaxy at high angular resolution. The observatory is designed to withstand landing loads so that it can be-reflown, making a large accurate telescope available to the balloon community at an affordable cost.

The ASHTROS project started in 2020. The observatory will be developed and built by a capable team including people from JPL, the Johns Hopkins University (JHU) Applied Physics Laboratory (APL), Arizona State University (ASU), Lockheed Martin, and University of Miami. Building on nearly 20 years of experience in scientific ballooning [1], JHU/APL will build the ASTHROS gondola and thermal control system. The latter will use a fluid loop and radiator very similar to that used by APL on GUSTO. Many of the other gondola subsystems will be nearly identical to those used on previous balloon missions such as the momentum transfer unit (MTU) from Sunrise 3, Roll Wheel

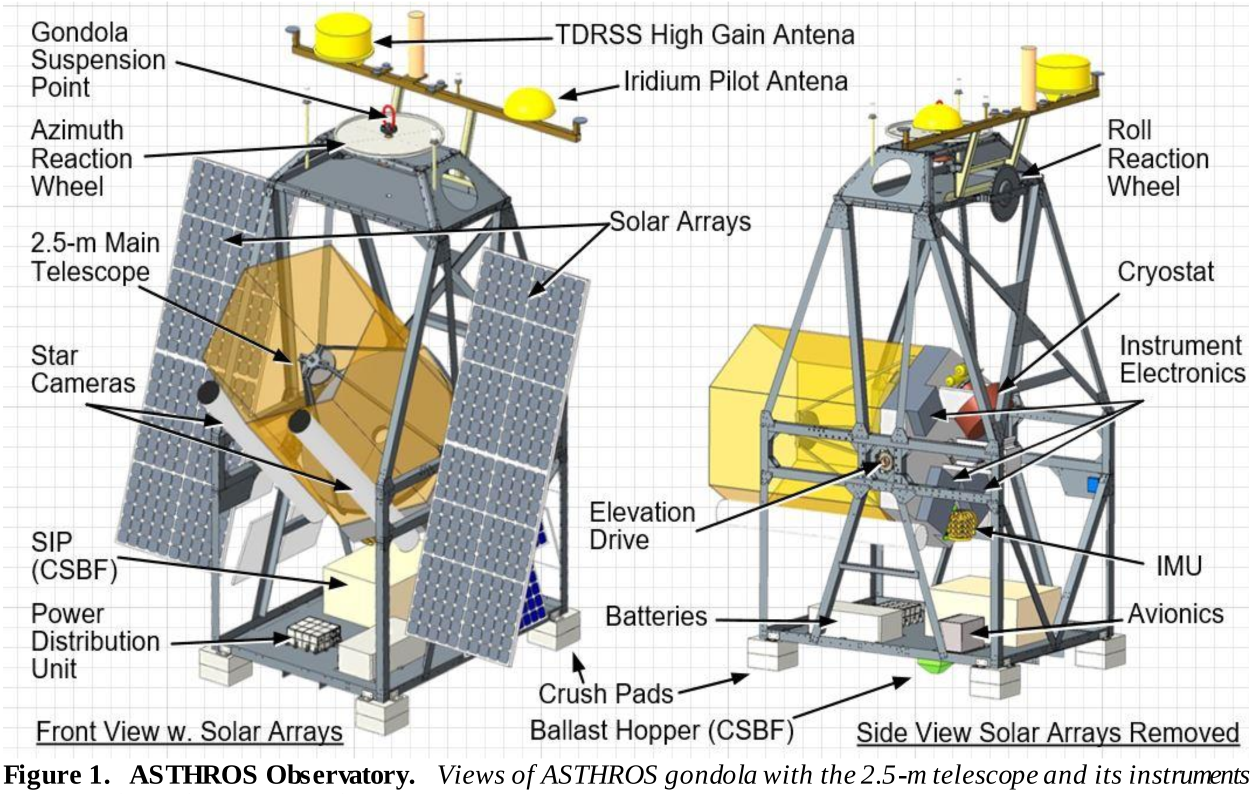

Figure 1. ASTHROS Observatory. *Views of ASTHROS gondola with the 2.5-m telescope and its instruments suite.The field of view (FOV) of the telescope is also shown. Italicized items are heritage or near-heritage.*

from STO2, Elevation Drive Assembly from GUSTO, Avionics from STO2, and the inertial measurement unit (IMU) from BOPPS. ASTHROS will use a 2.5-m telescope unit developed by Media Lario using heritage from ALMA and LMT. The telescope, including all secondary and backing structure, will be delivered fully qualified and ready to be integrated with the gondola and payload. The payload components are all at least TRL-6 and includes the cryocooler and electronics, linear arrays, recievers, local oscillators, and spectrometers. The receiver system will be cooled with a low-power pulse tube refrigerator (PTR) cryocooler (designed and built by Lockheed Martin Corp. [5] under the NASA Advanced Cryocooler Technology Development Program [6]) that does not require liquid helium to achieve a temperature of 4 K [2]. Overall, the payload has a power demand totaling 490 W for the crycooler, front-end electronics, back-end calibration system, and telescope controller; all of these will be cooled via the fluid loop and radiator. This paper will present an overview of the thermal design of the ASTHROS gondola and telescope.

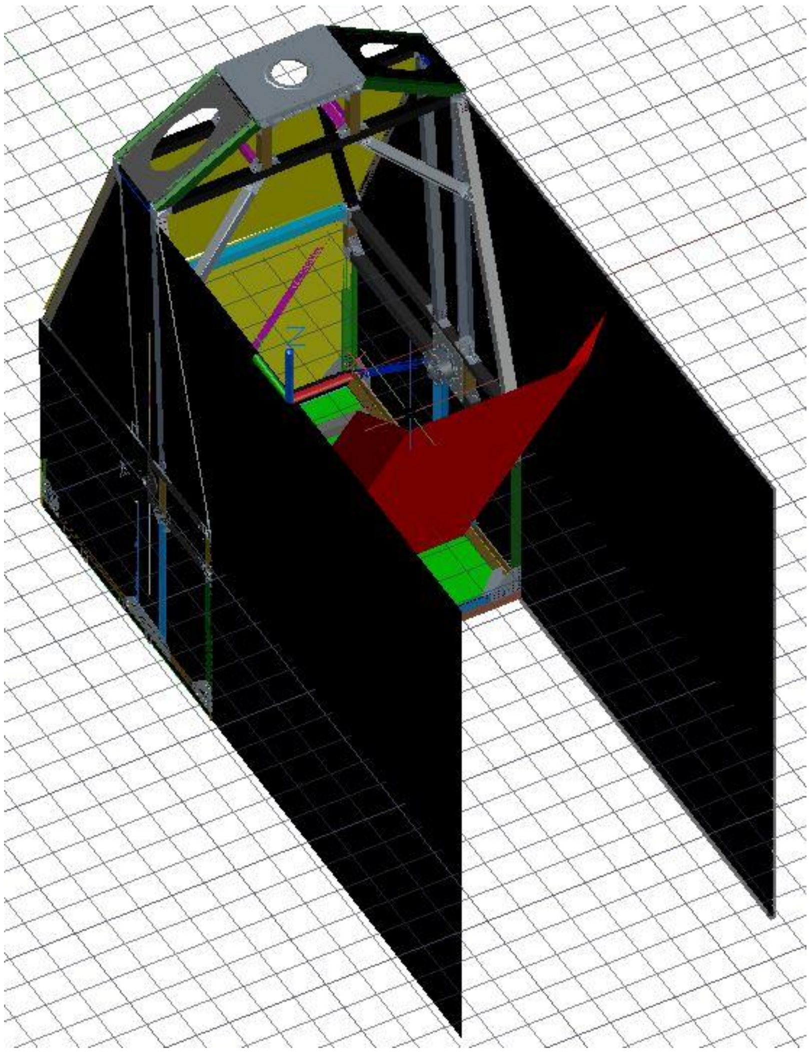

Figure 2. ASTHROS Thermal Shields. *Shields for the sides (black), bottom (green), and back (yellow) of the gondola are shown. Also shown is the telescope shield (red) that is below the antenna FOV (not shown).*

II. Observatory Design Overview

The preliminary layout of the ASTHROS observatory from two different views is shown in Figure 1. The antennas, ballast hopper, and support instrument package (SIP) are provided by Columbia Scientific Balloon Facility (CSBF) after the rest of the observatory is assembled. The azimuth (part of the MTU) and roll reaction wheels are used to maintain the gondola pointing. Elevation is controlled via a direct drive motor applying torque directly between the frame of the gondola and the telescope unit. An IMU with 3 gryoscopes and a magnetometer will determine attitude, while two star cameras will be used to find absolute pointing knowledge. This method for attitude determination and celestial pointing was used successfully on BOPPS and STO [3]. The solar array size and location are still in flux (for example, they will likely be more tilted inwards along the gondola structure due to the 30° sun keep out angle), but they will generate approximately 1.5 kW of power. Over the 21 days of the mission, ASTHROS will circle the Antarctic continent twice at a nominal altitude of 38 km. In that time, due to the South Pole Vortex (SPV), it is unlikely to leave the continent and head out over the ocean and will thus be recoverable.

Contrary to what might be thought, balloon flights over Antarctica are generally concerned with overheating, not freezing. This is primarily due to the high albedo (or high Earth-generated IR; the two are anit-correlated so tend to not happen simultaneously) of the continent reflecting a large amount of sunlight upwards, thus nearly doubling the solar heat load on any balloon-borne observatory. The primary cold concern occurs during the ~3 hr ascent when the observatory goes through the tropopause. However, most hardware is not on during ascent and the transition through the tropopause is fairly rapid, so that at most, some survival heaters may be required.

While the cryocooler and vacuum cryostat will help keep the detectors at their required 4 K during observations, the thermal load on the telescope unit as a whole at float altitude needs to be limited. To obtain good antenna efficiency for the ASTHROS observations in the far-infrared, the 2.5-m antenna will maintain the required surface accuracy of better than 8 micro-meters RMS when the primary mirror is between -28 °C and +12 °C. Therefore, it is critical that the antenna temperature be kept below the maximum operating range of +12°C and near the optimum operating temperature of -10 °C. To achieve this, ASTHROS will use large thermal shields as illustrated in Figure 1. The shields extend completely around the sides and back of the gondola from the avionics deck up to the penthouse. Shown in green in Fig.2 is a shield on the bottom of the avionics deck to block solar albedo loads. This shield will have cutouts for any high-load boxes on the deck, such as the SIP, so they can radiate downward. In front of the gondola structure, the shields extend for ~4m and will be supported via guy wires and composite rods. This shielding is necessary since the sun keep out angle is only 30°. The telescope unit has a bottom shield shown in red in Fig. 2; this is attached to

Table 1. ASTHROS Thermal Dissipations.

Component	CBE (W)
Pump & Converter	100
SIP	100
Cryocooler electronics*	230
Front-End*	180
Back-End*	60
Telescope Controller*	20
Gondola (Avionics, PDU, amps, MPPTs, etc)	100
Instruments	310
TOTAL	1100

the telescope structure and moves in elevation in tandum with the telescope. A "top" shield is not required since the mission is flying in Antarctica and thus the sun elevation angle (SEA) will never be high enough to peak over the sides. Even so, in all, over 100 m^2 of thermal shielding will be used.

To minimize the cost and mass impact of so much thermal shielding, a non-standard layup will be used. The air at an altitude of 36 km has a pressure of 2 to 5 mbar and a temperature of -20 °C to +10 °C. This is sufficient to result in a non-negligible convective heat flux at float and reduce the effectiveness of typical multi-layer insulation (MLI). The relatively warm instrument platform and telescope unit will be slightly cooled by this convective heat flux, whereas the shielding itself, with its large surface area, will be warmed to only ~ -30 °C by ~600 W of convective heating as well as over 2000 W of radiative heating. In addition, the thermal shield must be able to handle the mechanical loads seen during ascent. The shield layup design is illustrated in Fig. 3. Velcro with dual-sided adhesive will be used to hold the outer and middle shield materials of the thick drafting mylar and aluminized mylar, respectively, to the gondola structure. The adhesive is deemed mechanically insufficient to hold the inner black polyester layer to the velcro, so the velcro will be sewn to the polyester. Wherever necessary, aluminum-coated kapton tape will be used to close out any seams and the unpainted gondola structure. The gondola structural beams are approximately 4 inches in thickness, so the shield is ~4 inches thick, with 2 inches separation between each of the layers, sufficiently small to avoid the formation of internal natural convection cells between the layers. The design shown in Fig. 3 is in flux; for example, lower emissivity materials (that are still cheap and light) for the internal surfaces are being persued.

The current best estimates (CBE) of thermal dissipations for ASTHROS components are listed in Table 1. The SIP will have its own solar arrays and thus is not part of the gondola power system; its temperature will be self-regulated

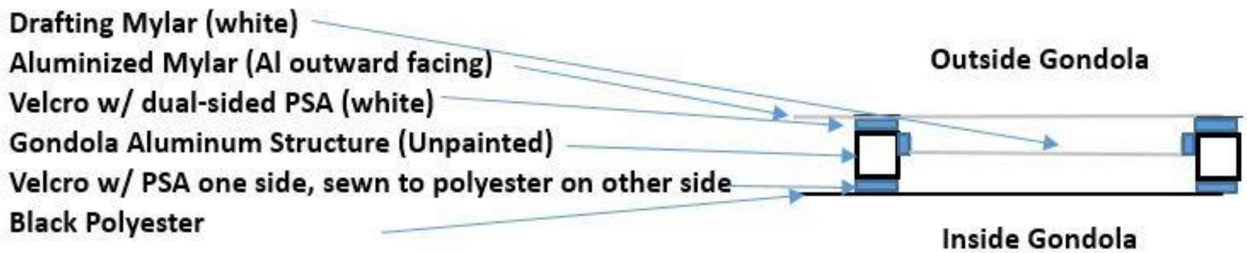

Figure 4. ASTHROS Thermal Shield Layup. *The thermal shields will use Velcro (blue) with pressure sensitive adhesive (PSA) to attach the mylar and polyester to the gondola structure.*

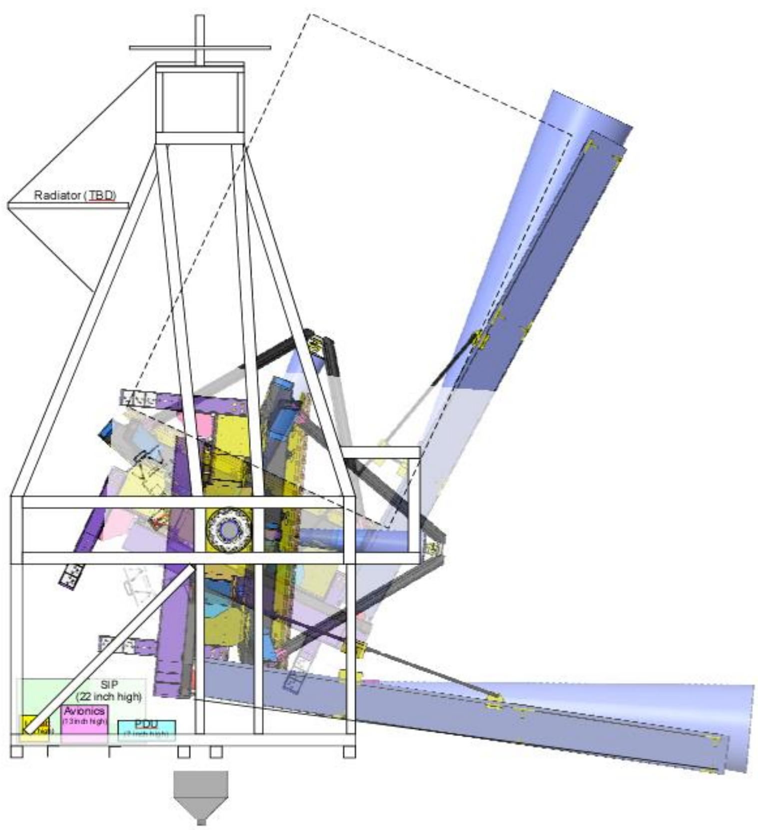

Figure 3. ASTHROS Schematic. *The observatory showing blue cones for the star cameras' FOVs on the right (the front) and the radiator on the left (the rear).*

by CSBF. The gondola solar arrays will deliver 1.5 kW of power, so there is plenty of power margin. Some of the components (marked with an asterisk in Table 1) will be cooled via a fluid loop. Their thermal loads plus most of that of the pump (so totaling nearly 600 W) need to be dissipated using a large (over 4 m^2) radiator. This radiator will have silver-coated polyester tape (PET) on its top for radiation and MLI-covered foam on the bottom to minimize heat loads from the ground and the rest of the observatory. It will be located outside of the thermal shield just below the penthouse; that is, above and behind the horizontal cyan bar visible in Fig. 2.

The single-phase fluid loop will be identical to that developed for GUSTO [4], using a mixture of water and 30% ethylene glycol (EG). The pump and dual-accumulator system will push ~8 liters per minute (LPM) through multiple fluid lines to cold plates in the payload components that require cooling and thence on to the radiator and back. Figure 4 shows a schematic of the observatory, illustrating the telescope unit at different elevations. When observing at high elevation angles, the instrument payload suite on the back of the telescope unit would see Earth, illustrating the need for the thermal shield on the bottom of the gondola. The radiator can be seen on the left of Fig. 4 projecting from the back of the gondola structure. The backside of the radiator sees primarily the observatory and at low elevation angles it looks directly at the hot instrument payload suite on the back of the telescope unit. Thus, good insulation (foam plus MLI) on the radiator backside is required. For mechanical reasons, the radiator is horizontal; thus, the top radiating surface has a slight FOV to the penthouse, which reduces the radiator efficiency. Further complicating the radiator performance is the fact that the sun, in order to meet the 30° keep-out zone requirement of the telescope unit, will usually be shining directly onto the radiator. However, the SEA will be low enough that the rays will impinge on the large horizontal radiator at a steep angle of incidence and thus the radiator can still reject over 600 W of heat.

III. Summary

Even with a raging global pandemic, the ASTHROS project spent 2020 proceeding with telescope, payload, and gondola development. Detailed thermal analysis of the design, however, will not be conducted until this spring; it will then be presented at ICES in July. Nonetheless, leveraging off of previous balloon misisons, the thermal design described herein is expected to meet the needs of the ground-breaking ASTHROS mission.

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