CASIMIR: the Caltech Airborne FIR/Submm, High Resolution Heterodyne Spectrometer

Michael L. Edgar**, Andrew I. Harris[#], David W. Hawkins[+], Alexandre Karpov*, David Miller*, Kevin P. Rauch[#] & Jonas Zmuidzinas*

Abstract— **CASIMIR, the Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver, is a far-infrared and submillimeter heterodyne spectrometer, being developed for the Stratospheric Observatory For Infrared Astronomy, SOFIA. CASIMIR will carry out observations in the frequency range from 500 GHz up to 1.4 THz, with extremely high spectral resolution, of order 10^6. Utilizing recent advances in SIS detector development, CASIMIR will cover this region of the spectrum with unprecedented sensitivity. CASIMIR is extremely well suited to observe the warm, ~100K, interstellar medium, particularly water lines, in both galactic and extragalactic sources. We present an overview of the instrument, its capabilities, systems and expected performance.**

Keywords: heterodyne, spectrometer, FIR/submm, SOFIA

1   INTRODUCTION

CASIMIR, the Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver, is a far-infrared (FIR) and submillimeter, very high-resolution, heterodyne spectrometer. It is being developed as a first generation, Principal Investigator class instrument for the Stratospheric Observatory For Infrared Astronomy, SOFIA[1,2].   Observations with CASIMIR on SOFIA are expected to begin in 2010 and the instrument should be available to guest investigators soon after. It is anticipated SOFIA will eventually achieve a flight rate of up to 160 flights per year, with a lifetime of 20 years.

Initially, CASIMIR will cover a frequency range from 500 GHz up to 1.25 THz. A 1.4 THz band will be added soon after initial operations and the frequency coverage may eventually be expanded up to 2 THz. It will be capable of covering this range at a resolution of ~10^6.

** Contact Author: California Institute of Technology, MS 320-47
  Pasadena, CA, 91125,USA
  mick@submm.caltech.edu
 * California Institute of Technology
 # Department of Astronomy, University of Maryland
 + Owens Valley Radio Observatory, California Institute of Technology

The FIR/submm is extremely important for the investigation of both the galactic and extragalactic warm (*T*~100 K), interstellar medium. This material is heated by shock waves or UV radiation, phenomena that are often associated with star formation or other high energy events, e.g. supernovae or active galactic nuclei. This excited material then re-emits either as dust continuum radiation or gas line emission. CASIMIR will be able to utilize recent advances in the sensitivity of superconducting mixers to study the fundamental rotational transitions of many astronomically significant hydride molecules, which cannot be observed with ground based telescopes.

2   FREQUENCY BANDS

2.1   Initial Channels

Four frequency channels will be available for initial observations. Table 1 shows a selection of significant spectral lines within these bands.   It is expected that initial observations will concentrate on lines from this list. Almost all of these lines are completely unobservable from the ground.

2.2   Water

As can be seen from Table 1, CASIMIR is particularly well suited to investigate the abundance and excitation of interstellar water, using a number of transitions of $H_2^{18}O$. While oxygen is the third most abundant element, its chemistry in interstellar clouds is poorly understood, since the atmosphere is opaque to many of its key species, such as O, O_2, H_2O, H_3O^+ and OH. Gas phase water also has an important role in the energy balance of molecular clouds due to radiative cooling or heating through FIR/submm rotational transitions[3]. Figure 1 shows the rotational energy levels for $H_2^{18}O$, indicating the large number of low excitation level transitions visible to CASIMIR. Figure 2 shows results from observations of the 547 GHz $H_2^{18}O$ line obtained on the Kuiper Airborne Observatory (KAO) and predictions of the line intensities that will be obtained for the same source with CASIMIR.

Freq. Band GHz	Species	Line Freq. GHz	% Atmos. Trans. @12km
500-600	$H_2^{18}O$ CH NH_3 CO	547 532,536 572 576	81 98,97 94 80
700-800	$H_2^{18}O$	745	82
900-1050	H_3O^+ CH_2 NH $H_2^{18}O$ CO	985 946 975 995 1037	65 99 96 73 94
1050-1250	$H_2^{18}O$ HF	1137,1181 1189,1199 1232	70,75 87,81 30

Table 1. A list of selected significant species and lines that will be observed with the first 4 frequency bands of the CASIMIR instrument. The atmospheric transmissions shown are for typical SOFIA operating altitudes, ~4o,ooo ft. or 12 km. At the Caltech Submillimeter Observatory (CSO), on the summit of Mauna Kea at 4.1 km altitude, of all the lines shown, only two have an atmospheric transmittance more than 0%: CH (1%) and CH_2 (13%).
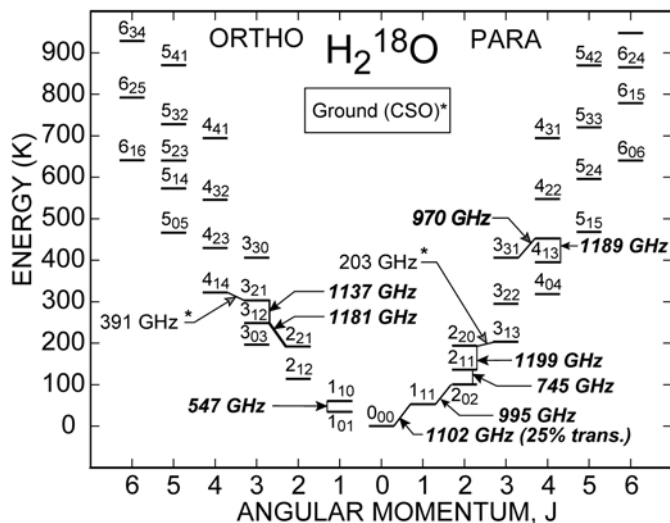

Figure 2. Comparison of $H_2^{18}O$ line sensitivities obtained with the Kuiper Airborne Observatory (KAO) and expected for CASIMIR. The top part of the figure shows 547 GHz observations of SgrB2, obtained on the KAO. The bottom part shows predicted performance for observations of SgrB2 with CASIMIR on SOFIA, for several lines. SgrB2 was modeled as a sphere, $n_{H2}(r) \sim r^{-2}$ and $T(r) \sim r^{-0.5}$, which matches existing CO, dust and $H_2^{18}O$ data.

2.3   1.4 THz Band and H_2D^+

A 1.4 THz band is expected to be available soon after CASIMIR begins observations on SOFIA. This band will concentrate on the H_2D^+ 1370 GHz ground state line. The H_2D^+ ion is of particular interest, since it is the deuterated version of H_3^+, which is believed to be responsible for driving much of the chemistry of molecular clouds. The 372 GHz line for this species has now been detected from the ground in several protostellar cores with the CSO[4] and the APEX telescope[5], in the Atacama Desert. However, this line traces hot, dense gas, in which the chemistry is more complicated and the abundance is expected to be low. The 1370 GHz line is a better choice. The only previous search for this higher frequency line was made towards Orion, using the KAO, and resulted only in a tentative detection of an absorption feature[6].

Figure 1. CASIMIR's coverage of the rotational energy levels of the $H_2^{18}O$ molecule. The first 4 bands of CASIMIR will be able to observe 9 transitions, including several low temperature lines, compared to only 2 relatively high energy transitions observable at the CSO, denoted by asterices.
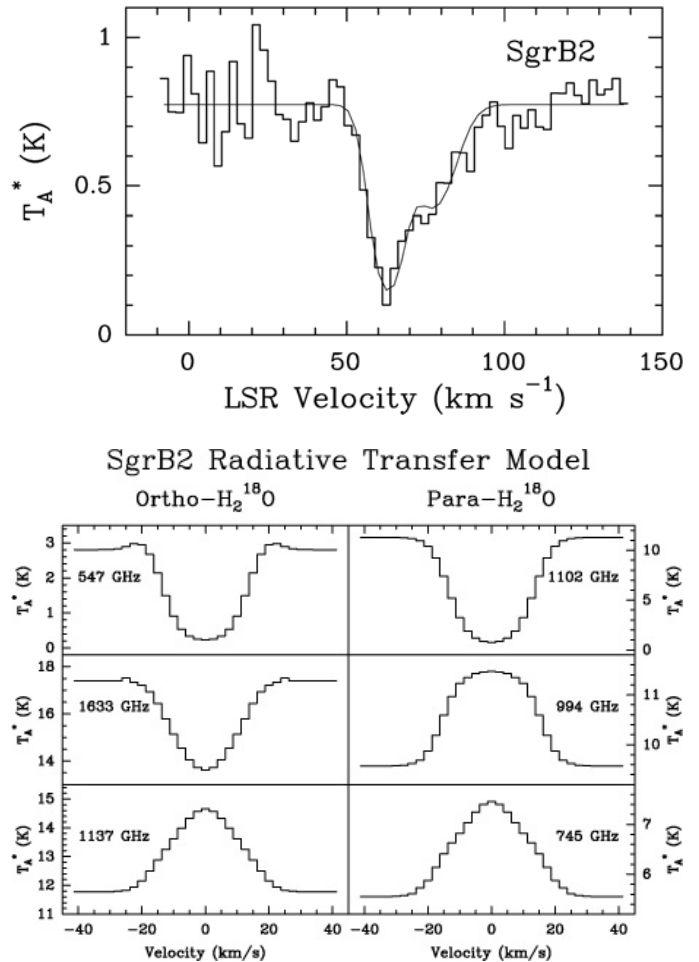
3 RECEIVERS, LOCAL OSCILLATORS AND INTERMEDIATE FREQUENCY SYSTEM

3.1 Receivers

The receivers for all of the first five CASIMIR bands, up to 1.4 THz, will be Nb/AlN/NbTiN Superconducting-Insulator-Superconducting (SIS), quasi-optically coupled, twin-slot mixers. These mixers and their development are discussed in detail elsewhere in these proceedings[7].

The ongoing development is expected to significantly reduce the noise temperatures compared to present receivers at these frequencies. It is expected that this development will achieve double side band (DSB) noise temperatures of the order of 3hυ/kB for devices operating at less than 1 THz and 6hυ/kB above.

It is also expected that the useful frequency range of SIS mixers may extended up to 1.6 THz.

3.2 Local Oscillators

The Local Oscillators (LOs) for all bands are tunerless and use solid state devices exclusively. The 550 GHz and 1370 GHz LOs have already been acquired from Virginia Diodes[8]. The 1200 GHz was developed at JPL and is similar to the LO developed for the same frequency on the Herschel satellite[9]. The 750 and 1000 GHz LOs are under development by N. Erickson at the University of Massachusetts.

All bands are driven from a single, commercial microwave synthesizer at a frequency in the range 26-40 GHz. Any one of four bands can be selected via software at anytime during the flight, without mechanical adjustment or physical access to the instrument.

As shown in Figure 6, up to two LOs can be mounted directly to the side of the cryostat. The LO output is via a feedhorn. The output divergent beam is reflected through 90° and converted into a ~f/10 converging beam, by an off-axis elliptical mirror, mounted directly below the feedhorn (see Figure 7). The beam passes through a window in the cryostat wall to a mylar beamsplitter mounted directly below the receiver elliptical mirror. The beamsplitter directs a portion of the LO signal power towards the cryostat cold work surface, combining it with the incoming, astronomical signal.

3.3 Intermediate Frequency System

The intermediate frequency (IF) is the output signal from the mixer. For all bands on CASIMIR, the IF bandwidth is defined to be 4 GHz, centered on 6 GHz. This wide frequency range will allow observation of the broad lines from extragalactic sources.

The low noise amplifier in all bands is a Chalmers[10] design. It is a two-stage amplifier using InP transistors and has a minimum gain of 27 dB with a nominal noise temperature of 3 K. It is mounted on the cold work surface of the cryostat, at LHe temperature, and is connected to the mixer via a cryogenic isolator, which reduces ripple in the IF due to impedance mismatches.

The room temperature IF electronics consist of a 4-8 GHz amplifier module. This is an integrated unit developed under contract by CTT Inc.[11], containing a low noise amplifier, a voltage variable attenuator (VVA), band defining filter, power amplifier, a directional coupler for monitoring the IF power level, and a switch for setting the IF power zero level. An integrated isolator at the input of the module minimizes standing wave ripples between the cryostat and amplifier module. The nominal gain of the unit is 65 dB with a typical noise temperature of 300 K. The bandwidth defined by this unit is shown in Figure 3. A diode is connected to the monitor port for measuring the signal strength and adjusting the VVA to prevent the saturating internal amplifiers. These units are mounted directly to the side of the cryostat (see Figure 6) and are designed for fully automatic operation.
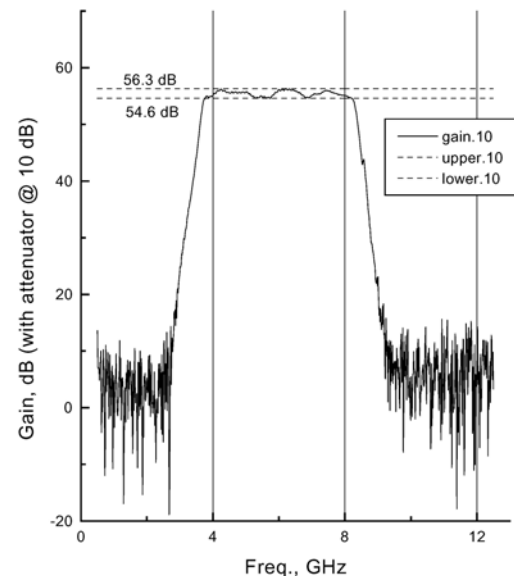

Figure 3. IF bandwidth defined by bandpass filter within the room temperature IF unit. At a typical operating point, with the VVA set for 10 dB attenuation, the IF unit demonstrates excellent uniformity, <+/- 1 dB, across the entire 4 GHz bandwidth.

4 MICROWAVE SPECTROMETERS

4.1 Wideband Analog Spectrometer (WASP2)

The WASP2[12,13] was developed at the University of Maryland. It is an analog correlator spectrometer, which in contrast to other spectrometer types, analyzes the entire 4 GHz bandwidth as a whole, without splitting the IF into sub-bands. This approach will be more suitable for wide extragalactic spectral lines.

It is based on an analog correlator card, see Figure 4. Signals propogate in opposite directions along two delay lines. As WASP2 is configured as an autocorrelator, it is the same signal propogating along both lines. At fixed points, i.e. fixed phase lags, along the delay lines, there are taps at which a fraction of the signal from both lines are analog-multiplied together by active mixers. The resolution of this spectrometer is defined by the physical spacing of these taps. There are 16 taps, therefore 16 lags per card, which corresponds to a resolution of 33.6 MHz per channel. Observing at 1 THz, the resolution would be $R=3x10^4$ with a velocity resolution of 10 km/s.

The spectrometer contains 8 correlator cards, connected by cable delays, giving a total of 128 channels, continuously covering the full 4 GHz of the IF bandwidth. Due to practical considerations, only the top 110 channels are available to the user for spectroscopy, limiting the full bandwidth to 3.7 GHz.
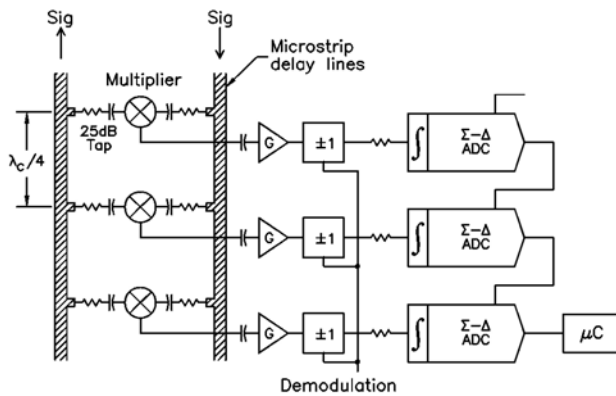

Figure 4. Schematic diagram of a part of the WASP analog correlator card.

4.2   High Resolution Digital Correlator, COBRA

The COBRA[14,15] digital correlator was developed at the Owens Valley Radio Observatory (OVRO) to create a 4 GHz, 6-antenna, correlator system. The design was re-used to create an 8 GHz, 8-antenna, correlator for the University of Chicago SZA array, and the OVRO hardware was recycled to create a 1.5 GHz, 15-antenna, correlator system for the CARMA observatory. The COBRA boards are FPGA-based and use a 6U compact PCI form-factor.

A COBRA digitizer board contains two 1 GHz 2-bit samplers and four FPGAs, while a correlator board contains ten FPGAs.
Each FPGA contains 5,000 logic elements (LEs), and can be configured to calculate up to 32-lags across 500 MHz bandwidth data.   Multiple FPGAs, and boards, can be cascaded to increase the number of lags calculated. For example, data from the dual samplers on a digitizer board can be fed to one or more correlator boards.

For CASIMIR's application, the COBRA hardware will be configured as an autocorrelator. Initially it will cover 2 GHz of the IF bandwidth, centered on 6 GHz. The 2 GHz IF is filtered into four 500 MHz bands, and downconverted to the digitizer input band from 500 MHz to 1 GHz. Each signal is then sampled at 1 GHz. The four sub-bands are processed by two digitizer boards and four correlator boards.

Each sub-band is processed using 2 FPGAs on the digitizer board and 10 FPGAs on a correlator board. The resulting power-spectrum has 384-channels, giving a resolution of ~1.3 MHz/channel. While observing at 1 THz, this would correspond to a resolution of $R=7.7x10^5$ and a velocity resolution of 0.4 km/s.

The channel resolution at 500 MHz can be improved by cascading the data through additional correlator cards, there are 320 lags per card.

The FPGAs on the digitizer board can also be used to implement digital (FIR) filtering   Reducing the input bandwidth, reduces the parallelism required to processes the data, and increases the number of lags each FPGA can calculate (up to 64-lags). At CARMA, the input bandwidth can be reduced to as a low as 2 MHz.   On CASIMIR, FIR filtering can be used to reduce the IF bandwidth from 500 MHz, to 250 MHz or 125 MHz. The mode changes can be made dynamically, take only a few seconds and could be carried out at any stage during the flight.

The CARMA observatory has revised the COBRA hardware, creating a new dual-purpose CARMA board. The board contains an 8-bit, dual-1GHz digitizer, and four FPGAs[16]. The digitizer can be operated as two 1GHz digitizers, or interlaced to operate as a single 2GHz digitizer. A CARMA digitizer board consists of a CARMA board populated with the digitizer components, and four 90,000LE FPGAs, while a CARMA correlator board is populated with four 130,000LE FPGAs, i.e., a CARMA correlator board contains 520,000LEs, whereas a COBRA correlator board contains 50,000LEs.   The CARMA hardware offers an order-of-magnitude increase in resolution, and we hope it will be available for use during initial observations with CASIMIR.

5   INSTRUMENT CONFIGURATION AND STRUCTURE

The general layout of the CASIMIR instrument is shown in Figure 5. Two cryostats are mounted side by side on top of a box, which contains the relay optics, see Section 5.3.

Two 19-inch racks are mounted directly behind this box. All the critical electronics components are mounted in these racks, eg. the LO drive electronics and the microwave spectrometers. This ensures very short cable runs to the cryostat and prevents any differential rotation. All electronic systems for the

instrument are packaged as 19-inch bins, which will allow easy replacement of any unit.
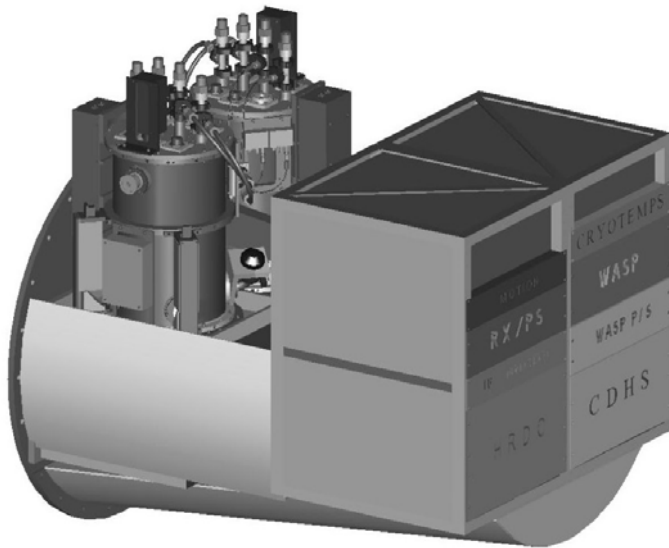

Figure 5. The CASIMIR instrument. The instrument is mounted to the telescope via the round flange at extreme left of the figure. This flange forms the pressure interface between the telescope cavity and the aircraft's cabin. The portion of the instrument shown is located in the cabin, with the observers. The telescope beam enters the instrument through the center of this round flange, about 150 mm below the bases of the cryostats. The instrument structure is constructed almost exclusively of aluminum. It is approximately 1.5 m long by 1 m square. It weighs approximately 550 kg, including 150 kg of electronics mounted in the racks, at the right of the figure. Approximately 150 kg more of ancillary electronics are located elsewhere in the aircraft cabin.

5.1   Cryostats

The cryostats are of conventional design with LN_2 and LHe reservoirs.   For frequencies below 1 THz, the mixers will operate at ~4 K. At higher frequencies, we will pump on the LHe reservoir to operate the receivers at ~ 2.5 K.

There will be two cryostats per flight and up to two frequency bands in each cryostat, so there will be up to four bands available per flight. Observations can be made with only one band at a time. Any one of the four bands can be selected at anytime during the flight. This selection is made by software alone, and does not require caging of the telescope, any mechanical adjustment or physical access to the instrument.

As shown in Figures 6 and 7, all the components specific to an individual frequency band are integrated directly onto the cryostat,   eg. the LOs, IF systems and relay optics.   All systems mounted elsewhere on the instrument are used for all of the bands. Therefore, changing the selection of the four bands which are to be used on a given flight only requires swapping cryostats, which could easily be carried out between flights. Also, any upgrades and improvements to the bands could be accomplished completely independent of the rest of

the instrument. This will allow continuous upgrades to the frequency bands, throughout the life of the instrument.
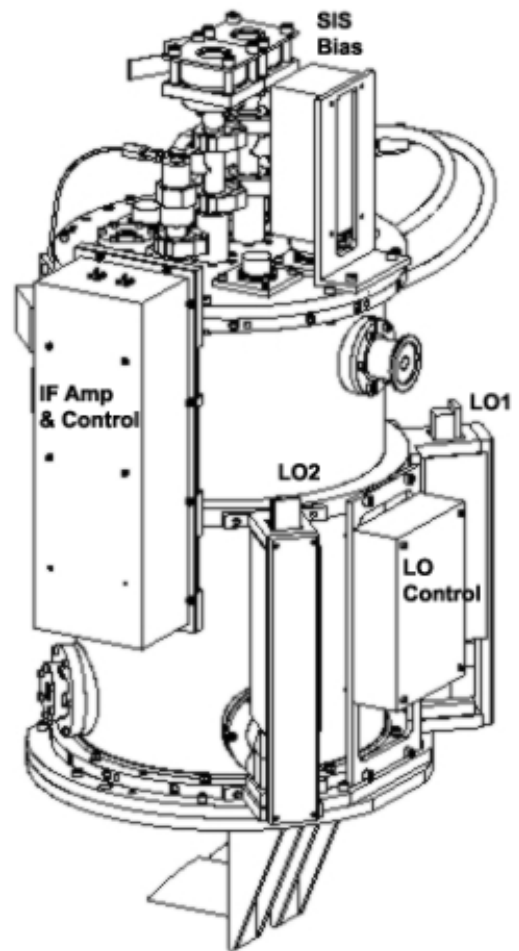

Figure 6 The CASIMIR Cryostat. The cryostat contains 5 liters each of LN_2 and LHe and has a 250 mm diameter cold-work-surface. This is the approximate, maximum, practical diameter for cryostats that can be used in the side-by-side configuration for SOFIA. It is 600 mm high and weighs ~40 kg. The LOs, IF system, receiver and LO bias electronics are mounted directly to the side of the cryostat. The electronics for the cryogenic amplifier bias and mixer electromagnet current are also mounted on the cryostat but are not shown in this view. The rather impressive array of plumbing fixtures on the top of the cryostat prevents the formation of ice plugs or the rupture of the cryogenic reservoirs. This design was required to obtain airworthiness certification of the cryostat by the Federal Aviation Administration. The two elliptical mirrors of the relay optics, mounted on the base of the cryostat, can be seen at the extreme bottom of the image.

5.2   Optics

Figure 7 shows a schematic of the relay optics, which uses two off-axis elliptical mirrors to match the incoming telescope beam to the output beam of the mixer.   Including the telescope, there are five mirrors at ambient temperature and one cryogenically cooled mirror, EM1, in the optical train.

This includes two plane mirrors, the fully reflective tertiary and a plane mirror in the Optics Box, see Figure 8.

The window in the base of the cryostat is the only pressure boundary in the optical path from the telescope. Therefore, this window and a lens in the mixer assembly are the only transmissive elements in the entire optical train from the telescope to the receiver.

The optical designs for all bands have an edge taper of 10 dB. Initially, SOFIA will have an oversize tertiary, which will produce an aperture efficiency of 0.64. A smaller tertiary may be available in the future, which will improve the aperture efficiency to 0.71. Main beam efficiency is calculated to be 0.77. The largest beam size is 0.8 arcmin, at 550 GHz.
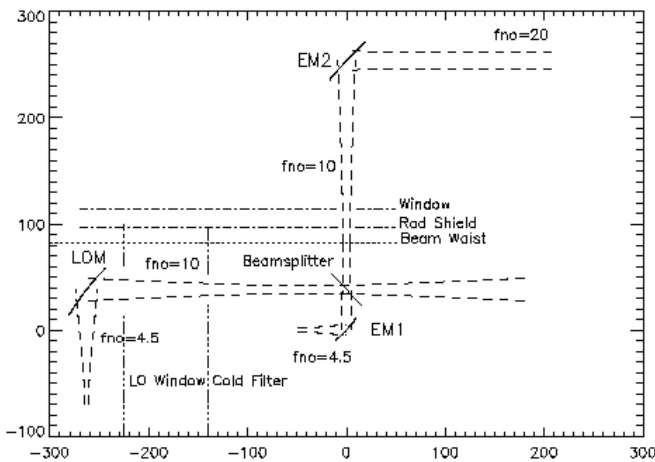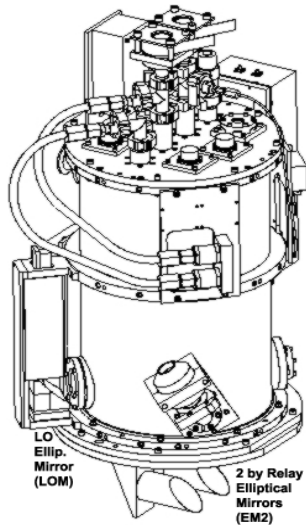

Figure 7 CASIMIR Relay and LO Injection Optics. The top image shows the location of the elliptical mirrors mounted on the cryostat. The bottom part of the image shows a schematic of the optics. In the lower image, the up down orientation is reversed and the units on the scale are mm, with the origin at the center of EM1, the elliptical mirror mounted on the cryostat cold-work surface. EM2 is the elliptical mirror mounted below the base of the cryostat, visible in the left image. EM2 is in the plane of the telescope beam, it converts the incoming, diverging f/20 telescope beam into an intermediate f/10 beam and reflects it through 90°, through a window in the base of the cryostat. LOM is the LO elliptical mirror, which matches the LO output beam to the incoming intermediate beam. EM1 converts the

intermediate beam to a converging ~f/4.5 beam, which matches the output beam of the mixer.

5.3   Optics Box

Figure 8 shows a 3D model of the Optics Box, which is the mount for the cryostats and contains all the optics common to all frequency bands. The central feature is a plane mirror, which can be commanded to rotate through +/- 180° in the plane of the telescope and up to +/-5° in tilt. This rotating mirror directs the telescope beam to one of the four elliptical mirrors mounted on the two cryostats, selecting the frequency band.

The calibration system consists of a chopper wheel at ambient temperature plus hot and ambient temperature loads. Moving the rotating mirror by ~180°, allows any of the frequency bands to be first illuminated with the sky signal and then the signal from a known temperature calibration load.
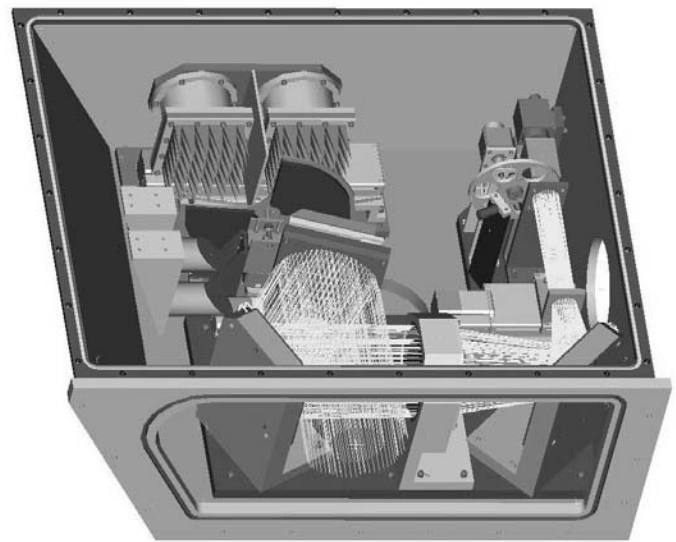

Figure 8 The Optics Box. The cryostats are bolted directly to the lid of this box, which has been removed for this image. The elliptical mirrors mounted on the base of the cryostats protrude trough an aperture in the lid and are located in the plane of the telescope beam. The two elliptical mirrors for one of the cryostats are shown in the left part of the image. The box forms part of the pressure interface between the aircraft cabin and the exteriorand wall thickness varies between 0.5 and over 0.75 in. The box interior is exposed directly to the telescope cavity, so that at altitude, the pressure inside is <200 Tr. The telescope beam enters from the front of the figure. In this image, the rotating mirror, at the center of the figure, directs the telescope beam to the optical boresight, at the far right rear corner. The calibration chopper wheel and the two loads are shown in the rear of the figure.

CASIMIR will use the fully reflective tertiary mirror on SOFIA's telescope. As a result, none of the observatory's guiding cameras will be able to image the telescope's focal plane. Therefore, we have included an optical boresight camera, inside the Optics Box, for alignment and

beamfinding. The boresight can also be used as a pupil imager by moving a biconcave lens into the optical path. The camera has a 6'x6' field of view and uses a 1024x1024 pixel, optical wavelength CCD. The rotating mirror also selects this camera.

Stepper motors are used to move all the optical components. All of these motors are mounted inside the Optics Box and are controlled remotely via software. There are only electronic feedthroughs mounted in the sides of the box, without any mechanical motions through the pressure boundary. Physical access to the Optics Box will not be required at any time during the flight.

6 CONCLUSIONS

CASIMIR is a FIR/Submm, heterodyne spectrometer for SOFIA. It is well suited for the studies of the warm (T~100K) interstellar medium, particularly water, measuring many significant lines unobservable from the ground. Initially, the instrument will cover 500 to 1250 GHz, with a 1.4 THz Band to be added soon after. Eventually the frequency coverage may be extended up to 2 THz. CASIMIR will have unprecedented sensitivity in this frequency region, due to recent advancement in SIS mixer design.

There will be up to 4 channels available per flight of the observatory. Any one of these channels can be selected at any time during the flight.

All bands will have an IF bandwidth of 4 GHz. A medium resolution ($R\sim3\times10^4$) spectrometer will simultaneously cover this whole band. There will also be partial coverage of this band with very high resolution, up to $\sim10^6$.

The instrument design is extremely modular and will be able to continuously incorporate new hardware and accommodate future improvements in mixer, LO and microwave spectrometer technology, throughout the life of the observatory.

7 ACKNOWLEDGMENTS

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