CASIMIR: A High Resolution Submillimeter Heterodyne Spectrometer for Airborne Astronomy

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Abstract

The **C**altech **A**irborne **S**ubmillimeter **I**nterstellar **M**edium **I**nvestigations **R**eceiver (CASIMIR) is a multichannel, heterodyne spectrometer being developed for the Stratospheric Observatory for Infrared Astronomy (SOFIA). It has a very high resolution, up to a million, over the submillimeter and far-infrared wavelength range of 150 to 600 microns, or 2.0 to 0.5 THz. CASIMIR is extremeley well suited to the investigations of warm, approximately 100 K, interstellar medium, both galactic and extragalactic. As a result of recent advances in both SIS and Hot Electron Bolometer (HEB) mixers, CASIMIR will cover this frequency range with very high sensitivity. We present a description of the instrument and its capabilities. CASIMIR is supported by the NASA/USRA SOFIA instrument development program.

Introduction

CASIMIR[1] will be a FIR/submillimeter, heterodyne spectrometer for SOFIA. It will study the warm, interstellar medium in a wide range of astronomical objects, including protostellar envelopes, molecular clouds and external galaxies.

The combination of the 2.5 m mirror of SOFIA with recent advances in superconducting mixer technology, will give CASIMIR unprecedented sensitivity. CASIMIR should have an improvment in sensitivity of a factor of up to 200, for compact sources, over NASA's SWAS satellite. CASIMIR will be able to carry out follow-up observations of many discoveries made with ISO, with much better spatial and spectral resolution. The sensitivity of the HIFI instrument, on the FIRST/Herschel satellite, is expected to be approximately 4 times better than CASIMIR, therefore, CASIMIR will be an important percursor instrument.

At first light in early 2005, CASIMIR will cover the frequency range, 0.5-1.25 THz, using **Super**conducting-**I**nsulating-**S**uperconducting (SIS) mixers. Soon afterwards, the range will be extended to 2 THz, using **H**ot **E**lectron **B**olometer (HEB) mixers. There will be a total of 8 bands, with two bands per cryostat. A combination of any two cryostats, out of the set of four can be flown on each flight, i.e. 4 frequency bands per flight. This availabilty of multiple bands for each flight will allow for efficient use of flight time. Searches for weak lines from rare species towards bright sources can be combined, on the same flight, with observations of abundant species towards faint or distant objects.

Selected Significant Transitions

Species	Transition	Frequency (GHz)	E_{lower} (K)	Atmospheric Transmission 1 mm H_20	SOFIA
CH	$F_1 \rightarrow F_2;\ J = 3/2^- \rightarrow 1/2^+$	536.76	0.0	0 %	97 %
$H_2{}^{18}O$	$1_{10} \rightarrow 1_{01}$	547.68	34.2	0 %	81 %
NH_3	$1_0 \rightarrow 0_0$	572.50	0.0	0 %	94 %
$H_2{}^{18}O$	$2_{11} \rightarrow 2_{02}$	745.32	100.6	0 %	82 %
NH	$N = 1 \rightarrow 0;\ J = 2 \rightarrow 1$	974.48	0.0	0 %	96 %
H_3O^+	$0_0^- \rightarrow 1_0^+$	984.66	7.5	0 %	65 %
NH^+	$3/2^+ \rightarrow 1/2^-$	998.90	0.0	0 %	95 %
CO	$9 \rightarrow 8$	1036.91	154.9	0 %	94 %
HF	$1 \rightarrow 0$	1232.48	0.0	0 %	30 %
H_2D^+	$1_{01} \rightarrow 0_{00}$	1370.09	0.0	0 %	94 %
N^+	$^3P\ J = 1 \rightarrow 0$	1461.13	0.0	0 %	92 %
^{16}OH	$^2\Pi_{1/2}\ J = 3/2^+ \rightarrow 1/2^-$	1837.82	181.9	0 %	94 %
C^+	$^2P\ J = 3/2 \rightarrow 1/2$	1900.54	0.0	0 %	88 %
CH_2	$1_{10} \rightarrow 1_{01}$	1917.66	22.4	0 %	99 %
CO	$18 \rightarrow 17$	1956.02	751.7	0 %	90 %

CASIMIR will study the fundamental rotational transitions of many astronomically significant hydride molecules. As shown in the table, the atmosphere is opaque to many of these lines, even from a site similar to Mauna Kea. Many of these lines have been observed by the ISO/LWS instrument. Observations of these species can provide critical tests of our understanding of interstellar chemical networks and reactions.

While oxygen is the third most abundant element, its chemistry in interstellar clouds is poorly understood, as the atmosphere is opaque to many of its key species, such as O, O_2 , H_2O, H_3O^+ and OH.

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 more highly excited transition of H_2D^+ at 372 GHz has been detected in one object after extensive ground based searches[2]. However, as this is a more excited transition, it traces hot, dense gas, with more complicated chemistry and the abundance of the species is expected to be low. The ground state line at 1370 GHz will be a better choice and there has only been one tentative observation of this line towards Orion with the KAO[3].

Another transition of major importance, is the 1461 GHz transition of the nitrogen ion, N^+ , which traces the warm, ionized interstellar medium. COBE[4] has shown that, apart from the 1900 GHz C^+ line, the two fine-structure N^+ lines are the brightest emmitted by our galaxy.

The high-J lines of CO will also be accessible to CASIMIR. These lines typically trace shocked gas and have been studied extensively with the KAO, including high-resolution, heterodyne spectroscopy[5].

References

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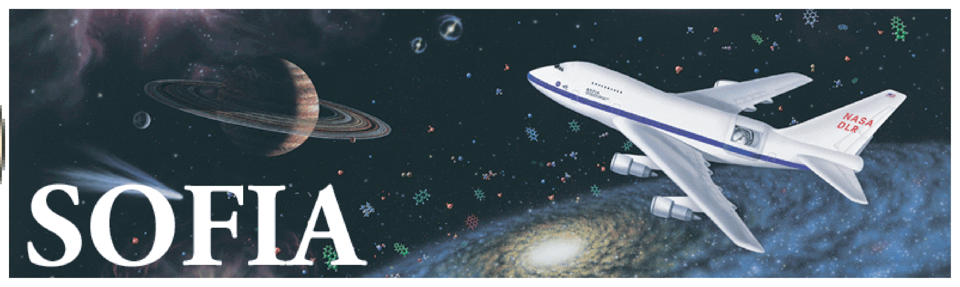
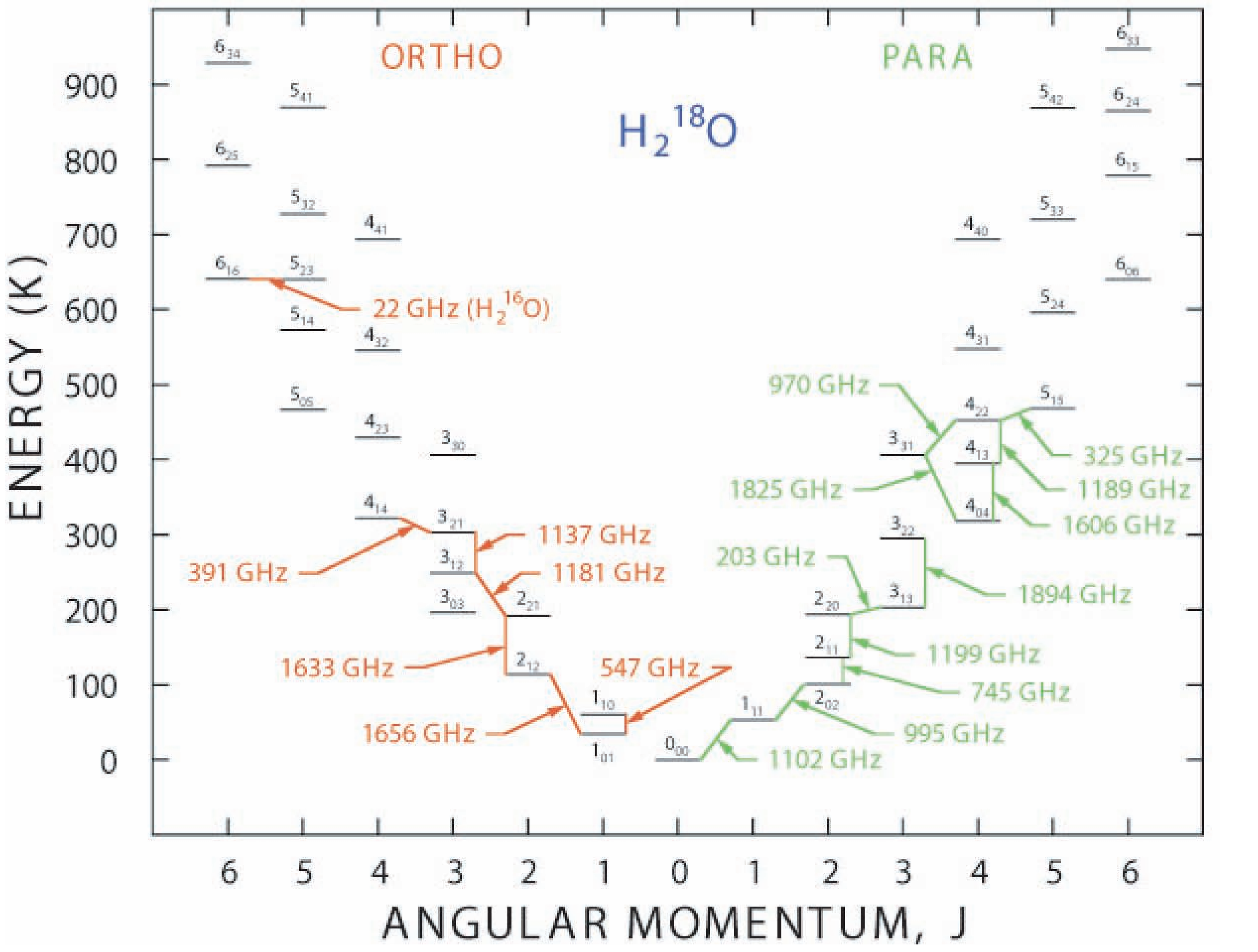
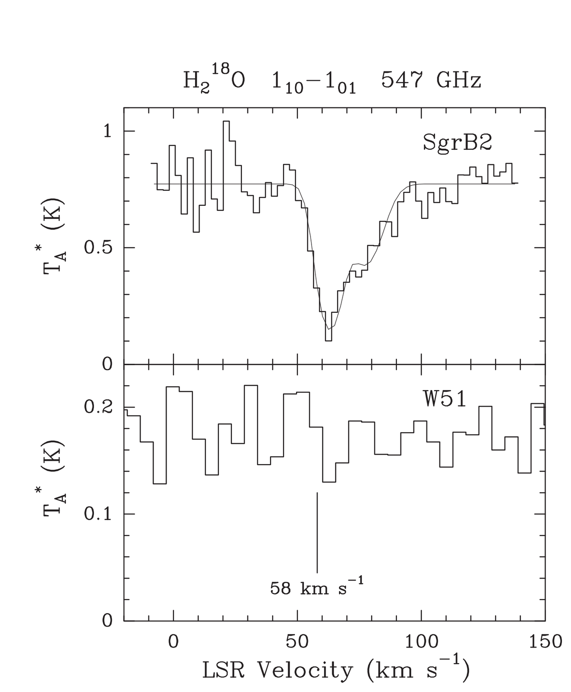
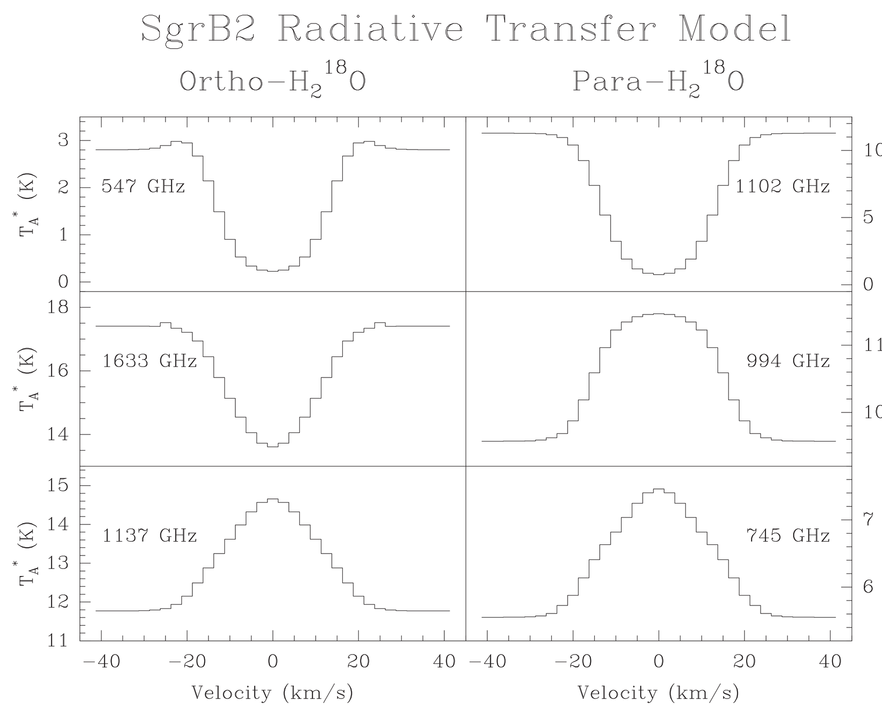


Interstellar Water



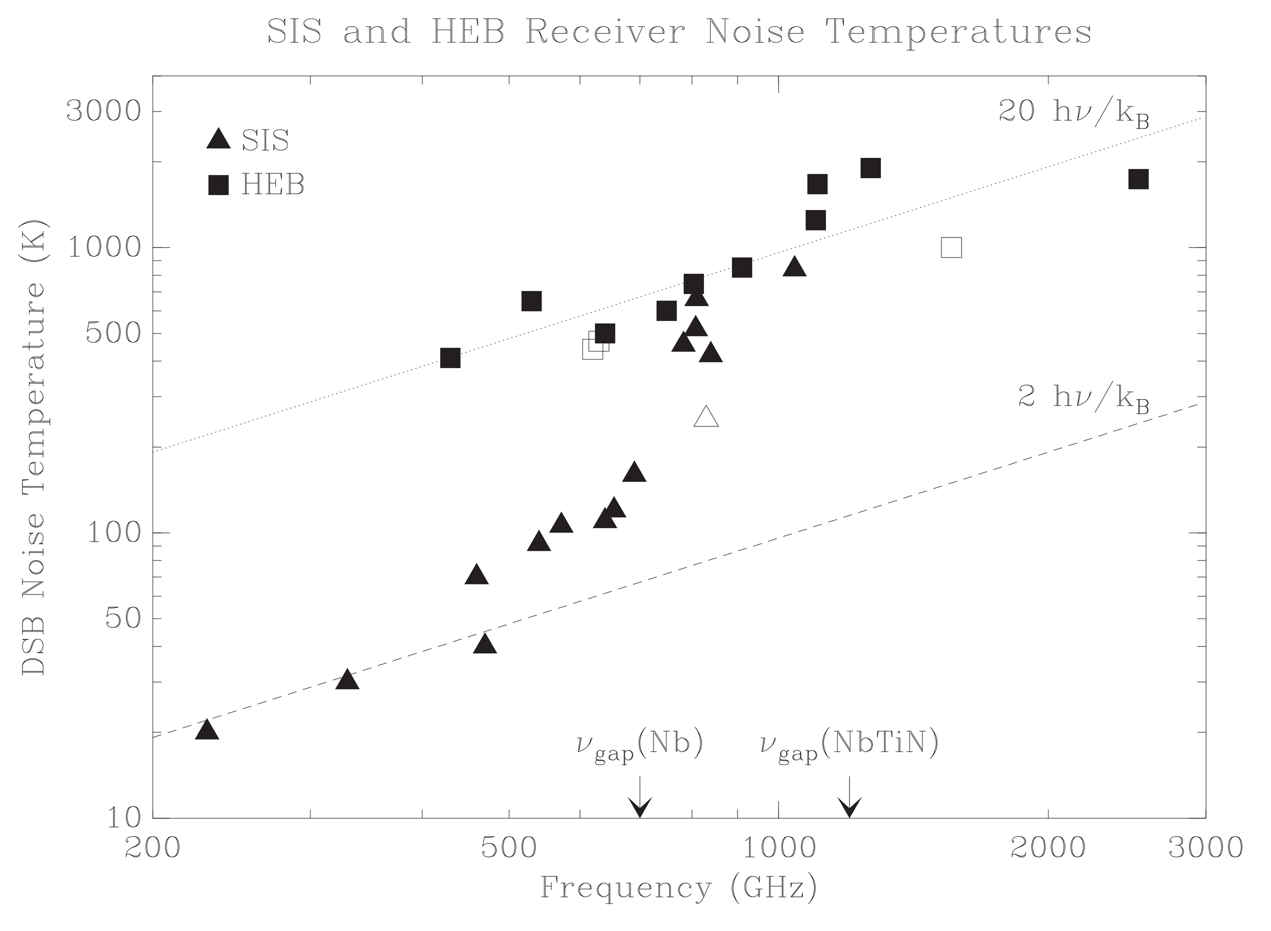
Gas phase water has an important role in the energy balance of molecular clouds, due to radiative heating or cooling through FIR/submillimeter rotational transitions. Even at the operating altitude of SOFIA, 41,000 ft, there is still too much water vapor to observe the ^{16}O isotope of water[6]. However, as the table shows, many transitions of the ^{18}O isotope of water lie within the frequency range of CASIMIR, including both the ortho and para groundstates, at 547 and 1102 GHz. The ^{18}O isotope is actually preferable for studying the abundance of water, as the ^{16}O isotope lines are often optically thick.





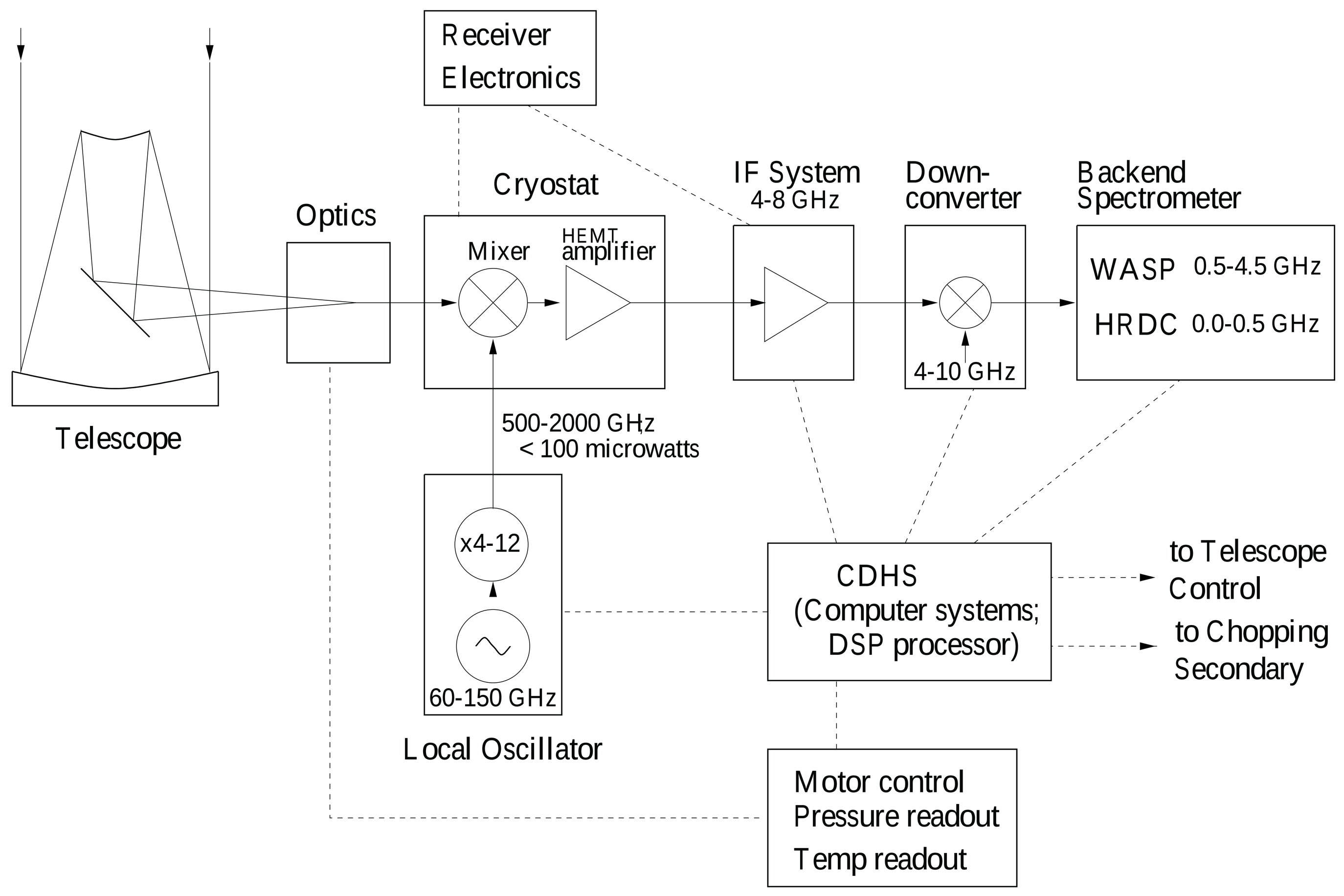
The figure on the left shows KAO observations at 547 GHz towards SgrB2 and W51. The figure on the right shows the predicted $H_2{}^{18}O$ line profiles for CASIMIR on SOFIA. The predictions are based on a radiative transfer model, which assumes a spherical model, with a r^{-2} density model and a $r^{-0.5}$ temperature variation, which match existing CO, dust and $H_2{}^{18}O$ observations . At 547 GHz, i.e. near the longest wavelength for CASIMIR, the beam diameter will be ~1'. CASIMIR will be able to study the abundance of water with unprecedented sensitivity, spatial and spectral resolution.

Mixer Performance



Below the Nb bandgap energy, 700 GHz, SIS mixers have achieved noise performances approximately twice the quantum limit. The hollow triangle in the figure indicates the best performance attained so far with an SIS mixer above 700 GHz, 650 K (DSB) at 1.15 THz. Above 1.2 THz, HEB mixers will be used. Sensitive HEBs have been operated at up to 2.5 THz. We expect that there will be significant further improvement in the noise performance of SIS mixers above 700 GHz and HEBs. When CASIMIR is in operation, the receiver noise temperatures are expected to be as low as 0.3 K/GHz for SIS mixers and 0.7 K/GHz for HEBs.

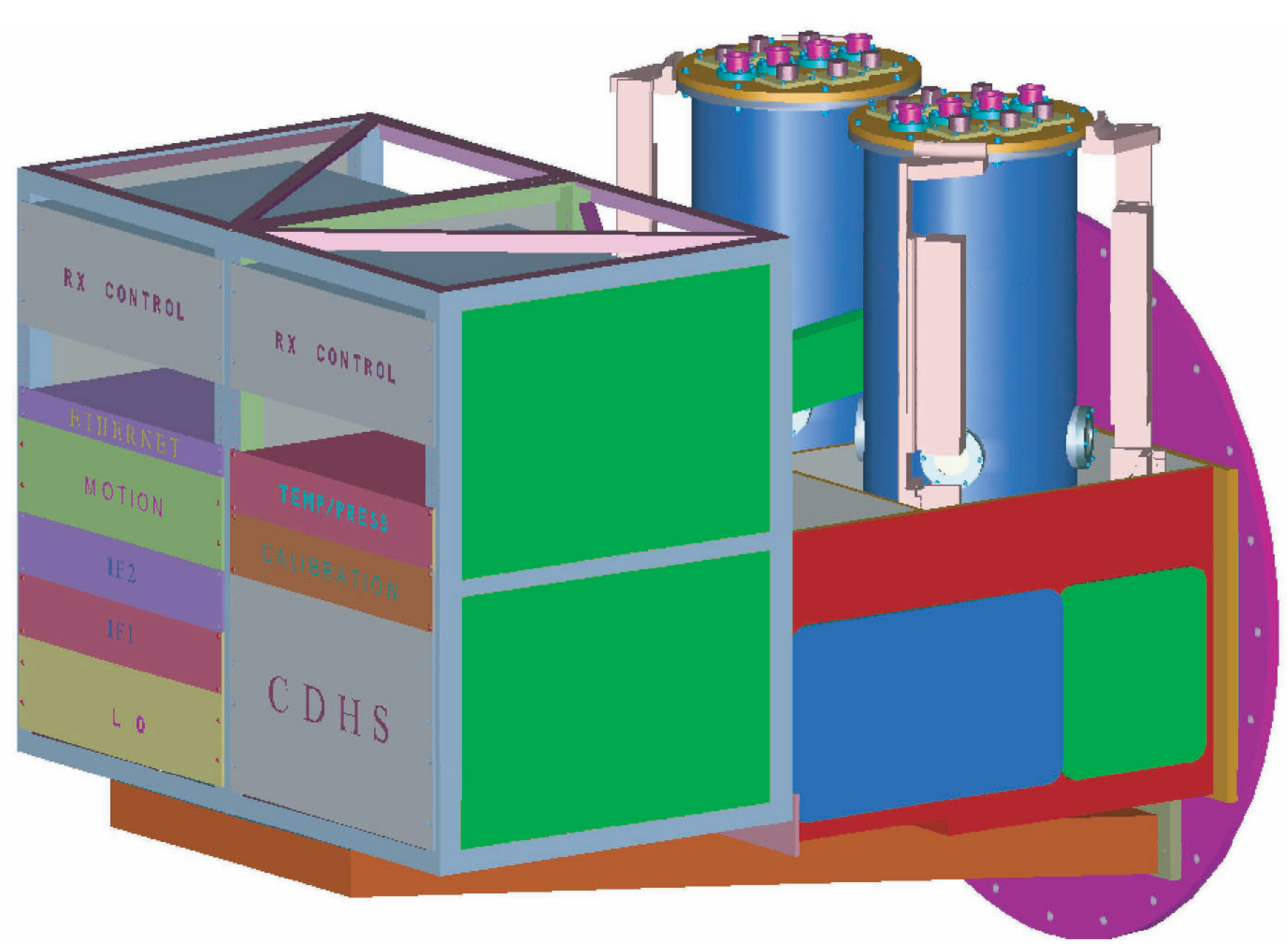
Instrument Configuration



The above figure is a schematic diagram of the CASIMIR instrument. The light passes from the telescope through the relay optics, which directs the light to one of two cryostats and converts the *f/#*=19 telescope beam to the *f/#*=4.5 of the mixer. The output from the local oscillator (LO) is also quasioptically coupled to the mixer. The resultant intermediate frequency (IF), 4-8 GHz, signal is amplified by a cryogenically cooled HEMT amplifier and then by a room temperature amplifier. This IF signal is downconverted to a frequency to match one of two backend, or microwave, spectrometers.

1) The **W**ide bandwidth **A**nalog **SP**ectrometer (WASP) covers the entire 4 GHz bandwidth, continuously with 256 channels.
2) The **H**igh **R**esolution **D**igital **C**orrelator (HRDC), covers 500 MHz with 2 MHz channels.

The instrument is controlled by a **C**ommand and **D**ata **H**andling **S**ystem (CDHS), a VME based system consisting of single-board computers and DSPs.



CASIMIR is approximately 1.5 metres long by 1 m by 1 m and weighs 550 kg. Each of the two cryostats, the blue cylinders in the figure, can contain up to 2 mixers, a total of up to 4 mixers per flight. The cryostats are mounted on top of a box, the interior of which is at the same pressure as that outside the aircraft. This box contains all the relay optics and calibration systems. All the optics are reflective, the windows in the base of the cryostats are the only transmissive elements in the optical train between the telescope and the mixers. The local oscillators are the pink structures mounted on the side of the cryostat. They are solid state and continuously tunable, driven by HEMT power amps. Almost all the electronic systems will be inserted in a rack mounted directly on the instrument, the green structure. The backend, microwave spectrometers will be mounted in a rack on the telescope's counterweight, preventing differential rotations and ensuring short cable runs. The design of the instrument is modular and extremely versatile, e.g. the optics system can accomodate the full 8' diameter FOV of SOFIA. CASIMIR will regularly be able to incorporate major improvements in detector, LO, and spectrometer technology.

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SOFIA and Other Instruments: **www.sofia.usra.edu**