CASIMIR – Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver

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***Abstract*— CASIMIR, the Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver, is a multiband, far-infared and submillimeter, high resolution, heterodyne spectrometer under development for SOFIA. It is a first generation, PI class instrument, designed for detailed, high sensitivity observations of warm (100 K) interstellar gas, both in galactic sources, including molecular clouds, circumstellar envelopes and protostellar cores and in external galaxies. Combining the 2.5-meter SOFIA mirror with state of the art superconducting mixers will give CASIMIR unprecedented sensitivity. Initially, CASIMIR will have two bands, at 1000 and 1250 GHz, and a further three bands, 550, 750, 1400 GHz, will be added soon after. Up to four bands will be available on each flight, contributing to efficient use of observing time. For example, searches for weak lines from rare species in bright sources can be carried out on the same flight with observations of abundant species in faint or distant objects.**

I. 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 (PI) class instrument for the Stratospheric Observatory For Infrared Astronomy, SOFIA [1], [2]. Observations with CASIMIR on SOFIA are expected to begin in mid-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. During the initial flights, CASIMIR will have two bands available, 1.0 and 1.25 THz. Three additional bands will be added with ongoing instrument development, providing frequency coverage from 500 GHz up to 1.4 THz. The frequency coverage may be expanded up to 2 THz later. It will be capable of covering this frequency range with a resolution of ~ 10^6.

The FIR/submm is extraordinarily 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. Even at excellent ground sites, such as Mauna Kea or the high Chilean Andes, the atmosphere is opaque to most of these lines. Observations of these species can provide critical tests of our understanding of interstellar chemical networks and reactions.

II. Scientific Objectives

A selection of significant spectral lines observable with CASIMIR is shown in Table I. It is expected that initial observations will concentrate on lines from this list. Most of these lines are completely unobservable from the ground. The atmospheric transmissions shown are for typical SOFIA operating altitudes, ~ 40,000 ft or 12 km. At the Caltech Submillimeter Observatory (CSO), on the summit of Mauna Kea, at 4.1 km altitude, only two of the lines listed have an

TABLE I
OBSERVING LIST OF SIGNIFICANT SPECTRAL LINES FOR CASIMIR

Band [GHz]	Species	Line [GHz]	Atm. Trans. [%]
550	CH	532, 537	98, 97
	$H_2{}^{18}O$	547	81
	NH_3	572	94
	CO	576	80
750	$H_2{}^{18}O$	745	82
1000	H_3O+	985	65
	CH_2	946	99
	NH	975	96
	$H_2{}^{18}O$	995	73
	CO	1037	94
1200	$H_2{}^{18}O$	1137, 1181	70, 75
		1189, 1199	87, 81
	HF	1232	30
1400	H_2D+	1371	94
	N+	1461	92

atmospheric transmittance more than 0%: CH (1%) and CH_2 (13%).

Oxygen is the third most abundant element, yet its chemistry in interstellar clouds is poorly understood. The atmosphere is opaque to many of its key species, such as O, O_2, H_2O, H_3O+ and OH, limiting detailed ground observations, but are prime candidates for investigation using CASIMIR. Also, the high *J* lines of CO will be observed with CASIMIR. These lines typically trace shocked gas and have been studied extensively with the Kuiper Airborne Observatory (KAO) with high-resolution, heterodyne spectroscopy.

A. Water

As can be seen from Table I, CASIMIR is exceptionally well suited to investigate the abundance and excitation of interstellar water, using a number of transitions of $H_2{}^{18}O$. Water vapor plays an important role in the energy balance of molecular clouds by mediating radiative heating and cooling through its rotational transitions in the far infrared and submillimeter [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. Only two relatively high energy transitions can be observed from the ground (i. e., CSO). Figure 2 shows the comparison between previous KAO observations at 547 GHz for $H_2{}^{18}O$ in SgrB2 and W51, and the line profiles and intensities predicted for CASIMIR on SOFIA, revealing the anticipated gain in sensitivity.

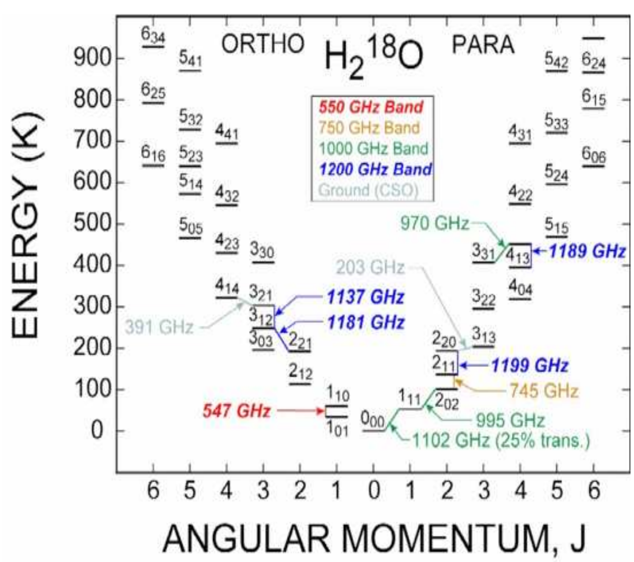

Fig. 1. The coverage by CASIMIR of the rotational energy levels of the $H_2{}^{18}O$ molecule. Four of the CASIMIR bands will be able to observe 9 of these transitions, including several low temperature lines

B. H_2D^+ and N^+

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, as 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 of H_2D^+ now has been observed in several molecular clouds with the CSO [4] and the APEX telescope [5] on the Chajnantor plateau in Chile. However, this is an excited transition that traces hot, dense gas, which has more complicated chemistry. In addition, the abundance of the species is low. The ground state line at 1371 GHz will be a better choice for studying the overall distribution of this important molecule. To date, there has been only one tentative detection of the 1371 GHz line in Orion with the KAO [6].

Another transition of major importance is the 1461 GHz transition of the nitrogen ion, N+, which traces the warm, ionized interstellar medium. COBE has shown that, apart from the 1900 GHz C+ line, the two fine-structure N+ lines are the brightest emitted by our Galaxy.

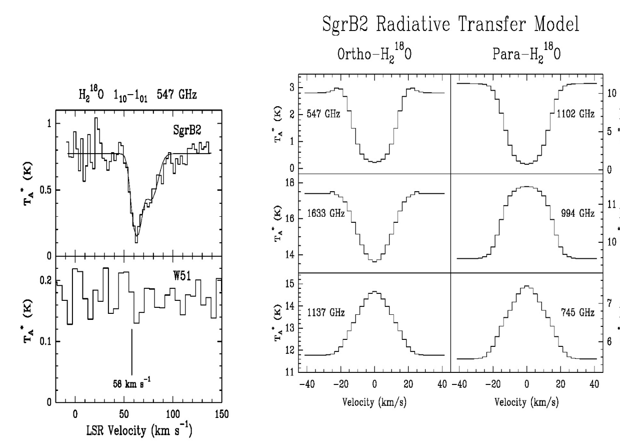

Fig. 2. Comparison of $H_2{}^{18}O$ line sensitivities obtained with the Kuiper Airborne Observatory (KAO) with these expected for CASIMIR. The left part of the figure shows 547 GHz observations of SgrB2 and W51, obtained on the KAO. The right part shows predicted performance for observations of SgrB2 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.

III. Instrument Configuration

CASIMIR embodies a versatile and modular design, able to incorporate future major advances in detector, LO and spectrometer technology. It mounts on the SOFIA SI telescope flange. The entire instrument is about 1.5 m long and 1 m diameter, and weighs about 550 kg. Two separate cryostats each can hold two mixers – thus up to four mixers are available on each flight. The optics box supporting the cryostats is open to the telescope cavity and contains the relay optics and calibration systems. Besides the cryostat windows, all the optics are reflective and can accommodate the entire 8' telescope field of view. Bias electronics and warm IF amplifiers are mounted on the cryostats, while independent electronics racks contain backend spectrometers, control electronics, and power supplies.

The general layout of the CASIMIR instrument is shown in Figure 3. Two cryostats are mounted side by side on top of a box, which contains the relay optics. Two standard 19-inch racks are mounted directly behind this box. All the critical electronics components are mounted in these racks, such as the LO drive electronics and the microwave spectrometers. This ensures very short cable runs to the cryostats and prevents any differential rotation and twisting of the cables. All electronic systems for the instrument are packaged as 19-inch bins, which will allow easy replacement of any unit.

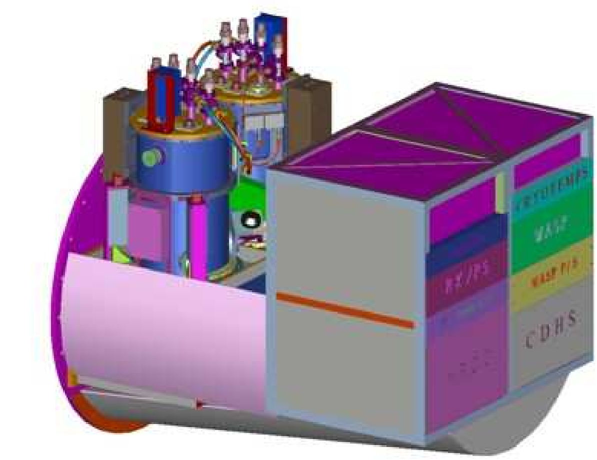

Fig. 3. The CASIMIR instrument. The instrument is mounted to the telescope via the round flange at extreme left of the figure. This flange forms the pressure interface between the telescope cavity and the aircraft's cabin. The portion of the instrument shown is located in the cabin with the observers. The telescope beam enters the instrument through the center of this round flange. 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 nearby in the aircraft cabin

A. 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, the LHe reservoirs will be pumped to operate the receivers at ~ 2.5 K. There will be two cryostats per flight and up to two frequency bands in each cryostat, thus four bands will be available per flight. Observations can be made with only one band at a time, but 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.

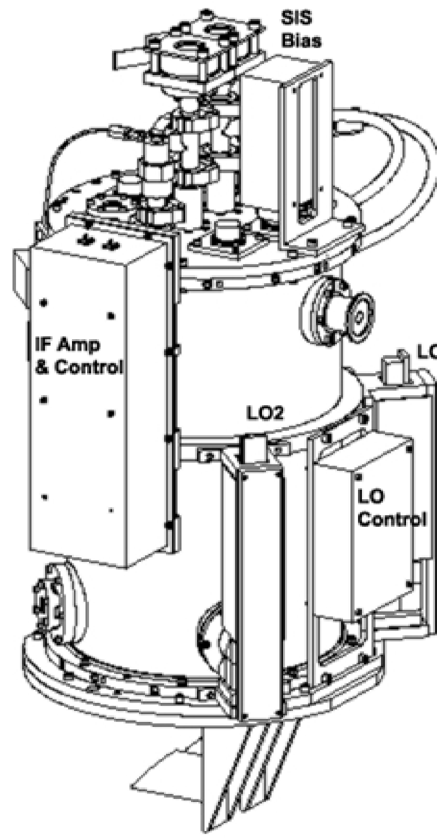

Fig. 4. The CASIMIR Cryostat. The cryostat contains 5 liters each of LN_2 and LHe and has a 250 mm diameter cold-work-surface. This is the maximum, practical diameter for cryostats that can be used in the side-by-side configuration for SOFIA. It is 60 cm high and weighs ~40 kg. The LOs, IF system, receiver and bias electronics are mounted directly to the sides of the cryostat. 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 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 bottom of the image.

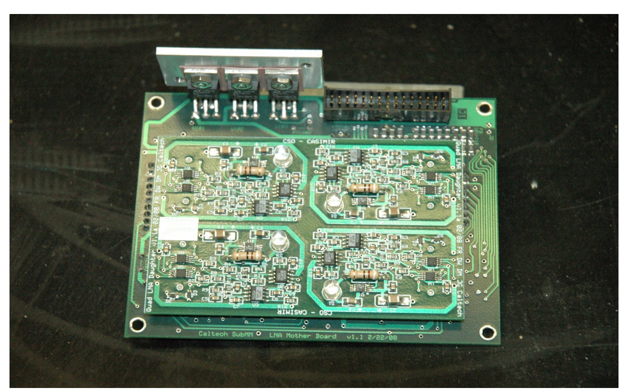

Fig. 5. Receiver bias electronics developed in collaboration with CSO. These circuit boards are for biasing the low-noise amplifier (LNA) on the cold LHe work surface of the receivers. These electronics are fully automated and controlled via computer interface, and also have the capability for manual control, allowing them to be used during mixer development

As shown in Figure 4, all of the components specific to an individual frequency band are integrated directly onto the cryostat, i. e., the LOs, IF systems, relay optics, and bias electronics (see Figure 5). All systems mounted elsewhere on the instrument are common to all of the bands. Therefore, changing the selection of the four bands which are to be available on a given flight only requires swapping cryostats, which would be a straight-forward task between flights. In addition, this modular approach allows future upgrades and improvements to the bands to be incorporated completely independent of the rest of the instrument. This will allow continuous enhancements to the frequency bands throughout the life of the instrument.

B. *Mixers*

All of the receivers for the five bands of CASIMIR, up to 1.4 THz, use advanced Superconductor-Insulator-Superconductor (SIS) mixers fabricated with Nb/AlN/NbTiN junctions in the JPL Micro Devices Lab. These planar mixers are quasi-optically coupled with twin slot antennas, and silicon hyperhemisphere lenses with Parylene antireflection coatings. These mixers and their development are discussed in detail elsewhere [7]. Simulations show this mixer technology is usable up to 1.6 THz. With ongoing development, DSB noise temperatures of $3h\nu/k_B$ at frequencies below 1 THz (see Figure 6), and $6h\nu/k_B$ above 1 THz (see Figure 7) are expected.

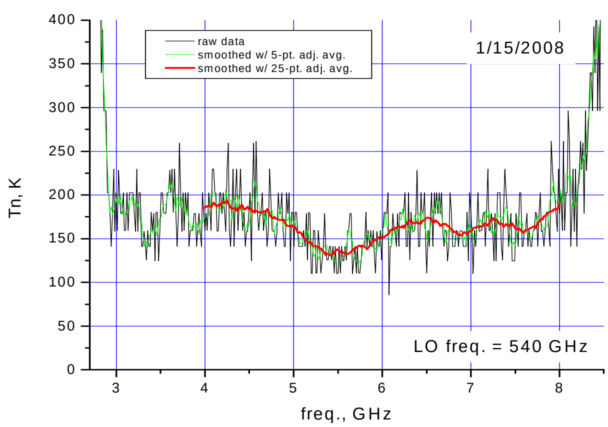

Fig. 6. Noise temperature results for the full 4 GHz IF band using an old-style quasi-optical SIS mixer with NbTiN/AlO_x/NbTiN junctions at LO frequency of 540 GHz. Input optics consisted of mylar beamsplitter, mylar pressure window, Zitex IR filters, HDPE focusing lens, and silicon hyperhemisphere lens. The IF output included cryogenic isolator, Chalmers LNA, and room-temperature IF amplifier module.

C. *Intermediate Frequency System*

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

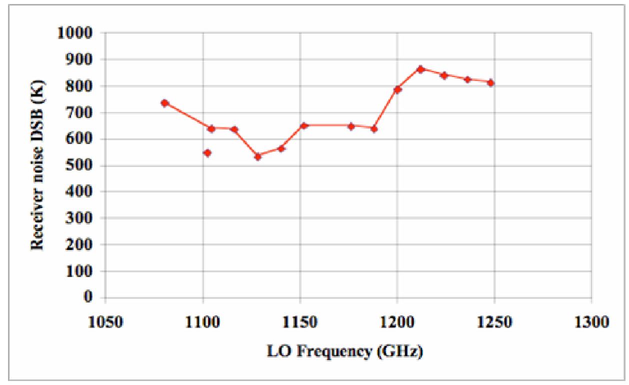

Fig. 7. Noise temperature results for 1.2 THz SIS mixer. The receiver noise is uncorrected for beamsplitter and cryostat window losses. With these corrections, the noise temperatures would fall to approximately $6h\nu/k_B$

The low noise amplifier in all bands is a Chalmers [8] design. It is a two-stage amplifier using InP transistors, with minimum gain of 27 dB and 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 Passive Microwave Technologies (Pamtech) [9] 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. The bandwidth defined by this unit is shown in Figure 8. This is an integrated unit developed under contract by CTT Inc. [10], containing a low noise amplifier, a voltage variable attenuator (VVA), band defining filter, power amplifier, a directional coupler for monitoring

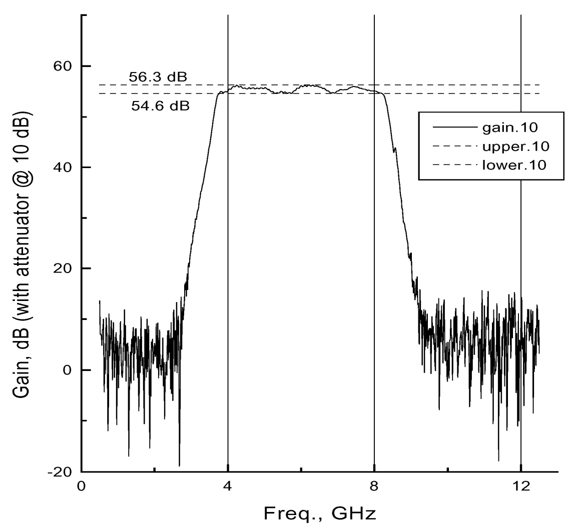

Fig. 8. IF bandwidth defined by bandpass filter within the room temperature IF unit. At a typical operating point, with the VVA set for 10 dB attenuation, the IF unit demonstrates excellent uniformity, < ± 1 dB, across the entire 4 GHz bandwidth.

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. A diode is connected to the monitor port for measuring the signal strength and adjusting the VVA to prevent saturating the internal input amplifier stage. These units are mounted directly to the side of the cryostat and are designed for fully automatic operation.

D. Local Oscillators

The Local Oscillators (LOs) for all bands are tunerless and use solid state devices exclusively. At present, 550 GHz and 1.37 THz LOs made by Virginia Diodes [11], and a 1.2 THz LO developed at JPL, based on a Herschel/HIFI design [12], are used for mixer development. The 750 GHz LO will be acquired from Virginia Diodes, while the 1.0 THz and 1.4 THz flight LOs will be developed at JPL. All bands are driven from a single, commercial microwave synthesizer at a frequency in the range 26–40 GHz.

As shown previously in Figure 4, up to two LOs can be mounted directly on the outside of the cryostat. The LO output is via a feedhorn, with the output divergent beam reflected through 90° and converted into a ~ *f*/10 converging beam by an off-axis elliptical mirror mounted directly below the feedhorn (see Figure 9). The beam passes through a window in the cryostat wall to a cryogenically-cooled mylar beamsplitter mounted directly below the receiver elliptical mirror. The beamsplitter directs a fractional part (~ 10%) of the LO signal power towards the cryostat cold work surface and into the mixer, where it combines with the incoming, astronomical signal.

E. Spectrometers

CASIMIR will have a high resolution digital FFT spectrometer developed by Omnisys [13], [14] as a turnkey COTS system. This instrument consists of two processing modules, each with two high speed samplers and an FPGA engine. The spectrometer covers the entire 4 GHz IF bandwidth, providing over 16 k channels and a maximum resolution 250 kHz per channel, which corresponds to a velocity resolution 75 m s^{-1} at 1 THz observing frequency. Lower resolution is possible by averaging channels. Two single height, 3U, correlator cards will handle processing the full 4 GHz IF bandwidth, at a total power consumption of less than 50 W, which is a major advantage for an airborne instrument. The spectrometer is scalable to provide IF bandwidths of 8, 12, or 16 GHz, and we plan to be able to exploit this capability on CASIMIR in the future.

F. FIR Relay Optics

Figure 9 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 path. This includes the two off-axis elliptical mirrors, the rotating, beam selecting plane mirror in the Optics Box (see Figure 10) and the fully reflective tertiary of the telescope. 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 path from the telescope to the mixer.

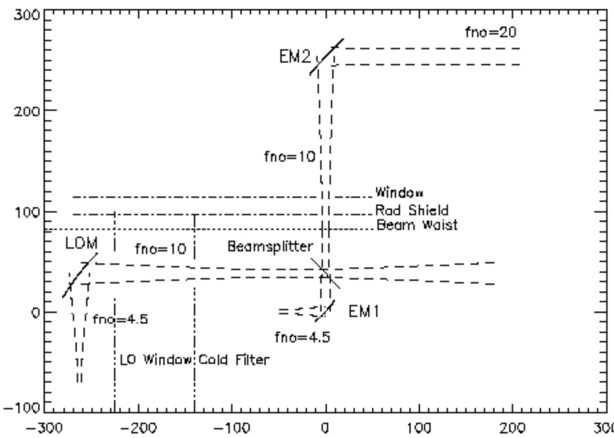

Fig. 9. CASIMIR Relay and LO Injection Optics. The up down orientation is reversed, as compared to the cryostat, meaning that the telescope beam, which is shown coming into the cryostat from the top in this figure, and enters the actual instrument from the bottom. The units on the scale are mm, with 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. EM2 is in the plane of the telescope beam, and 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

The relay optics for all bands are designed to have an edge taper of 10 dB. This corresponds to an aperture efficiency of 0.71. Initially, SOFIA will use an oversize tertiary mirror, which would reduce the aperture efficiency to 0.64; however, a smaller tertiary mirror may become available later, allowing for increased efficiency. All bands will have a main beam efficiency of 0.77. The beam size at 550 GHz (the largest beam) is 0.8 arcmin.

G. Optics Box

Since CASIMIR will use the fully reflective tertiary mirror on the telescope in SOFIA, 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' × 6' field of view and uses a 1024 × 1024 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. Besides the electronic feedthroughs mounted in the sides of the box, there are no mechanical motions through the pressure boundary, thus avoiding the possibility of dynamic motion seals failing during observations. Physical access to the Optics Box will not be required at any time during the flight.

Apart from providing the pressure boundary between the inside and outside of the aircraft and being the mechanical mount for the two cryostats, the Optics Box also contains all of the optics that is common for all FIR/submm bands. Figure 10 shows a 3D model of the interior of the Optics Box and these optics. Figure 11 shows the Optics Box with the flight cryostats mounted on top.

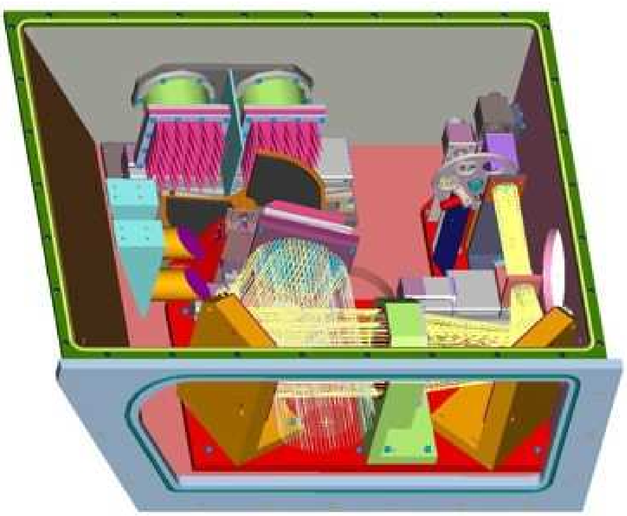

Fig. 10. The Optics Box interior. The cryostats are bolted directly to the lid of this box, which has been removed for this image. The elliptical mirrors mounted on the base of the cryostats (see Figure 4) protrude trough an aperture in the lid and are located in the plane of the telescope beam. The two elliptical mirrors for one of the cryostats are shown in the left part of the image. The 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.

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

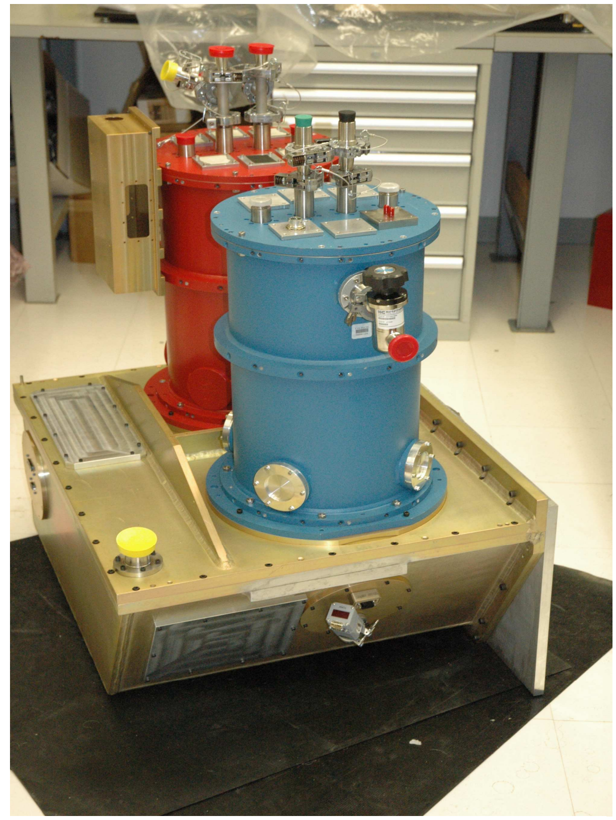

Fig. 11. The Optics Box with Cryostats Mounted. The cryostats mount directly to the top of the Optics Box. The Optics Box is constructed of welded Al 6061-T6, with dimensions of approximately 0.8 × 0.7 × 0.3 m, and wall thicknesses varying between approximately 15 and 20 mm. During observations, the interior of the box is exposed directly to the pressure in the telescope cavity, approximately 200 torr at 12 km altitude. The box is the pressure boundary between the aircraft cabin and this exterior air pressure. The baseplates of the two cryostats also form part of this pressure boundary. The telescope beam enters from the right of this figure, approximately 150 mm below the bases of the cryostat. It is then reflected through 90° and directed through windows in the cryostat baseplates. This is the only pressure boundary in the entire astronomical signal beam path, i. e., between the aircraft exterior pressure and the high vacuum within the cryostat.

and then the signal from a known temperature calibration load.

IV. Conclusions

CASIMIR is a FIR/Submm, heterodyne spectrometer for SOFIA, well suited for the studies of the warm (T ~ 100 K) interstellar medium. Particularly suited to detect water, it will also measure many other significant lines unobservable from the ground. Initially, the instrument will cover 500 to 1400 GHz. Eventually the frequency coverage may be extended up to 2000 GHz. CASIMIR will provide unprecedented sensitivity in this frequency region, due to recent advancements in SIS mixer design and local oscillator development. 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 observing bands will have an IF bandwidth of 4 GHz. A FFT digital spectrometer will provide continuous coverage of this band with very high resolution, up to greater than 10^6. The instrument design is extremely modular and will allow the continuous incorporation of new hardware, accommodating future improvements in mixer, LO and microwave spectrometer technologies, throughout the lifetime of the SOFIA observatory.

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