The Stratospheric Terahertz Observatory (STO)
Annual Report: Year 2

Program: APRA-2007
Grant Number:
Title: The Stratospheric Terahertz Observatory
PI: Christopher K. Walker
Co-PI: Craig Kulesa
Organization: University of Arizona, 933 N. Cherry Ave, Tucson AZ 85721
Contact: cwalker@as.arizona.edu
ph. 520-621-8783, cell: 520-331-2442

1. Introduction

This is the Second Annual Report from the University of Arizona (UAz) for the Stratospheric Terahertz Observatory (STO). STO is a Long Duration Balloon (LDB) experiment designed to address a key problem in modern astrophysics: understanding the Life Cycle of the Interstellar Medium (ISM). During its upcoming science flight STO will survey a section of the Galactic plane in the dominant interstellar cooling line [C II] (158 μm) and the important star formation tracer [N II] (205 μm) at 1 arcminute angular resolution, sufficient to spatially resolve atomic, ionic and molecular clouds at 10 kpc. The goals for the survey are to:

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 the galaxy.
4) Provide templates for star formation and stellar/interstellar feedback in other galaxies

On Oct. 15, 2009 STO had its test flight from Ft. Sumner, NM. During its 12 hours at float altitude (~126,000 ft.) key components of STO were tested to help ensure the system would meet the objectives of the upcoming science flight. STO consists of 3 major components; a gondola, an 80 cm telescope, and a THz heterodyne receiver system. The gondola and telescope have been refurbished from the successful Flare Genesis Experiment. The gondola was upgraded by APL to use 3 gyroscopes for inertial guidance and an optical tracker for absolute pointing. The telescope was light-weighted and its primary and secondary mirrors re-aluminized. A cryogenic and room temperature receiver system were constructed and flown on the test flight. A computer-controlled, sliding weight was added to dynamically compensate for cryogen evaporation during flight.

The primary results from the test flight were:
1) The gyros performed well, allowing the telescope/gondola to track at the 5 arcsecond level (rms) after settling from a slew or a momentum transfer.
2) With appropriate baffling, the star tracker provides absolute pointing knowledge that meets mission requirements.
3) The sliding weight successfully controlled the telescope CG during all phases of flight.

4) The room temperature receiver, instrument control electronics, IF processor, and spectrometer performed well throughout the flight.
5) Problems with the test flight dewar prevented optical alignment of the cryogenic receivers before flight, however the dewar itself and the associated venting system performed well at altitude.
6) Control of the telescope, gondola, and instrument was maintained throughout the flight.
7) As an end-to-end test of the system, a ^{13}CO J=3-2 spectrum of the Orion molecular cloud was obtained by STO at float altitude.

These points are discussed further in Section 2.

The goal of the upcoming year is to have a successful science flight in Antarctica. To achieve this goal we will build upon the test flight experience; making necessary repairs and upgrades to the telescope/gondola systems and push toward the completion of the science flight instrument package. In parallel the Science Team is preparing a detailed observing plan for STO, with the planned publication of 12 papers within a year after the flight. All STO data will be calibrated and placed on a web site in a timely manner where it can be accessed by the astronomical community. Details concerning the telescope and gondola test flight performance and planned upgrades are discussed in the APL annual report. Here we will provide a more complete description of the test flight instrument package/results and the status/plans for the science flight, focusing on the UAz's role in the project.

The UAz's role includes: 1) Initiating and coordinating Science and Instrument team discussions. 2) Working with teams to develop a detailed list of instrument requirements to achieve proposed science goals. 3) Developing a technical concept for STO with team members that meets mission requirements while working within the gondola/ telescope operating environment. 4) Assigning detailed design and fabrication tasks to team members based upon their skill, interest, and institutional resources. 5) Taking the lead on the design and fabrication of the science flight instrument package. 6) Developing an observing strategy for conducting the STO Galactic plane survey.

2. Test Flight Instrument Description

2.1 Instrument Development and Integration

The STO flight from New Mexico was designed to provide a complete and faithful test of the full Antarctic gondola, telescope, and science instrumentation. Antarctic-ready versions of the telescope/gondola systems, instrument electronics, computing, control, and data storage systems would be flown. To faithfully characterize the performance of the telescope drives and pointing system, the test flight instrument was designed with the same CG and weight as the full Antarctica flight instrument. The STO test flight would carry three astronomical detectors, one cooled receiver for each STO THz frequency band, and a third un-cooled receiver for pointing on the submillimeter ^{13}CO line. This represents a subset of the 8 cryogenic and 1 ambient temperature detectors that would be slated for Antarctica. For a short flight, a simple, small liquid dewar met the cooling requirements. JPL provided an existing, Infrared Laboratories dewar for this purpose. The dewar required extensive modification to operate at float altitude.

Figure 1 shows the STO telescope and instrument package as it was configured for the test flight, Figure 2 shows the implementation of the instrument package itself, Figure 3 shows the design and implementation of the instrument optical systems, and Figure 4 depicts the subsystem contents in a block diagram.

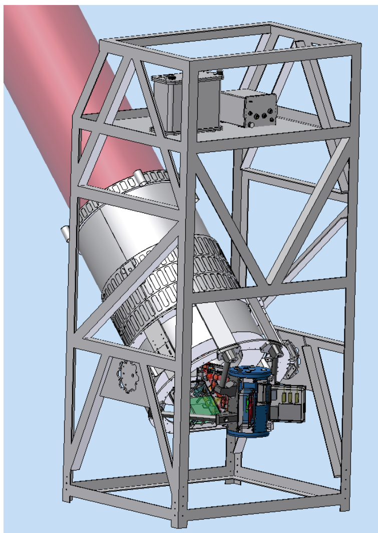
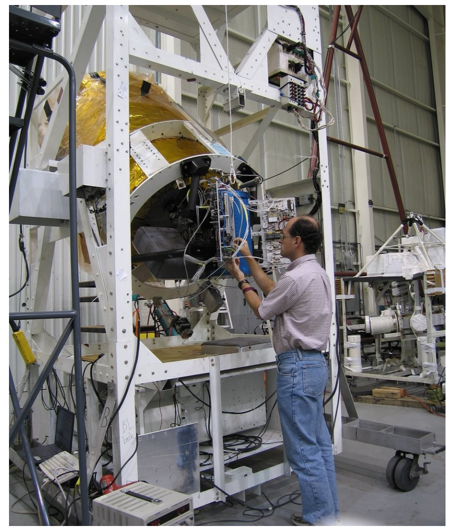


Figure 1: STO test-flight telescope and instrument package configuration, as conceptualized (left) and being integrated at Fort Sumner in early October, 2009 (right).



The instrument flight system as deployed contained the following subsystems:

- an *optics box* containing one frequency-selective surface to isolate the 330 GHz light, a wire grid to polarization-split the 1.4 and 1.9 THz beams, two Martin-Pulplett interferometers (MPIs) to diplex the LO beams with the THz sky beam, and calibration load actuators.
- an *electronics box* containing the instrument control computer, bias electronics for the Schottky and HEB receivers, housekeeping temperature monitors, analog multiplexers, and solid state relays for calibration actuators.
- an *RF box* containing the LO drive synthesizers, amplifiers for the HEB mixer IFs and a downconverter and amplifier IF chain for the Schottky mixer receiver.
- a 330 GHz *Schottky mixer receiver* from JPL, kept at ambient temperature and pressure.
- the 4K *dewar*, containing two Hot Electron Bolometer (HEB) mixers and bias tees from the University of Cologne, and two SiGe discrete LNAs from Sandy Weinreb at Caltech/JPL. The nitrogen and helium cryogenic vessels were pressure-regulated to approximately sea level pressure, to maintain a helium bath temperature of 4.2K.
- A *pressure vessel* containing the FFT spectrometer, data control computer, and Cisco router to isolate the instrument network traffic from the gondola. Figure 5 shows the pressure vessel contents just before they were sealed and installed onto the gondola mezzanine level.

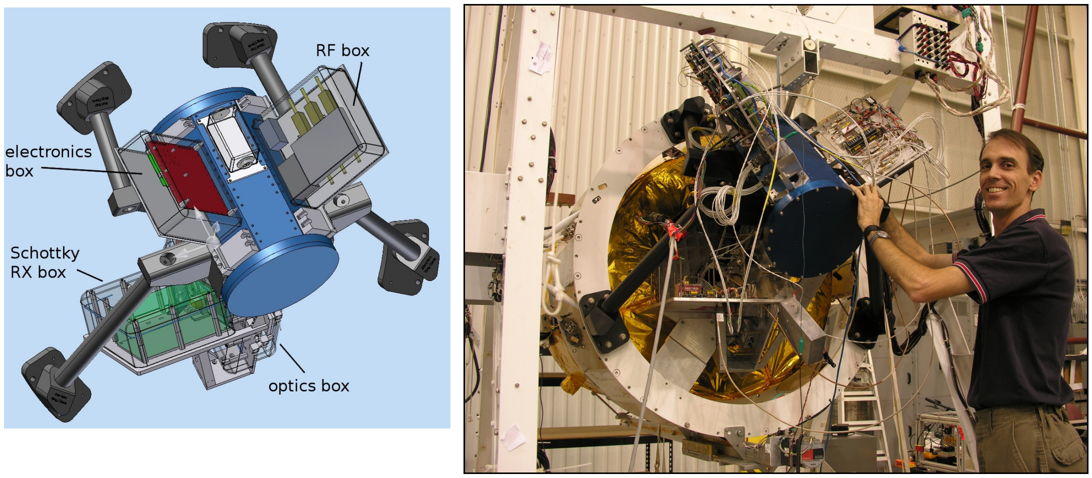


Figure 2: STO test flight instrument package, as conceptualized (left) and being integrated at Fort Sumner in early October, 2009.

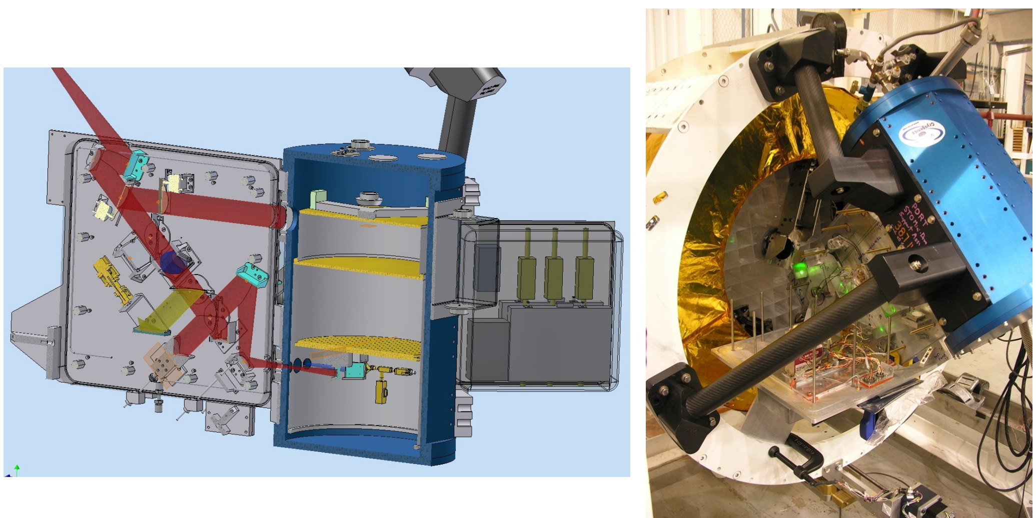


Figure 3: (Left) Signal path from telescope focus through optics box for the 330 GHz and 1.45 THz receiver. The optics for the 1.9 THz receiver are located on the other side of the optics plate. (Right) Laser alignment of the deployed optics box and receiver system on the telescope in Fort Sumner.

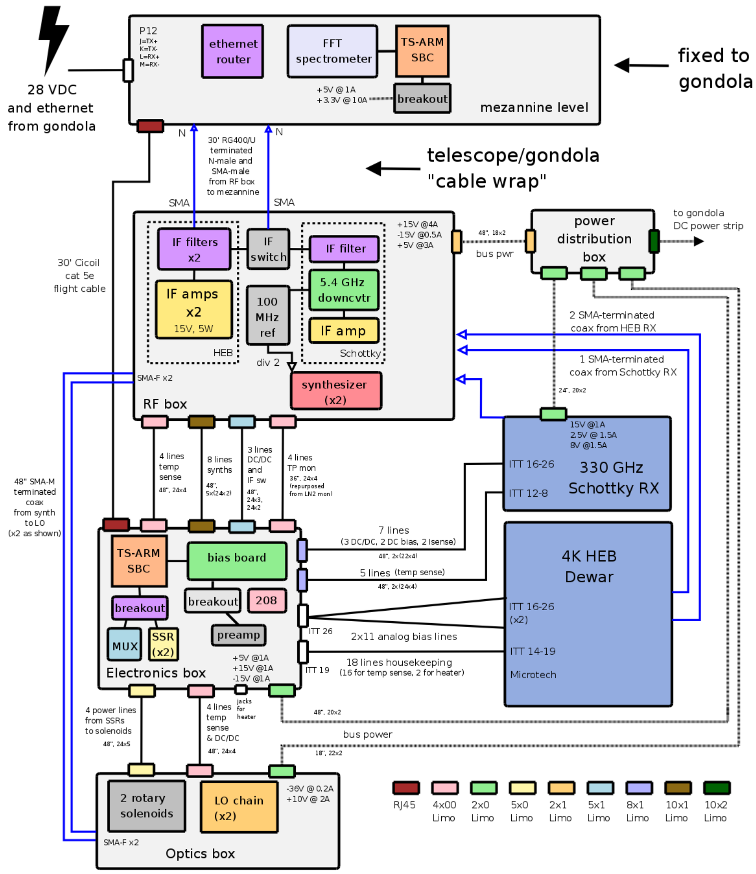
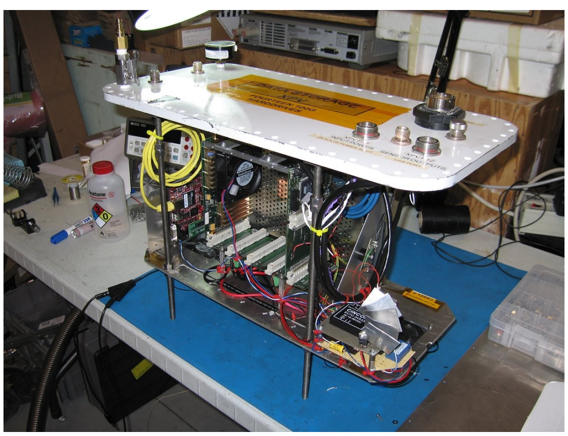


Figure 4: Detailed block diagram of the instrument control electronics and their location on the gondola.



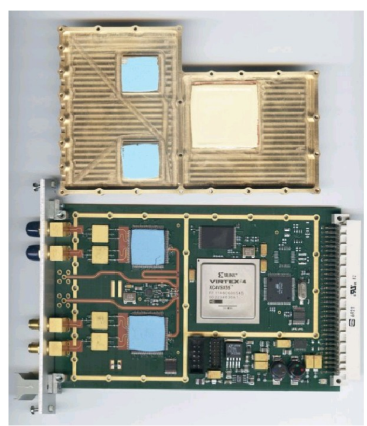


Figure 5: The pressure vessel used on the STO test flight (left), containing the data acquisition and control computer, solid state storage, network router and FFT spectrometer. For the test flight, only a single FFT card (right) was needed. The remaining 3 spectrometer slots will be utilized during the upcoming Antarctic science flight.

End-to-end testing of the complete system was performed on the ground using the ambient temperature Schottky receiver system, observing a 330 GHz test tone emitted by an outdoor transmitter through the telescope and instrument optics, IF downconverters and amplifiers, and measured using the pressure vessel's FFT spectrometer, all orchestrated by the data acquisition and instrument control computers (Figure 6).

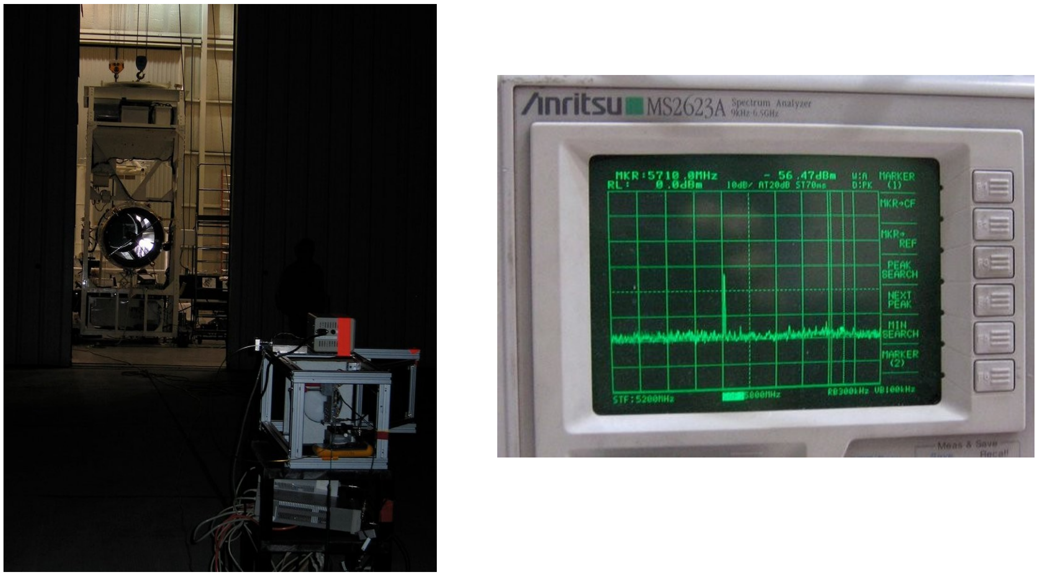


Figure 6: (Left) End-to-end testing of the entire STO instrument using the ambient temperature Schottky receiver and a 330 GHz test transmitter placed ~50m away from the telescope. (Right) Spectrum analyzer view of the Schottky receiver IF, showing the test transmitter tone passing through all telescope and instrument optics and correctly downconverted and amplified by the IF processor. This test represented the final “go” for launch.

2.1 Test Flight Results

STO was uneventfully launched at 10:03 AM MDT on 15 October, 2009 from the NASA facility at Fort Sumner, New Mexico under excellent launch conditions (Figure 7).

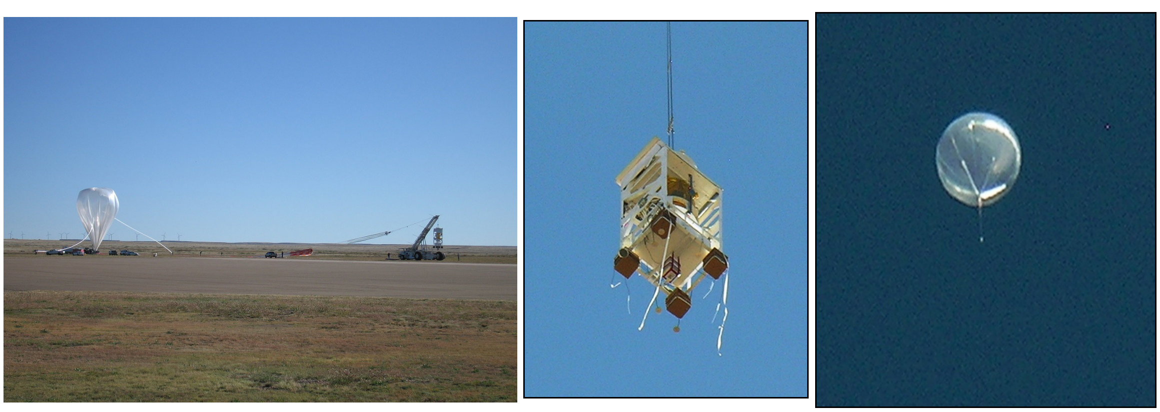


Figure 7: (Left) Balloon inflation is nearly complete at 9:50 AM on 15 October. (Center) STO launches at 10:03 AM, and reaches float altitude two hours later, hanging overhead (Right) for nearly the entire flight, and landing < 100 miles away at 1:15 AM on 16 October.

After reaching float altitude (126 kft) the telescope was successfully unstowed and gondola and telescope operations began. While gondola operations are discussed thoroughly in the (separate) JHU/APL annual report, two results are particularly noteworthy for science operations and deserve recognition here. First, the three-axis gyroscopes newly implemented on this flight as rate sensors for pointing and tracking were extremely effective. As shown in Figure 8, the root-mean-square pointing errors were typically well less than 10 arcseconds in undisturbed flight (i.e. tracking only, no sudden momentum dumps). For significant periods of time, rms tracking errors were under 5 arcseconds. While undamped pendulation prevented the use of the gyros for an initial gross azimuth fix, future flights will implement sun sensors or magnetometers to fulfill this need. Secondly, the star tracker used for initial pointing fixes suffered from excessive scattered light, precluding its effective use during daylight hours. After sunset, the star tracker correctly and autonomously provided good star fixes and pointing solutions, with repeatability good to less than 10 arcseconds.

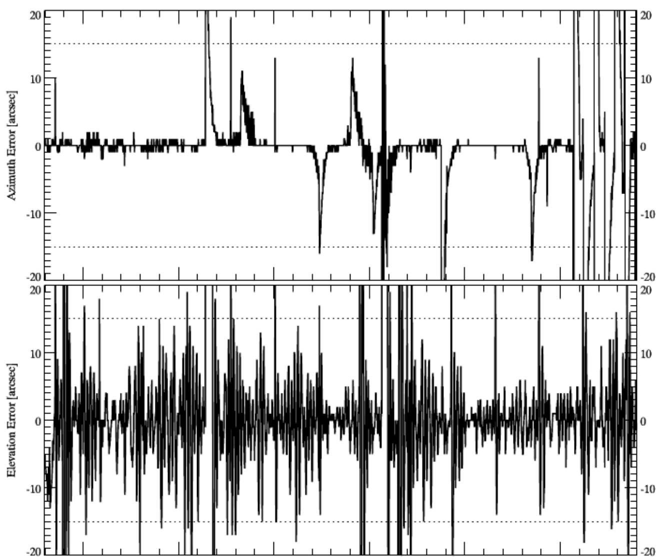


Figure 8: (top) Azimuth and (bottom) elevation tracking errors as a function of time during a 30 minute period near the end of the STO test flight. Added in quadrature, the tracking errors during observations were always below the required 15 arcseconds except during slews and momentum transfers, frequently accurate to better than 5 arcseconds.

The STO instrument performed well throughout the flight, with positive control maintained without interruption from launch to cut-down. The STO computer control system, IF processor, and FFT spectrometer operated through temperatures as high as +45ºC when exposed to the Sun during the day, and -45ºC exposed to the cold sky at night. All of the instrument electronics were able to survive the temperature extremes and the near-vacuum environment. While the cryogenic receiver was flown cold, insufficient time was available to properly align the receiver optics and thus only the ambient temperature Schottky receiver was operated in data-taking mode. Data operations in flight were hampered by a minimal gondola-to-instrument software interface which will be augmented in 2010 to allow all instrument functions to be controlled from the gondola control system. Nevertheless, Figure 9 shows a ^{13}CO J=3-2 spectrum taken toward the Orion molecular cloud by STO from float altitude, demonstrating that the optics, detectors, IF processing, spectrometer and data system functionality were operational, if not optimized, during the flight.

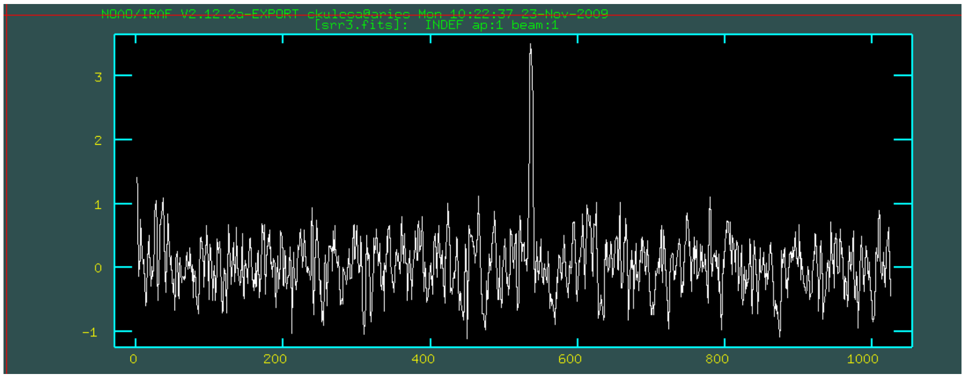


Figure 9: STO first-light spectral observation of the ^{13}CO J=3-2 line toward Orion taken from float altitude.

3.0 Plans for 2010

3.1 Science Flight Instrument Description

A 3-D model of the planned science flight instrument configuration is shown in Figure 6. To achieve the goals of the science flight STO will fly 2x2 pixel arrays of heterodyne receivers operating at 1.9 THz and 1.46 THz, the frequencies of the [CII] and [NII] lines respectively. Niobium superconducting hot electron mixers (similar to those used on *Herschel* – HiFi) provide state-of-the-art noise performance at THz frequencies. These mixers operate just below the transition temperature of niobium at 9K. Therefore, a key component of STO is a cryogenic system to maintain the mixers at this operating temperature for the duration of the flight. For the 2010 science flight, a liquid helium dewar will be used for this purpose. Figure 10a illustrates how the dewar will be mounted to the telescope.

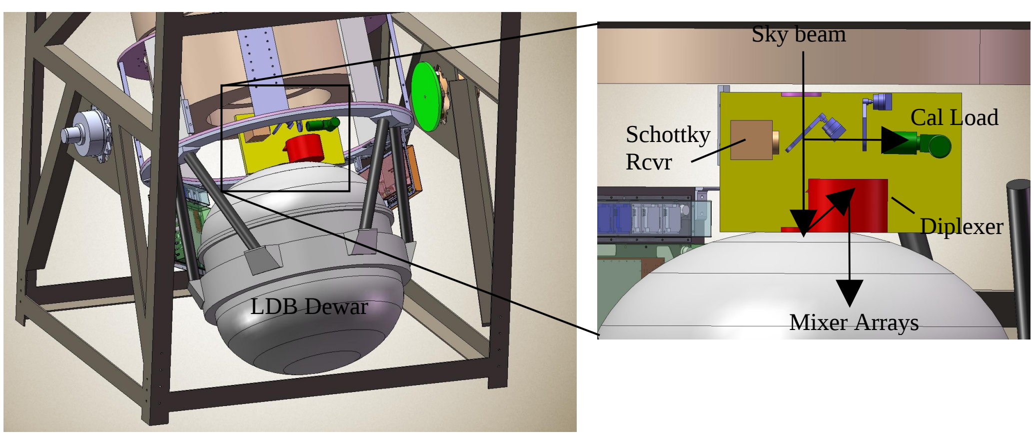


Figure 10: LDB dewar mounted to STO telescope. a) Dewar and optics box attached to telescope ring. b) Close-up of optics box containing relay optics, 330 GHz Schottky receiver, flip mirrors, calibration load, and Fabry-Perot ring diplexer.

Between the telescope and the dewar is an optics box (see Figure 10b) containing flip mirrors for directing the *f*/12 telescope beam to either a room temperature Schottky receiver, calibration loads, or a Fabry-Perot ring diplexer designed to efficiently inject the local oscillator (LO) beams into the telescope beam (Figure 11). The LO beams originate from two solid-state sources (not-shown; one at 1.9 and the other at 1.46 THz) whose output are divided into 4 equal power beams by a Fourier grating. From the diplexer, the combined telescope+LO beams enter the dewar through a 130 mm diameter window and continue to a wire grid located on the 4K cold plate. The grid splits the beams into horizontal and vertical polarizations. The horizontal polarized components proceed to the 1.9 THz mixer array and the vertical components to the 1.46 THz mixer array. Off-axis mirrors convert the f# of the telescope beam to match that expected by each mixer's feedhorn. As shown in the figure, each 2x2 mixer array is formed by bolting individual mixers to a common ring.

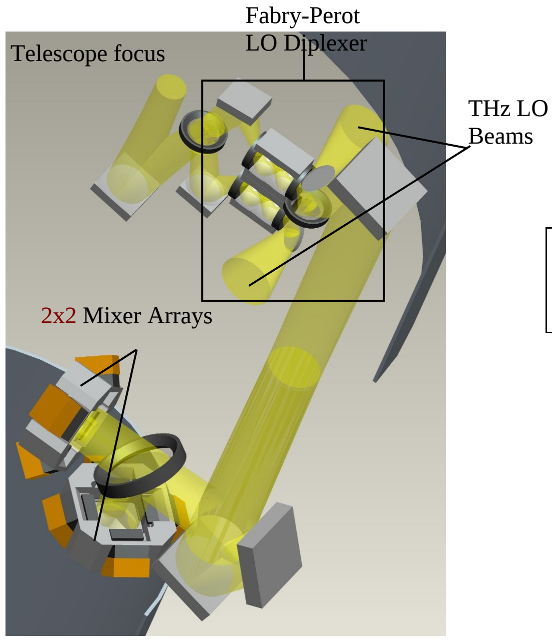


Figure 11: Optical assembly of Fabry-Perot diplexer (ambient temperature) and mixer arrays (at 4K).

The hot electron bolometer (HEB) mixers for the [CII] arrays are being provided by JPL and the HEB mixers for the [NII] arrays by the University of Cologne. Waveguide technology is being used by both groups to meet the instrument noise and optical coupling requirements. A plot showing the characteristic performance of the mixers is shown in Figure 12.

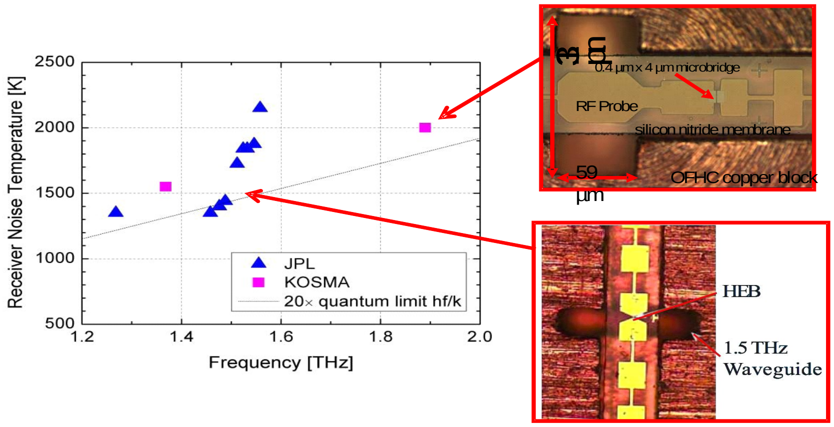


Figure 12: Performance and waveguide structures of JPL and Cologne mixers for STO

Each HEB device is DC biased to operate at the transition point between a normal conductor and a superconductor. The impending local oscillator signal acts to switch the HEB between the two states. In the process the telescope signal is also switched, with serves to multiply the telescope and LO signals together. The product of this multiplication contains both sum and difference frequencies between the two. The signal at the difference frequency is referred is the intermediate frequency (IF) signal. The IF signal for STO has a bandwidth of 1 GHz and is centered at 1.5 GHz, appropriate for low noise operation of our HEBs. The IF output of each mixer is conveyed through coaxial cable to low-noise, low-power amplifiers operating at a physical temperature of ~40K. These amplifiers (see Figure 13) were designed and fabricated by Co-I Weinreb at Caltech specifically for STO.

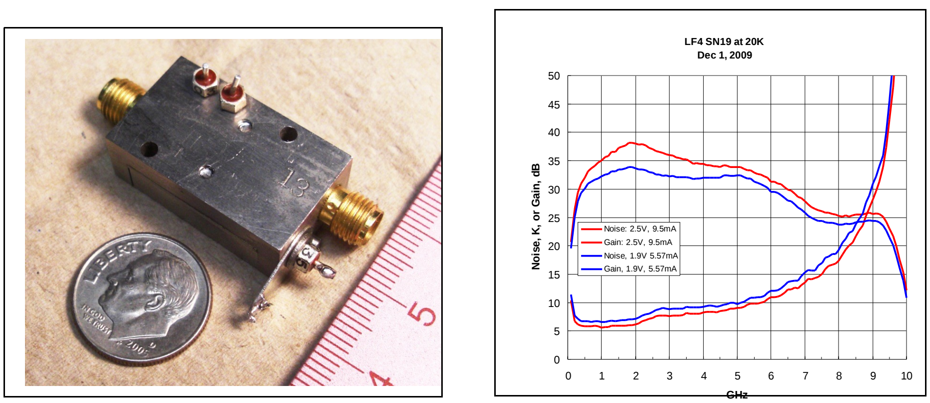


Figure 13: STO IF amplifiers (left). Performance curves (right).

After being amplified ~30 dB, the IF signals are brought out of the dewar via coaxial cable to the IF Processor bolted on the frame of the telescope (see Figure 14). The IF Processor Box further amplifies the signal from each HEB mixer and provides a DC signal proportional to each pixel's total power. An Electronics Box, also bolted to the telescope frame, contains a bias card and computer for the receiver frontend. From the IF processor eight coaxial cables (one for each focal plane mixer) carry the downconverted telescope signals up to the pressurized vessel containing the spectrometer (see Figure 5) located at the mezzanine level of the gondola. The pressure vessel contains a single board computer and 4 FPGA cards that digitize and perform FFTs on each 1 GHz wide, input signal. The resulting power spectra are stored in non-volatile flash memory and made available to the gondola computer via ethernet. The IF Processor, Electronics Box, and Spectrometer Box for the science flight are only slightly modified versions of what flew on the test flight.

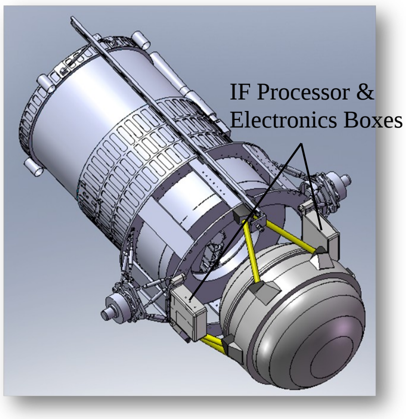


Figure 14: Location of IF Processor and Electronics Boxes on telescope assembly.

3.2 Dewar Options

EXPORT OR RE-EXPORT OF INFORMATION CONTAINED HEREIN MAY BE SUBJECT TO RESTRICTIONS AND REQUIREMENTS OF U.S. EXPORT LAWS AND REGULATIONS, AND MAY REQUIRE ADVANCE AUTHORIZATION FROM THE U.S. GOVERNMENT.

3.2.1 Option A: Ball Aerospace LLC Dewar

The University of Arizona and Ball Aerospace Corporation propose to increase the science return from each STO flight by using an existing Ball high performance, space flight based dewar, referred to as the Lightweight, Low Cost (or LLC) Dewar. This dewar (see Figures 15 and 16) was designed, fabricated, assembled, and tested on Ball funds using state-of-the-art space cryogenic systems technology. The LLC dewar was a prototype for the *Spitzer/SIRTF* dewar that has since been operating for over 5 years (exceeded 2 year design and 5 year goal) in space. By incorporating the LLC dewar into STO, the mission duration will be increased by a factor of 2 to 3. With the future addition of a moderate temperature (20-35 K) cryogenic refrigerator, the LLC would also provide the capability to increase STO mission life to over 200 days.

This immediate and potential future increase in mission life is the result of the lab tested, high cryogenic performance of the LLC dewar. As shown in the cutaway in Figure 2, the LLC dewar features include:

1. 95 liter, toroidal liquid helium, cryogenic tank
2. 8 inch diameter by 17.5 inch long instrument cavity at the center of the tank

3. Two vapor cooled shields that intercept heat leak into the cryogenic tank
4. Isogrid vacuum shell dome for mass reduction
5. Low thermal conductance ribbon cables
6. Twelve low thermal conductance gamma alumina support straps
7. High performance, space cryogenic grade multi-layer insulation (MLI)
8. Imbedded cooling lines for potential attachment of cryocooler circulation system for 200+ day lifetime

The LLC will extend the STO flight cryogenic lifetime from the previous target of 14 days to between 34 (with 50% margin) and 52 (no margin) days, **making it the first cryogenic ULDB mission.** The LLC performance has already been measured and correlated in test. The LLC has also passed qualification level structural; and vibration testing that encompasses the STO Balloon environment. The LLC dewar represents several million dollars of Ball investment. Ball's commitment to the STO project is shown by Ball's willingness to donate the LLC hardware to the mission. Funds are being requested only for Ball personnel to modify the dewar for use on STO (see attached quote).

Modifications to the LLC for the STO mission are relatively low risk. These consist of adding vacuum and radiation shield windows, running coaxial cables, integrating the HEB mixer arrays, and adding a constant pressure control valve on the vent line. The 52 day hold time is based on a combination of empirical measurements of the dewar performance coupled with a complete thermal model of the full STO instrument package; includes thermal loading from the windows, mixers, IF amplifiers, 50 wires, and 8 coaxial cables. The size and mass of the LLC is an excellent match to the physical constraints imposed by the STO telescope, gondola, and instrument. Indeed, the 3D model of the LLC is pictured in Figures 10 and 14.

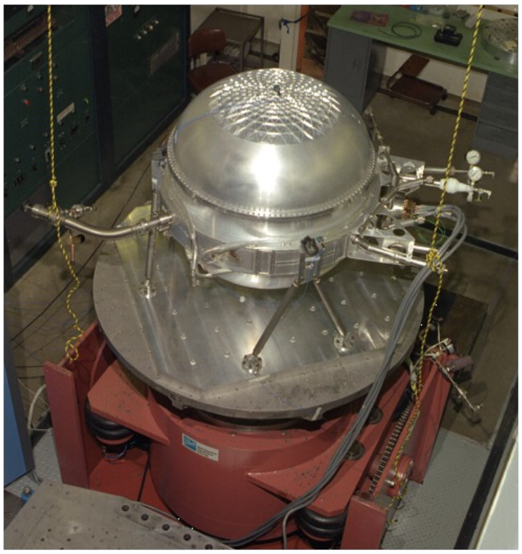


Figure 15: Lightweight Low Cost Dewar during Vibration Testing at Ball.

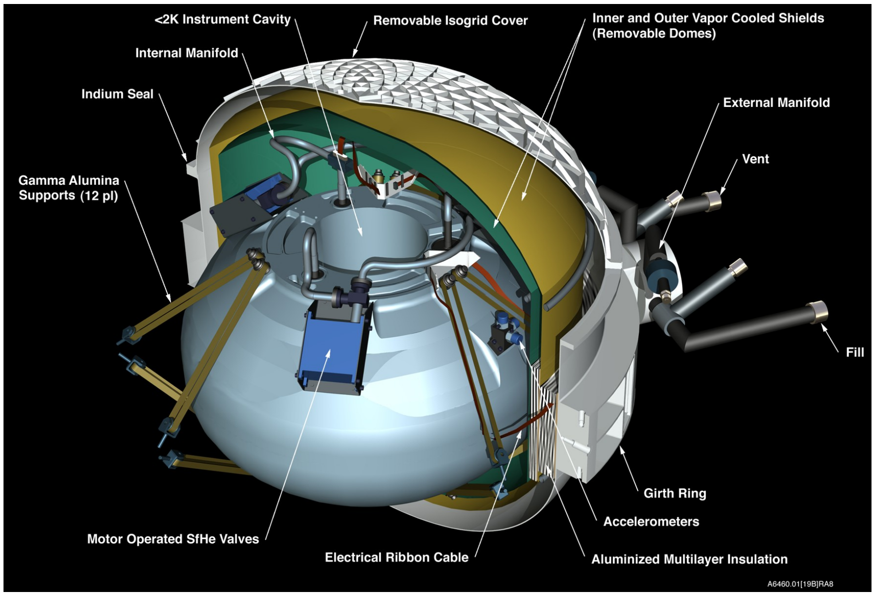


Figure 16: Lightweight Low Cost Dewar Major Elements

3.2.2 Option B: Custom Built Dewar

The alternative approach to using the Ball LLC dewar is to construct one from scratch. Using standard, non-space-rated, design/fabrication techniques, we estimate a 200 liter liquid helium dewar could be built for STO that has a design hold time of ~20 days. A 3D CAD model of the custom dewar attached to the telescope is shown in Figure 17. Compared to the LLC, this custom built dewar has less than **half** the hold time, even though it uses **twice** as much helium. The 20 day hold time estimate is also purely theoretical, while the LLC hold time estimate is based on experimental data from an existing dewar. Also, building a dewar from scratch adds schedule risk, since new deliverables can be subject to completion delays. Pushing the project into a 5th year would result in increased program costs. Clearly, leveraging the extensive investment in time and money Ball has made in the development of the LLC is the preferred option.

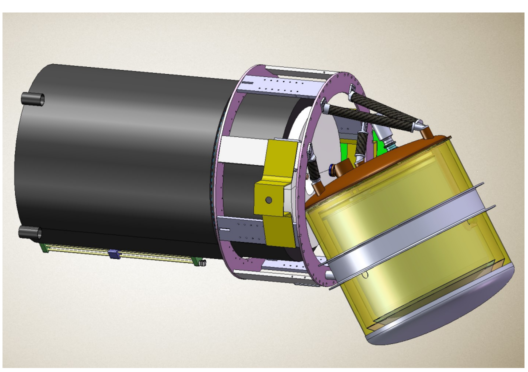


Figure 17: Custom Dewar mounted to telescope assembly.

4. New Science Flight Capabilities with an Extended Mission

With the possibility of flying more than one circular orbit around Antarctica using the Ball dewar, the original STO science mission is made **more robust** against variations in the delivered instrument sensitivity/stability and **new science capabilities** are enabled that dramatically increase the impact of each single STO flight. Three such capabilities are depicted below: the ability to measure the $^{13}C^+$ ion in combination with $^{12}C^+$, and extended mapping of new regions such as the eta Carina molecular cloud complex, and natal ionized and neutral clouds located well above the plane of the Galaxy.

4.1 Mapping Observations of the Carina Nebula

An extended duration flight enables us to pursue new and important science objectives. Amongst these are detailed maps of resolved Galactic star formation regions with known geometry. A primary source is the Carina molecular cloud complex, a series of star-forming molecular clouds that lie at a distance of about 2 kpc along the Carina spiral arm of the Galaxy. The optical Carina Nebula and molecular cloud complex subtend several square degrees on the sky. At its core are the bright HII regions Carina I and Carina II, illuminated respectively by the Trumpler 14 and Trumpler 16 star clusters. These two clusters contain 36 O stars, including 6 of the 17 known O3 stars in the Galaxy, 3 WN-A stars, and the enigmatic, luminous blue variable star eta Carinae.. The extra-ordinary concentration of O stars is unique within the Galaxy and rivals the 30 Doradus region of the Large Magellanic Cloud in total luminosity.

Carina is unique, bright, and well placed for Antarctic studies so that our STO [NII]/[CII] observations will be well supported by prior studies. Much of the Carina molecular cloud was mapped in the CO rotational lines (J= 4-3 and J=2-1) and the 370 mm [CI] fine structure line with the AST/RO telescope (e.g. Zhang et al. 2001), in CO(1-0) with Columbia CO survey of the southern Milky Way (Grabelsky et al. 1988), and the radio and far-IR continuum. In addition there are ***sparse intensity*** maps of the [NII] 122 μm, [OI], [CII], [NIII], and [OIII] fine structure lines obtained with ISO (70" beam) and a fully sampled (54" beam) map of the [NII] 205 μm line obtained with SPIFI on AST/RO of the Carina I and II HII regions. This broad array of ancillary observations makes Carina an excellent laboratory in which to study the structure of molecular clouds, PDRs and ionized gas in the presence of young stars. We plan to map the entire molecular cloud in the [NII] 205 μm and [CII] lines with STO providing for the first time fully resolved spectra from which gas dynamics and the interplay between the various components of the ISM can be deduced. To match a 3 deg^2 region, mapped on a 1' grid as with the AST/RO CO and [CI] observations will take 3-5 days of integration time with STO.

4.2 Extended b-strips to high Galactic latitude

The fundamental goal for the STO experiment is to characterize the physical conditions of the various phases of the ISM through deep velocity resolved spectroscopy of the 158 μm [CII] and 205 μm [NII] fine structure lines. These lines are especially important as the [CII] line cools PDRs on the surfaces of molecular clouds, the cold neutral medium, the warm neutral medium ***and*** the diffuse ionized gas. The [NII] line is an important coolant for the diffuse ionized gas, can serve as a proxy for the numbers of Lyman continuum photons in an ionization bounded HII region, and, since it has the same critical density for thermalization as [CII] in ionized gas regions, it is an excellent probe of the fraction of the observed [CII] line emission that arises from the diffuse ionized medium. In other words, the measure of the 205 μm [NII] line yields the fractions of the observed [CII] line that arise from either the ionized, or the neutral ISM. This is an important measurement since in general the [CII] line dominates the cooling of PDRs, the CNM and the WNM in galaxies, but up until now, it has been difficult to deduce the fraction of the [CII] line emission that arises from the ionized gas. Estimates range from 10% to more than 50%!

Using the Ball dewar we will be able to extend the latitude coverage and depth of the "b-strips" obtained in our survey to ensure that we cover and detect, the [NII] and [CII] line emission in regions far removed from the molecular disk. The molecular disk will emit strongly in [CII] and [NII] from PDRs/HII regions associated with the molecular clouds, but is narrowly confined to the plane with scale-heights ~ 80 pc. By extending our b-strips to regions 2 to 4° above and below the plane, we ensure that we are out of the molecular disk, and are looking through the diffuse ionized gas regions. In these regions, we expect both lines to be dominated by emission from the diffuse ionized gas (although there may be some [CII] from atomic gas regions, which we can account for with existing HI 21 cm line maps) making it much easier to characterize the diffuse ionized gas and to deduce the fraction of the observed [CII] line that arises from such gas on Galactic scales. The best region in which to perform this experiment is at the tangent points of the molecular ring where the distance ambiguity vanishes. At this distance (~ 6 kpc) 100 pc subtends 1° so that a 4° excursion above and below the plane will be devoid of [CII] emission from molecular clouds. These extensions and deeper integrations will require 4-6 days of additional integration time.

4.3 Measurement of $^{13}C^+$

During an extended duration flight, we will also conduct deep pointed observations of bright PDRs, for the purpose of measuring and mapping the [^{13}CII] line. In the $^{13}C^+$ isotope, the $^2P_{3/2}$–$^2P_{1/2}$ fine structure transition is split into three components by the hyperfine interaction; these lie at velocity shifts of –65, +11, and +63 km s^{-1} relative to the [^{12}CII] line. Laboratory measurements have determined the exact frequencies with the accuracy required for astrophysical purposes (Cooksy, Blake & Saykally 1985, ApJ, 305, L89). To date, observations [^{13}CII] have been limited to a single nearby source: the Orion bar (Stacey et al. 1991, ApJ, 383, L37; Boreiko & Betz 1996, ApJ, 467, L113). By comparing the [^{13}CII] and [^{12}CII] line emissions, we will obtain valuable constraints upon the [^{12}CII] optical depth and the $^{12}C/^{13}C$ isotopic ratio. The optical depth is important, because it reveals the degree to which the observed [^{12}CII] intensities have been diminished by self-absorption; it also constrains PDR models and provides information about the geometry of the emitting gas. The $^{12}C/^{13}C$ isotopic ratio – which has been studied previously using observations of carbon-bearing molecules (e.g. CO, CN and

HCO^+) in cold molecular clouds – probes the nucleosynthetic history of the observed material (e.g. Milam et al. 2005, ApJ, 634, 1126): the ^{13}C isotope, an intermediary in the CNO cycle, is produced almost exclusively in low- to intermediate-mass AGB stars and is preferentially enhanced at small Galactocentric distances, while ^{12}C, the product of the triple alpha reaction, is also produced in Type II supernovae. The current observational picture is somewhat unclear because of the possibility that fractionation may lead to molecular abundance ratios that do not exactly reflect the elemental $^{12}C/^{13}C$ ratio; therefore, our planned observations of $^{12}C^+/^{13}C^+$ will provide a valuable check on the assumptions underlying previous isotopic studies that used carbon-bearing interstellar molecules. By observing several bright PDRs, we will measure the $^{12}C^+/^{13}C^+$ ratio over a range Galactocentric distances.

5. Schedule for Year 3

The goal for 2010 is to have a successful Antarctic science flight. On December 10th and 11th, 2009 fifteen members of our Instrument Team met at the University of Cologne to establish a project schedule to meet this objective. This meeting was followed by a Science Team telecon where this schedule was reviewed. The important milestones and associated dates are listed below. There are two important branch points in the schedule. The first is whether to proceed with the Ball dewar or with a custom designed dewar. As discussed in the Budget Justification section, additional funds are needed in order to pursue the Ball dewar option. This decision needs to be made in early January, to maximize the time Ball has to perform the necessary modifications or to maximize the time available to construct a custom dewar. The Ball dewar has two major advantages; 1) it exists, providing schedule margin for a 2010 Antarctic deployment and 2) it can potentially triple the flight time in 2010, dramatically increasing the science return and mission reserve. Even assuming we fly STO on average every other year, it would take an additional **4 years** and **two Antarctic campaigns** to achieve the same scientific goals if the custom dewar is used. The second branch point will be at the end of the integration and testing period at APL, near the end of June. This is when we would plan to make a Go/NoGo decision to proceed with the Antarctic campaign in 2010 or delay by a year.

2010

Jan. 15: Process Initiation Conference for 2010-2011 campaign
Feb. 1: Optical/mechanical design of science flight system complete (UAz/KOSMA).
    Option A: Begin modifications of spaceflight dewar (Ball)
    Option B: Begin fabrication of custom dewar (UAz)
    Solar array design finalized (APL)
March 1: Fabre-Perot diplexer complete (KOSMA)
    Gondola refurbishment finished (APL)
    Magnetometer on hand (APL)
April 1: Warm Optics Box complete (UAz)
    Cold optics assembly complete (KOSMA)
    Mixers complete (JPL/KOSMA)
    Telescope refurbishment completed (APL)
April 1 – April 30: Receiver Tests at KOSMA with Optic Box and mixers (UAz/JPL/KOSMA).

May 1: Option A: I/T of receiver at Ball in modified spaceflight dewar
(UAz/ JPL/KOSMA/Ball)
Option B: I/T of flight receiver in custom dewar at UAz
(JPL/KOSMA/UAz)
Magnetometer implemented
Star tracker modifications/improvements implemented & tested
June 1: I/T of receiver system at APL with telescope/gondola
June 30: Antarctic Go/NoGo Decision
July 15: All testing complete
Aug. 1: STO arrives at Palestine, TX for Hang-test.
Aug. 15: CSBF ships STO to Antarctica
Nov. 1: Initial deployment of personnel to McMurdo
Nov. 15: I/T of STO at Williams Field
Dec. 1: Hang Test/FRR
Dec. 15 – Jan. 31: STO Launch window

2011
Feb. 1 -15: STO recovery/Preparations for Retro- Begin writing papers!

6. Budget Justification

Here we describe two potential budget options for STO funding in Year 3.

<u>Option A</u> includes all Year 3 costs described in the original University of Arizona budget plus ½ the cost ($275K) for modifying the existing Ball Aerospace ~50 day hold time dewar. The second half of the Ball cost would appear in our 2011 budget. The dewar, originally developed for use in space, is arguably the highest performance helium dewar on Earth, and represents a $5 million dollar investment by Ball. This very same dewar was designated as flight hardware for our team's most recent SMEX proposal. The modifications, technical support, and costing for the dewar are described in the attached letter from Ball. The above hold time estimate includes all the thermal loading from wires, coax, windows, etc. for the STO instrumentation. With this dewar it will be possible for STO to make as many as **three** circuits of Antarctica, dramatically **decreasing** the number of **years/cost** associated with surveying the Milky Way. The Option A budget also includes additional costs for personnel and ground support equipment (tools, test equipment, etc.) which we found through the test flight experience are essential to a successful flight. The total cost of pursuing Option A in Year 3 is <u>$881,343</u>.

<u>Option B</u> includes all Year 3 costs described in the original University of Arizona proposal plus the cost of fabricating a custom dewar. This dewar would have a hold time of ~20 days. Some funds for a custom dewar had originally been designated in Year 2, however, a significant portion of these funds were needed for modifying the test flight dewar from JPL to work at altitude and for fabricating the test flight optics. For the upcoming science flight our colleagues at the University of Cologne will fabricate and test the majority of instrument related optics. Based upon our test flight experience the science flight dewar will be designed from scratch to meet all flight and instrument requirements. The Option B budget also includes additional costs for personnel and ground support equipment (tools, test equipment,

etc.) which, through the test flight experience, we found essential for a successful flight. The total cost for pursuing Option B in Year 3 is $733,456.

Ball Aerospace & Technologies Corp.
1600 Commerce Street
Reply to: P.O. Box 1069, Boulder, Colorado 80306-1062

ISO 9001
CERTIFIED
FM 39220

04 December 2009
ND.09.KAP.089

University of Arizona
933 North Cherry Avenue
Tucson, AZ 85721

Attention: Christopher Walker
Professor of Astronomy

Subject: Rough Order Magnitude DO9.R.211
Stratospheric Terahertz Observatory (STO) Cryostat

Reference: a) Email Request for Quote dated 01 December 2009

Ball Aerospace & Technologies Corp. (Ball Aerospace) is pleased to submit our Cost-Plus Fixed Fee Rough Order Magnitude (ROM) DO9.R.211 in response to the referenced a) request. Our estimate represents our best understanding of the requirements stated in the request. Ball will deliver the modified cryostat dewar for use on the STO program and provide technical assistance to the University of Arizona (U of A) during the integration and test of the instrument.

Our estimated price is $550K and contingent upon the following assumptions:

1. Ball to perform the following tests:
    - Leak test internal plumbing
    - Leak test dome
    - Wiring continuity test
    - Boil off testing with helium (includes temperature monitoring). Boil off testing to be performed with receiver integrated.
    - No structural testing will be performed
2. Ball will provide the following deliverables:
    - Dewar (537340-500) hardware available for use on STO for the length of the project for use "as-is" with no warranty
    - 1 design / status review to be held at Ball, ½ day if needed or requested (can be web ex meeting)
    - Monthly status report
    - Weekly telecom
3. Technical assumptions (Attachment A)
4. Customer furnished equipment (CFE) need dates will be specified prior to contract award
5. Shipping cost to be paid by U of A
6. FOB Boulder, CO
7. No travel is assumed in costs
8. No post delivery support is assumed in costs
9. Period of performance is four (4) months after receipt of order
10. This ROM is not a binding offer on the behalf of Ball Aerospace and is provided for budgetary purposes only.
11. Our estimate will remain valid for 90 (ninety) days from the date of this ROM.

We want to express our appreciation for this opportunity to provide this ROM in support of the STO program and look forward to working with the University of Arizona team. If you have questions of a technical nature, please contact Mr. Dave Glaister, 303.939.5842 (dglaiste@ball.com). Questions of a contractual nature should be addressed to Ms. Kathy Prentice at 303.939.7288 (kprentic@ball.com).

Sincerely,

Tami K. Oswald
Sr. Manager of Contracts, National Defense
Ball Aerospace & Technologies Corp.

Attachment A

Additional Assumptions:

1. VCS shields will be redesigned to allow receiver installation with minimal disassembly.
2. Ball Aerospace to provide performance predictions.
3. MLI between vapor cooled shields in top of dewar will be omitted to reduce costs and schedule. There is a small impact to life performance (58 days (without margin) with MLI between shields, 51 days without MLI between shields).
4. Ball Aerospace to define interfaces for dewar tank and plumbing. U of A to provide detail design for interfacing to dewar.
5. Will use existing removable dome with modifications.
6. Wire harness for receiver to be provided by U of A (interface to existing inline cable connectors)
7. Existing temperature sensors to be used for shields and helium tank temperature monitoring.
8. Helium quantity reduced from maximum fill capacity by telescope pointing angle – 94 liters at level; 86 liters at 45 degrees.
9. Ball Aerospace to provide relief valves and automatic value to maintain helium at 1 atmosphere pressure.
10. No electronics will be provided, with the exception of existing fill valve controller.

U of A to provide (need dates TBD):

- exterior interface hardware and structure. (existing struts will be provided to U of A)
- vacuum pump out equipment
- vacuum monitoring equipment
- receiver temperature sensors
- dewar windows
- shield windows
- vacuum dome modifications (design, fab., and assembly) for window, window bezel and coax feedthru plate
- all receiver interface hardware and parts (Ball Aerospace to define interfaces)
- integration of receiver and LNA into dewar at Ball Aerospace
- temperature monitoring electronics and wire harnesses