The Stratospheric Terahertz Observatory (STO)

An LDB Experiment to Investigate the Life Cycle of the Interstellar Medium

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***Abstract*— The Stratospheric Terahertz Observatory (STO) is a balloon-borne, 0.8-meter telescope designed to investigate the structure of the interstellar medium and the life cycle of interstellar clouds. In its first long duration flight, STO will use two, 4-beam HEB receiver arrays to survey part of the Galactic Plane in the [C II] line at 158 microns (the brightest spectral line in the Galaxy) and the [N II] line at 205 microns (a tracer of the star formation rate). At ~1' angular resolution and < 1 km/s velocity resolution, STO will detect every interstellar cloud with $A_V > 0.3$ in the surveyed region, and, through excitation and kinematic diagnostics provided by [C II] and [N II] line emission, will illustrate how atomic and molecular clouds are formed and dispersed in the Galaxy. STO 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. In future flights, STO will observe the important far-infrared lines of [O I], [N II], and HD.**

I. SCIENCE GOALS AND OBJECTIVES

STO will 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 from diffuse atomic gas, the feedback of high mass star formation on the lives of atomic and molecular 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 with its interstellar environment is pivotal to the evolution of galaxies.

In its first flight, STO addresses the following high priority goals:

1. Determine the life cycle of Galactic interstellar gas.
2. Study the creation and disruption of star-forming clouds in the Galaxy.
3. Determine the parameters that affect the star formation rate in a galaxy.
4. Provide templates for star formation and stellar/interstellar feedback in other galaxies.

STO will utilize two heterodyne receiver arrays to produce a total of eight ~1' pixels in the focal plane, each with 1024 spectral channels. In the first long duration (10-14 day) flight, STO will map a 35 square degree area ($-20^{\circ} > l > -55^{\circ}$; $|b| < 1^{\circ}$, see Figures 1 and 2) spanning the Molecular Ring, the Crux-Scutum-Centaurus spiral arm, and at least one interarm region. Two deeper, 1/2 square degree maps will be performed within the larger survey in both arm and interarm regions. STO has the sensitivity to detect and the ability to resolve spectrally and spatially all Giant Molecular Clouds (GMCs), all significant HII regions, and all cold neutral medium (CNM) atomic clouds with $A_V > 0.3$ mag in the surveyed region.

The STO heterodyne receivers provide sub-km/s velocity discrimination and sufficient bandwidth to detect and resolve line emission from every Galactic cloud in the surveyed region. The data product will be a high fidelity database of spatially and velocity resolved far-infrared [C II] 158 micron and [N II] 205 micron fine-structure line emission in the Galaxy.

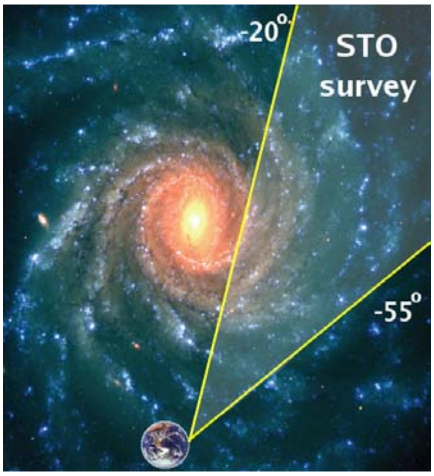

Fig. 1 STO will survey 35 square degrees of the plane of the Milky Way in the Terahertz fine structure lines of ionized carbon and nitrogen. This longitudinal swath of the fourth quadrant reveals major components of the Galactic Interstellar Medium, such as the molecular ring, the Scutum-Crux spiral arm, and two interarm regions.

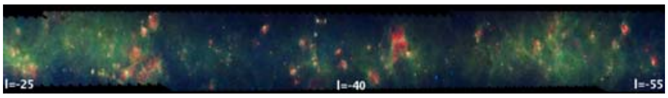

Fig. 2 This composite map of the Galactic plane from 3.5 through 24 microns, from Spitzer's MIPSGAL and GLIMPSE surveys, shows a rich and dynamic interstellar medium revealed by thermal dust emission. The STO survey will provide complementary high resolution spectroscopic followup that will put these structures in a 3-dimensional context and connect dust properties to the associated gas.

A combination of STO's data products with existing line and continuum surveys will characterize the structure and dynamics of interstellar clouds and their relation to star formation. STO's potential for additional flights provides the ability to more fully map the Galaxy in the [C II] and [N II] lines and to change receivers to include other important interstellar lines such as [N II] at 122 microns, [O I] 63 & 145 microns, and HD at 112 microns wavelength.

STO is timely. It will provide the best corresponding interstellar cloud survey to the GLIMPSE[1] and MIPSGAL[2] Spitzer programs (Figure 1) and contemporary HI and CO line surveys. STO will enhance the interpretation of these data sets by completing the observational links required to trace the cloud life cycle. In addition, STO complements other [C II] and [N II] observations taken on the Cosmic Background Explorer (COBE) and the Balloon-borne Infrared Carbon Explorer (BICE) in having much greater spatial and spectral resolution. Using Galactic rotation to place the clouds along the line of sight, STO's high spectral resolution enables 3 dimensional maps of Galactic interstellar matter, from which many physical parameters in the Galaxy (e.g., pressure and star formation rate) can be extracted.

STO also complements the capabilities of heterodyne receivers on contemporary far-IR platforms. The Herschel Space Observatory (Science phase: 2009-2013) and the Stratospheric Observatory for Infrared Astronomy (SOFIA, 2009+) will have the capability to observe both [C II] and [N II] using the same high spectral resolution heterodyne techniques used on STO. However, due to their much larger apertures each facility will map only a few percent of the area of STO's first survey during their lifetimes.

II. Instrument Description

The observational goal of the first STO flight is to make high spectral (< 1 km/s) and angular resolution (~1 arcminute) maps of the Galactic plane [N II] at 1.45 THz (205 micron) and [C II] at 1.9 THz (158 micron). To achieve the angular resolution requirement we have designed STO to utilize an aperture of 80 cm. To achieve the target spectral resolution, STO will utilize a heterodyne receiver system. STO will be a long duration, balloon-borne observatory which will be launched from McMurdo, Antarctica to an altitude of 120,000 ft, where it will remain for ~14 days. The instrument portion of STO consists of (1) the telescope (2) eight heterodyne receivers: four at the1.5 THz [N II] line and four at the 1.9 THz [C II] line, (3) an eight-channel FFT spectrometer system, (4) the instrument control electronics, (5) the hybrid ^{4}He cryostat, and (6) the gondola.

A. Telescope System

STO will use the same telescope and gondola that Johns Hopkins University Applied Physics Laboratory has previously employed for its successful Flare Genesis Experiment[3] (FGE) depicted in Figures 3 and 4. The primary mirror is an 80-cm diameter, f/1.5 hyperboloid made of Ultra Low Expansion titanium silicate glass (ULE), and honeycombed to a weight of just 50 kg. Its surface is polished to visible-band optical quality, therefore over-specified for imaging in the 100 to 200 micron wavelength range. Its support and spider arms are made of light weight graphite-epoxy, which provides high thermal stability over a wide range of temperatures. Figure 3 shows the FGE telescope during a Sun pointing test session.

A tertiary chopper will be located near the backside of the main mirror on a counterbalanced mount to minimize reaction forces. A calibration box will be located between the telescope and the receiver cryostat. This subsystem places blackbody loads at known temperatures in the path of the detectors. One of the loads is allowed to come into thermal equilibrium with the temperature of the surrounding air; its temperature is monitored and recorded by an embedded sensor. Another load is located on the 77K stage of the receiver cryostat. Periodic measurements of the power radiated from these loads allow determination of the detector gain. The power from these loads will also be compared to the variation in power resulting from a change in telescope elevation. These measurements suffice to determine the detector noise, the telescope efficiency, the opacity of the atmosphere and the absolute flux of astronomical sources[4].

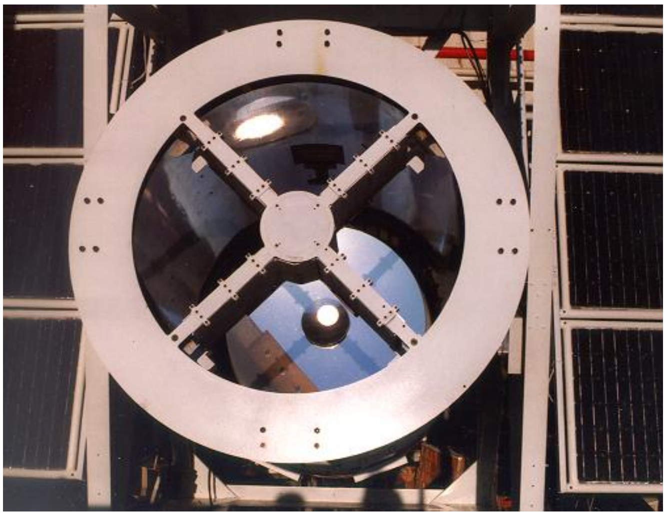

Fig. 3 The 80 cm telescope to be used for STO is the same as deployed for the Flare Genesis Experiment in 1995/6 and 1999/2000. Here, the FGE telescope is being tested, pointing at the Sun.

Characteristic	**Design Specification**
Telescope Aperture	80 cm
Telescope Type	on-axis Cassegrain
Spectral Range	60 to 210 microns
Pointing Knowledge	15 arcseconds
Target Frequencies	[C II] 1.901 THz [N II] 1.461 THz
Angular Resolution	1-1.5 arcminutes
Receiver Type	Two, 4-pixel HEB Mixer Arrays
Receiver Noise	< 2000 K DSB
Spectrometer Type	8 FFT digital analyzers
Spectral Bandwidth	1 GHz (~200 km/s)
Channel Resolution	1 MHz (~0.2 km/s)
Cryogenic System	^{4}He + 77K cryocooler
Cryostat Hold Time	> 14 days

TABLE 1: SUMMARY OF STO MISSION REQUIREMENTS

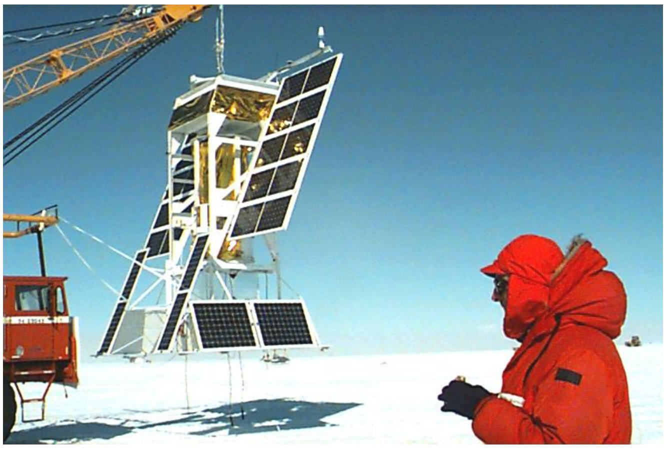

Fig. 4 The Flare Genesis Experiment (FGE) gondola and telescope just before its launch from Antarctica in 2000. The STO mission will use nearly the same flight configuration for its Antarctic flight in late 2010.

B. Receiver Description

A cut-away view of the STO cryostat showing the placement of the receiver system is shown in Figure 5. A block diagram of the instrument is shown in Figure 6 and a diagram showing integration with the telescope is shown in Figure 7.

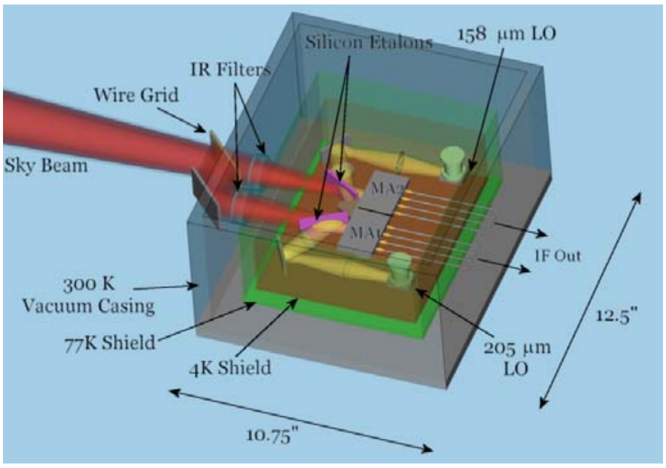

Fig. 5 Three-dimensional cutaway of the STO receiver cryostat.

The f/7 telescope beam first encounters a free-standing wire grid that divides the incident light into horizontal and vertical polarization components. One polarization passes through the grid into the first vacuum window. The other polarization reflects off a 45^o mirror and enters a second vacuum window. The vacuum windows and subsequent 77, 25, and 4K IR filters are made from low-loss, AR coated, single crystal quartz. The first flight receiver will consist of two, orthogonally polarized 1x4 arrays of superconductive hot-electron bolometer (HEB) mixers operating at 4K. One array is optimized for the [C II] (1.90 THz) line, the other for the [N II] (1.46 THz) line. The mixers will be pumped by two, frequency tunable, solid-state Local Oscillators (LO's). To increase output power, the final multiplier stage is mounted to the 77K radiation shield.

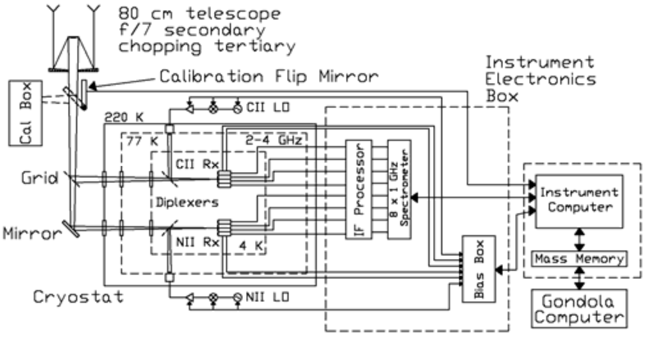

Fig. 6 Block diagram of STO instrument subsystems.

Eight, low-noise, IF amplifiers will be mounted to the 25K radiation shield of the cryostat. The IF center frequency will be 1.5 GHz, with an instantaneous bandwidth of 1 GHz. This IF frequency and bandwidth can be supported by NbN phonon-cooled mixers. At our highest observing frequency (1.9 THz, the [C II] line) a 1 GHz IF bandwidth will provide 160 km/s of velocity coverage. A velocity coverage of this order is needed to accommodate the wide velocity dispersion expected toward the inner parts of the Galaxy. Doppler tracking of the LO frequency will keep the received signal centered within the IF band. The eight IF signals from the mixers pass through an ambient temperature IF processor where they are further amplified and downconverted to baseband (0-1 GHz). STO will use eight 1 GHz wide, 1024 channel digital FFT analyzers as backend spectrometers for the mixer arrays. A flight instrument electronics box will house (1) the IF processor board, (2) the 8x1 GHz spectrometer boards, (2) the LO/HEB/LNA bias board, (4) calibration flip mirror controller board, and (5) the Instrument Computer. The Instrument Computer communicates to the Gondola computer via a RS-422 bus.

STO will use a 200 liter, ^{4}He cryostat to cool the mixer arrays. An off-the-shelf mechanical refrigerator will cool the first radiation shield to 77K. The second radiation shield will be vapor-cooled to 25K. The expected hold time is > 14 days.

C. STO Gondola Structure

The STO observing platform (gondola), shown in Figure 7 is the one previously used by APL for its FGE[3] (Figures 3 and 4) and SBI[5] balloon programs. The gondola has successfully endured two test flights in New Mexico (in 1994 and 2003) and three Antarctic flights (in 1996, 2000, and 2006). During the past ten years the gondola and its subsystems have undergone many improvements and upgrades. The STO project will benefit directly from this flight heritage.

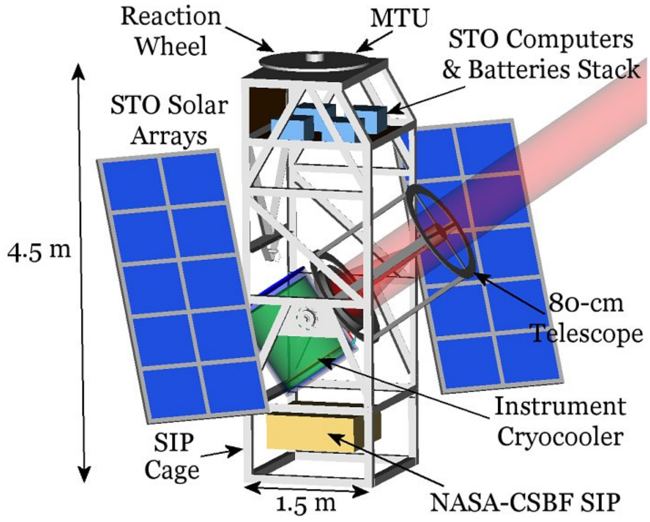

Fig. 7 Three-dimensional rendering of the STO gondola package, including 80 cm telescope and science payload.

The gondola 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 of <15". The gondola can be separated into lighter components for easy post-flight retrieval in the field.

D. Communications

Similar to the preceding FGE and SBI missions, STO will rely entirely on the NASA-CSBF provided remote link to/from the gondola for the communications between STO and the ground. The communications interfaces are shown schematically in Figure 8.

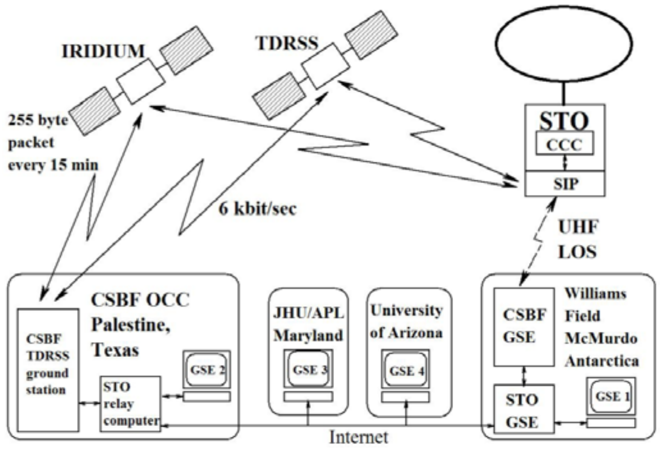

Fig. 8 Schematic of the communications systems between the STO gondola and the ground.

E. Schedule

The first test flight will take place from Ft. Sumner, New Mexico and is scheduled for September 2009. The test flight duration is < 24 hours. For this flight a two pixel system (one at 1.9 THz and the other at 1.45 THz) will be flown. The final instrument and gondola integration and test will take place at APL in the Spring of 2010. STO will be shipped to Palestine in July-August 2010 where APL will integrate the STO payload with CSBF's balloon control and communication equipment. STO will then be shipped to McMurdo in September 2010. The window for flight operations is December 2010 through January 2011. During its 14 day flight STO will circle Antarctica and (ideally) return safely to a recovery location near the launch site. Science data reduction and analysis will start immediately after conclusion of flight operations.

REFERENCES

[1] Benjamin, R.A., et al., 2003, "GLIMPSE. I. An SIRTF Legacy Project to Map the Inner Galaxy", *PASP*, 115, 953.

[2] Carey, S.J., et al., 2005, "MIPSGAL: A Survey of the Inner Galactic Plane at 24 and 70 microns, Survey Strategy and Early Results", *Bulletin of the American Astronomical Society*, 37, 1252.

[3] Bernasconi, P. N., Rust, D. M., Eaton, H. A. C., Murphy, G. A. A., 2000, ``A Balloon-Borne Telescope for high resolution solar imaging and polarimetry'', in *Airborne Telescope Systems*, Ed. by R. K. Melugin, and H. P. Roeser, SPIE proceedings, 4014, 214.

[4] Ulich, B.L., & Haas, R.W., 1976, "Absolute calibration of millimeter-wavelength spectral lines", *ApJ Supplement*, 30, 247

[5] Bernasconi, P. N., Eaton, E. A. C., Foukal, P., Rust, D. M., 2004, ``The Solar Bolometric Imager'', *Adv. Space. Res.*, 33, 1746.