Cryogenics on the stratospheric terahertz observatory (STO)

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Abstract The Stratospheric Terahertz Observatory (STO) is a NASA funded, Long Duration Balloon experiment designed to address a key problem in modern astrophysics: understanding the Life Cycle of the Interstellar Medium. STO surveys a section of the Galactic plane in the dominant interstellar cooling line at 1.9 THz and the important star formation tracer at 1.46 THz, at \(\sim\)1 arc minute angular resolution, sufficient to spatially resolve atomic, ionic, and molecular clouds at 10 kpc. The STO instrument package uses a liquid helium cryostat to maintain the THz receiver at \(\sim\)9 K and to cool the low noise amplifiers to \(\sim\)20 K. The first STO mission (STO-1) flew in January of 2012 and the second mission (STO-2) is planned for December 2015. For the STO-2 flight a cryocooler will be added to extend the mission lifetime. This paper discusses the integration of the STO instrument into an existing cryostat and the cryogenic aspects of the launch and operation of the STO balloon mission in the challenging Antarctic environment.

1.0 Introduction

The Stratospheric Terahertz Observatory (STO) is a NASA-funded long duration balloon (LDB) experiment designed to address a key problem in modern astrophysics: understanding the life cycle of star-forming molecular clouds in our Milky Way Galaxy. STO is a balloon-borne 80 cm telescope with 4-pixel cryogenic heterodyne receiver arrays at 1.46 to 1.9 THz, exploring the Milky Way using the far-infrared emission lines of CII and NII [1, 2, 3]. STO-1 had a successful 14-day Antarctic flight in January 2012. The STO-2 mission will fly in December 2015. A follow-on, longer duration mission has been proposed called GUSTO.

The 4-pixel heterodyne receiver arrays on board STO possess the sensitivity and spectral resolution needed to see molecular clouds in the process of formation, measure the rate of evaporation of molecular clouds and separate the bulk motion of gas in our Galaxy from local kinematic effects. STO's 0.8m telescope provides \(\sim\)1 arc minute spatial resolution, providing more than two orders of magnitude improvement in spatial resolution over existing data. By building a three-dimensional picture of the interstellar medium of the Galaxy, STO is able to study the creation and disruption of star-forming clouds in the Galaxy, determine the parameters that govern the star formation rate, and provide a template for star formation and stellar/interstellar feedback in other galaxies.

The gondola structure carries and protects the telescope and instrument, the command and control systems, and the power system. Its basic dimensions (without solar arrays) are: 2m wide, 1.5m deep, and 4.5m high. The frame is made of standard aluminum angles bolted together and painted with a white thermal coating. The structure is strong enough to support up to 2000 kg even under the 10 g shock experienced at the end of the flight when the parachute inflates. It is rigid enough to allow the required telescope pointing stability. The gondola can be separated into lighter components for easy post-flight retrieval in the field.

STO had its first science flight in January 2012. CII, CO J=12-11, and CI observations began within 12 hours of reaching float altitude. Early observations were hindered by several technical issues that were resolved in flight. Once the liquid helium supply was exhausted (after \(\sim\)4 days), STO-1 continued observing using an uncooled 492 GHz CI receiver until the end of its 14-day mission. STO-2 will fly with an upgraded, robust cryogenic/receiver system that will allow it to fulfill its baseline mission objectives and continue THz observations until stratospheric conditions or recovery constraints require terminating the mission.
In its long duration flight, STO-2 will survey part of the Galactic plane in the C II line emission at 158 μm, the brightest spectral line in the Galaxy; and N II line emission at 205 μm, a tracer of the formation rate of massive stars. With ~1' angular resolution and <1 km/s velocity resolution, STO-2 will detect every interstellar cloud with AV ≥ 0.4 mag (hydrogen column density ≥ 4x10²⁰ cm⁻²) in the surveyed region, and, through excitation and kinematic diagnostics provided by C II and N II line emission, will study how atomic and molecular clouds are formed and dispersed. STO-2 will make 3-dimensional maps of the structure, dynamics, turbulence, energy balance, and pressure of the Milky Way’s Interstellar Medium (ISM), as well as the star formation rate.

STO-2 will help provide a comprehensive understanding of the inner workings of our Galaxy by exploring the connection between star formation and the life cycle of interstellar clouds. We will study the formation of molecular clouds, the feedback of high mass star formation heating and disrupting clouds, and the effect of these processes upon the global structure and evolution of the Galaxy. The detailed understanding of star formation and evolution of stars and gas in the Galaxy is directly relevant to star formation in other galaxies. The nature of the feedback mechanism of massive star formation is pivotal to the evolution of galaxies.

2.0 Instrument
STO (1&2) is configured to have a telescope, eight heterodyne receivers (four for each line to be observed), an eight-channel Fast Fourier Transform spectrometer system, control electronics, a hybrid He cryostat, and a gondola capable of pointing the telescope to better than 15 arcseconds.

The receivers are fed by the beam from the telescope which first encounters a free-standing wire grid. The grid divides the incident light into horizontal and vertical polarization components. One polarization passes through the grid into the first vacuum window while the other reflects off a 45º mirror and enters a second vacuum window. The vacuum windows and subsequent 77, 25, and 4K IR filters are made from low-loss, anti-reflection coated, single crystal quartz. The flight receiver consists of two, orthogonally polarized 1x4 arrays of superconductive hot-electron bolometer (HEB) mixers operating at < 6 Kelvin. One array optimized for the 1.9 THz line and the other for the 1.46 THz line. The mixers are pumped by two, frequency tunable solid-state local oscillators (LO’s).

![Figure 1. STO instrument block diagram](image)

A cross sectional view of the full science payload for STO-2 is shown in Figure 1. Several components of the STO instrument require operation at cryogenic temperatures. Hot electron bolometer (HEB) mixer arrays require operation at less than ~6 K. The downconverted signals from the mixers are amplified to power levels suitable for digitization. The first stage, low-noise amplifiers (LNAs) require operation at < 40 K.
3.0 Cryogenic system
To cool the mixer arrays, STO uses a 90 liter liquid helium cryostat that was originally built as a prototype space flight cryostat for small instruments. The cryostat was designed to operate in low gravity with liquid helium II, but those features are not used for STO, which uses normal liquid helium in one gravity and are not shown here.

The cryostat consists of six functional elements: cryogen tank subassembly, tank supports, insulation system, fluid management subassembly, outer shell, and instrumentation as shown in Figure 2.

![Figure 2. STO-2 cryostat major elements](image)

The cryogen tank consists of two 6061-T6 aluminum alloy ellipsoidal heads welded together at the girth and at the midpoint inside of the instrument cavity. The cryogen tank is supported from the girth ring by six bipod tension strap supports, three bipods are attached to the upper head and three are attached to the lower head. Each support is made of uniaxial filament wound gamma alumina bonded in an epoxy matrix to form a strap.

The insulation system consists of multilayer insulation (MLI) spaced by two vapor cooled shields supported through flexures by the support system. The flexure attachments are thermally efficient and provide for cooling the supports. Surrounding the tank under the inner vapor cooled shield is a layer of aluminum which reduces the effective emissivity of the tank and internal plumbing manifold. The
MLI is \( \frac{1}{4} \) mil mylar layers aluminized on each surface and spaced by dacron net. All penetrations are buffered to minimize radiation tunneling through the penetration. The insulation system is installed one layer at a time except for the upper dome insulation which is made in 5 layer quilts. This is done to ease access into the instrument area. There are 3 quilts between the inner vapor cooled shield (IVCS) and outer vapor cooled shield (OVCS) and 5 quilts between the OVCS and outer shell. The upper VCS domes are installed with screws for easy access to the instrument.

STO-2 will have these enhancements to the cryogenic system: a small, robust cryocooler will be added to extend the helium hold time to \(~60\) days and a new vacuum collar and lid will be machined to reduce the number of vacuum seals and simplify the optical alignment of the cryostat- afforded by the use of new, high-power local oscillators. Figure 2 shows a cutaway view of the STO-2 cryostat. The STO mixer arrays and associated optics are mounted on the lower insert stage which bolts to the top of the helium tank. The beamsplitter for LO diplexing is mounted on the upper stage of the insert just above the mixers (see Figure 1). The mixers dissipate approximately one milliwatt of heat and operate at \(< 4.5\) K. The IF output of each mixer is connected to an LNA via a short (\(~6\) cm) length of stainless-steel coax. The first stage of each LNA dissipates \(~2\) mW. The LNAs and IVCS operate at 16 and 30 K, respectively, and are cooled primarily by the helium tank vent gas. A low-loss, AR-coated silicon window passes the desired signals from the telescope through the vacuum shell. There is a THz low-pass filter in the signal path through the OVCS. The 1.46 and 1.9 THz LO signals enter the cryostat through a vacuum window in the side collar and pass through an IR blocking filter on the OVCS. A cryocooler will be mounted on the side collar to provide additional cooling of the OVCS and beamsplitter plate. The cryocooler chosen is the Sunpower Cryotel CT, a low cost, commercial, linear Stirling cycle cooler. This cryocooler has 5 watts of capacity at 65 K, which is a margin of 50%. With all instrumentation on, the cryostat thermal model predicts the dewar will have a hold-time of \(~60\) days. The STO-2 cryostat will undergo extensive thermal-vac testing before its hang-test. After the hang-test it will be packed in a padded, steel reinforced shipping container for the trip to Antarctica.

A steady state thermal model of the STO-2 cryogenic was created using the TAK 2000 software [4]. A thermal schematic of the STO-2 cryogenic system based on results of the model is shown in Figure 3. The schematic shows the effective use of vapor cooling and cooling from the cryocooler to minimize the heat reaching the helium tank, minimizing liquid helium boil off.

![Figure 3: STO thermal model; heat flows are in milliwatts](image)

**4.0 Cryogenic operations in Antarctica**

Following a successful I&T and Hang Test in Palestine (TX) in August 2011, the gondola was cleared for flight and shipped to McMurdo Station, Antarctica. The gondola, including the cryostat, were
prepared for launch in a hangar near the balloon launch runway. Before each launch attempt, the cryostat was topped off with liquid helium. The liquid helium is shipped by supply aircraft from New Zealand. After 8 unsuccessful launch attempts, mostly due to high wind, STO was finally launched on January 15, 2012. After launch, STO reached 40 km altitude in about 3 hours. For about 30 hours we took advantage of the high rate line-of-sight telemetry and commanding link to check-out all the subsystems and perform instrument commissioning. Following loss of LOS communications, contact with the payload was maintained through TDRSS relay radio link, and operations control was handed over to the Mission Operation Center at APL and the Science Operation Center at Oberlin College, where a staff of three people monitored the payload health and commanded changes in the science operations.

Approximately four days into the flight, temperatures within the focal plane unit began to rise slowly, indicating a premature loss of liquid within the dewar. A post flight investigation revealed the helium loss was due to the pressure relief valve on the helium vent line being frozen open during ascent. With the vent line open the pressure above the helium reservoir was at ambient, corresponding to ~3 millibar by the time float altitude was achieved. This low pressure resulted in ~50% of the liquid helium boiling off prematurely. On STO-2 we will use a simple heater (e.g. ~3 watt power resistor) to keep the pressure regulator assembly safely above freezing during ascent. Such heaters were used on other pieces of hardware flown on STO-1.

The circumpolar winds take the balloon and gondola in a counter clockwise direction around the Antarctic continent, making a complete circuit in approximately 14 days. At the end of the mission the gondola is released from the balloon and descends by parachute to a location favorable to recovery. Gondola recovery is accomplished by helicopter and/or airplane.

5.0 Conclusions
The STO-2 cryogenic system will effectively and efficiently support the operation of the STO instrument and mission. The use of a re-purposed liquid helium cryostat proved feasible and provides considerable cost savings to the STO program. By adding an off-the-shelf cryocooler the mission lifetime and science return is significantly increased.

Figure 4. The STO-1 gondola ready for its first flight from Antarctica in January 2012.
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