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Icy Target Thermal Test Apparatus and Calibration of a Planetary Spectrometer

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The Compositional Infrared Imaging Spectrometer (CIRIS) is currently under development at JPL for outer planetary missions, and is undergoing thermal-vacuum environmental testing as part of the TRL progression effort. This involves analyzing icy targets under cryogenic vacuum conditions with the spectrometer and the use of an optical calibration device designed for integration with the test setup. CIRIS was designed for use on a future Europa orbiter, with applications for missions to other worlds including Mars. It has a compact and rugged design due to its spinning refractor, which replaces the moving mirror setup of a traditional Michelson interferometer. We have designed and fabricated a test apparatus to calibrate CIRIS using a black body source and to measure reflectance of ice specimens. The apparatus presented here is validating the performance of CIRIS under Europa-like conditions, including temperature of the spectrometer, temperature of the target, and illumination of the target. A dewar assembly resides inside the vacuum chamber and is filled with liquid nitrogen using a fluid feedthrough. A cold plate mounted directly to the dewar will freeze/ contain the ice or rock targets. An external blackbody light source will illuminate the targets via a mirror/ window assembly, and a second mirror will direct the reflected light into the spectrometer. The mirror configuration can be moved in six degrees of freedom for optical alignment. The calibration source is designed to emit blackbody radiation at known and controllable temperatures between 150 and 350K via interchangeable apertures. To maintain an emissivity as close as possible to that of an ideal blackbody, the calibration source is a conical cavity coated with highly emissive paint within a solid cylinder. The cavity is made of aluminum and contains multiple heaters to ensure isothermal conditions, with ceramic standoffs to create a long thermal path which allows the cavity to be at a high temperature while the spectrometer and other nearby hardware remain cryogenic.

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Nomenclature

CIRIS = Compositional Infrared Imaging Spectrometer
IR = Infrared
LN2 = Liquid Nitrogen
FTIR = Fourier Transform Infrared
FFT = Fast Fourier Transform
ZnSe = Zinc Selenide IR transmissive glass

I. Introduction

Future missions are planned to continue the investigation of the surface chemistry of icy planets to explore the possibility of past or present subsurface habitability on other worlds (e.g. Europa, Enceladus, and Ganymede)[1]. Such missions require a rugged and efficient spectrometer for studying the chemistry and topography of the planetary surfaces. The Compositional Infrared Imaging Spectrometer, CIRIS (Figure 1), was developed for a future orbiter to Europa[2], but is applicable for examining the surface composition of other worlds and is currently being proposed for the Mars 2020 mission. It was designed to overcome various obstacles that will be experienced during long-term space travel and while orbiting Europa, such as highly varying temperature and the intense radiation and magnetic field of Jupiter[2]. It also has a high signal-to-noise ratio in the mid-infrared region, allowing it to perform mid-infrared reflectance spectroscopy in the outer planetary region without interference from the radiation environment near Jupiter[2]. The spectrometer can function in cryogenic temperatures from 70-130K with the use of passive cooling methods while onboard a spacecraft that is orbiting Europa[2].

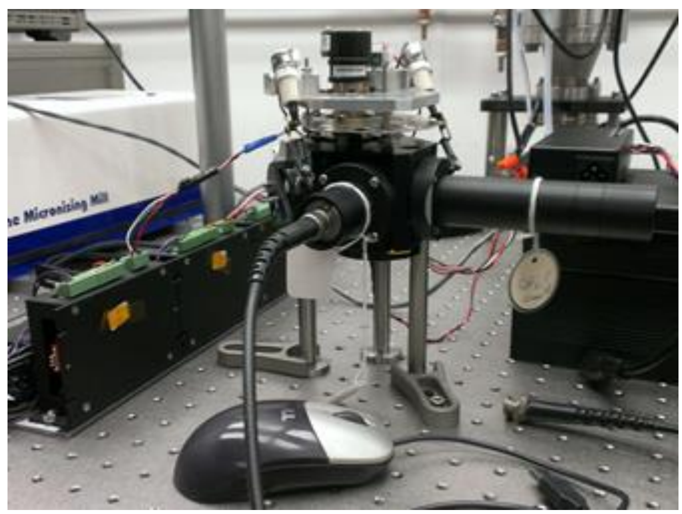

Figure 1. Picture of the CIRIS in lab.

Although Fourier Transform Infrared (FTIR) spectrometers have been used for past spaceflight missions[3,4], most space missions in the past have used some form of grating spectrometer. Compared to a FTIR spectrometer, grating is less photon-efficient and has a lower end detector throughput[5]. For the purposes of planetary exploration, an FTIR (Figure 2) is more suitable. In a traditional Michelson Fourier Transform spectrometer, a beamsplitter separates incoming light into two beams. One beam travels a fixed length, and the other is reflected off of a linearly translating mirror. These beams then recombine before striking the detector, which creates a fringe interference pattern. A fast Fourier Transform (FFT) is performed on this time-varying signal, which produces a spectrum of light intensity versus wave number[5,6]. Unlike the Michelson setup, the CIRIS is a rotary Fourier Transform Spectrometer. The CIRIS spectrometer is currently under development in conjunction with Designs & Prototypes, Ltd., and is based on the TurboFT spectrometer design, which was developed under an SBIR contract for the US Army Edgewood Chemical and Biological Center (ECBC), and with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia[7]. Figure 2 shows the optical path of light as it travels through the CIRIS spectrometer. Light enters the CIRIS (A) and passes through the beamsplitter (B). Both beams reflect off the mirrors (C) and hit the refractor (D), which spins

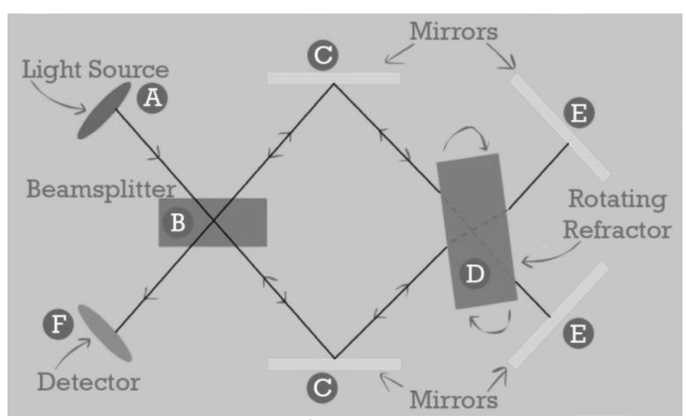

Figure 2. Internal optics of the CIRIS.

at a constant speed. The light then reflects off of another set of mirrors (E) and enters the detector (F). This creates an optical path difference in accordance with Snell's Law. As the refractor rotates, the angle of incidence of one beam decreases while the other increases. For every rotation, there will be four points at which the optical path difference will be zero. This occurs when the refractor is fully horizontal or vertical, resulting in four interferograms per revolution[7]. This design makes the CIRIS more compact, lightweight and rugged than traditional spectrometers, which makes it very suitable for use in long-term spaceflight missions[2,7].

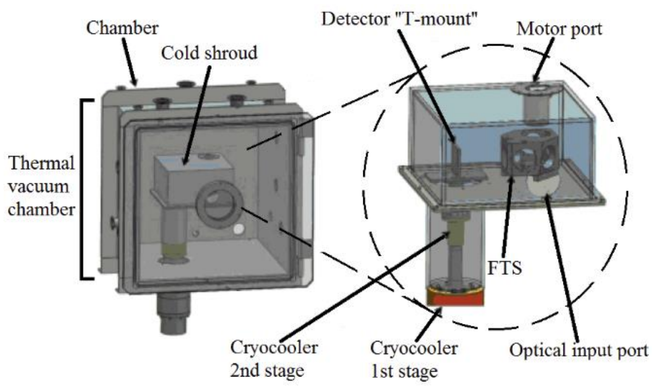

Figure 3. Components of the vacuum chamber.

The CIRIS prototype must undergo thermal-vacuum environmental testing as part of the technology development and Technology Readiness Level (TRL) progression effort. For this purpose, a thermal vacuum chamber was created to simulate the environments the CIRIS will encounter near Europa and on the surface of Mars. Figure 3 shows the various components of the thermal vacuum chamber. This chamber contains the CIRIS and all associated experimental hardware. The two-stage cryocooler is used to remove heat from the chamber so that all internal components will reach cryogenic temperatures as low as 30K at the detector[8]. The detector is mounted to the T-shaped mount, which is connected to the second stage of the cryocooler. The first stage of the cryocooler cools the cold shroud, optical components and the FTS chassis to a minimum temperature of 80K. Resistive heaters are attached under the cold shroud and T-mount to maintain desired set point temperatures within 0.5K using a Lakeshore temperature controller with feedback from temperature-sensitive diodes mounted close to the heaters. The CIRIS mounts to the base of the aluminum cold shroud with maximum contact area to minimize the temperature difference to within 1K between the cold shroud and the top of the FTS chassis. The motor that is currently being used to rotate the refractor within the CIRIS is an off-the-shelf product that is not designed for use in cryogenic temperatures. To account for this, the motor protrudes through a hole in the cold shroud and is mounted in a plastic housing on plastic standoffs to minimize thermal conductivity. This allows the motor to operate near 273K while the body of the spectrometer is maintained at 100K[2].

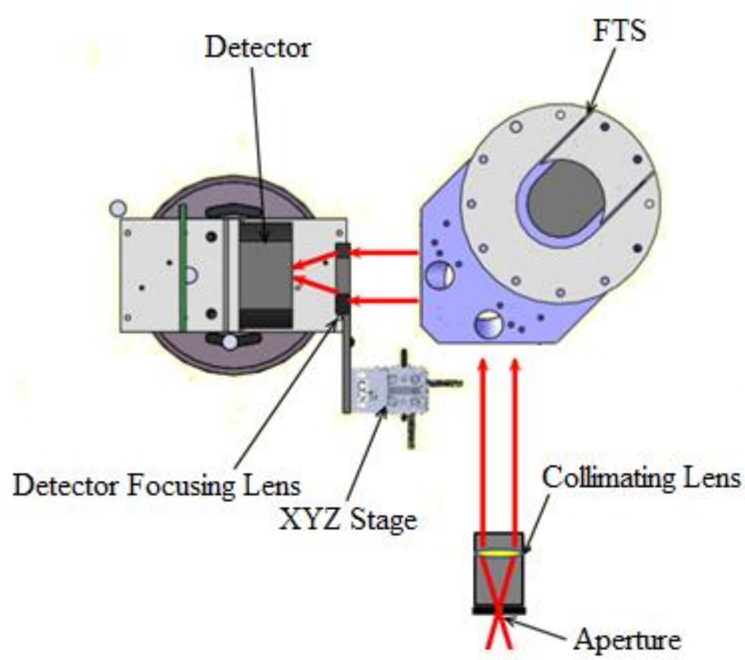

Figure 4. Optical setup within the vacuum chamber.

The optical setup within the thermal vacuum chamber (Figure 3) directs incoming light to within the field of view of the spectrometer. The light input of the spectrometer uses external collimating optics to ensure that parallel light beams enter the thermal vacuum chamber. A 25.4mm diameter Zinc Selenide lens with a 130mm focal length and a 1mm diameter aperture located at the focal point is used to collimate the light. A Zinc Selenide lens is located at the output of the spectrometer to focus the light onto the detector. Light enters from the window on the chamber door, passes through an opening in the cold shroud and through spectrometer optics to reach the detector. Basic functionality of this system has been shown through preliminary tests of its ability to produce a spectrum of a flat blackbody source[2].

The goal of the work presented here is to allow the CIRIS to perform reflectance spectroscopy measurements on targets consisting of materials representing planetary surfaces, such as ice or soil, in a controlled thermal vacuum environment. An additional goal is to perform calibration measurements between tests to increase measurement accuracy and test for spectrometer drift over time. We have constructed a testing apparatus within the existing thermal vacuum chamber to test the functionality of the CIRIS. This apparatus will allow us to test ice samples that simulate the surface of Europa, as well as samples of soil for future exploration of other worlds such as Mars.

II. Thermal Vacuum Chamber

The existing vacuum chamber has been expanded by adding a 6" conflat six-way cross mounted on the window opening of the vacuum chamber. The inside of this cross is kept under vacuum, and is evacuated by a separate roughing pump from the main chamber to minimize contamination of the cold spectrometer optics and detector from water vapor. A gate valve separates the sample chamber from the main chamber, and this valve can be opened to allow light to pass from the sample to the spectrometer during measurements. A custom flange adapter machined by Thor Labs interfaces the six-way cross to the vacuum chamber door (Figure 5). The cross contains a fixed horizontal sample tray for the test sample, which is connected to a liquid nitrogen dewar that can quickly freeze water into ice samples. A mirror setup inside the cross facing the opening of the thermal vacuum chamber directs reflected light from the sample towards the spectrometer. This sample chamber can also be used as a stand-alone unit. A spectrometer or other viewing device can be placed facing the top opening and can view the target through a ZnSe window.

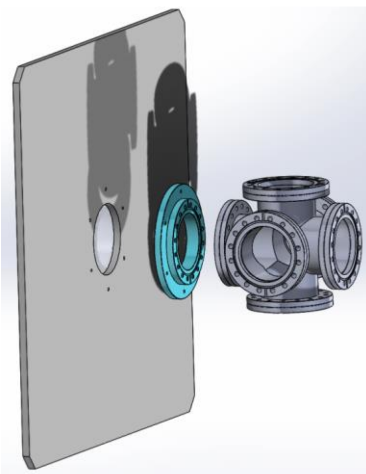

Figure 5. Custom flange adaptor. *Connects six-way cross to vacuum chamber door.*

A cylindrical copper c101 dewar assembly with a volume of 1400cc resides inside the vacuum chamber. Copper caps are silver soldered directly to the 22.86cm long copper pipe, making up the dewar apparatus (Figure 5). This dewar is filled with liquid nitrogen using a gravity feed (Figure 6). It is mounted to the bottom of the 6-way cross using a ConFlat full 304L stainless steel nipple. A cylindrical aluminum 6101 sample plate is mounted directly to the top of the dewar to freeze the ice target. The sample plate can also be used to contain rock or soil targets for testing. The sample tray is attached directly to the top cap, allowing the contents of the sample tray to freeze.

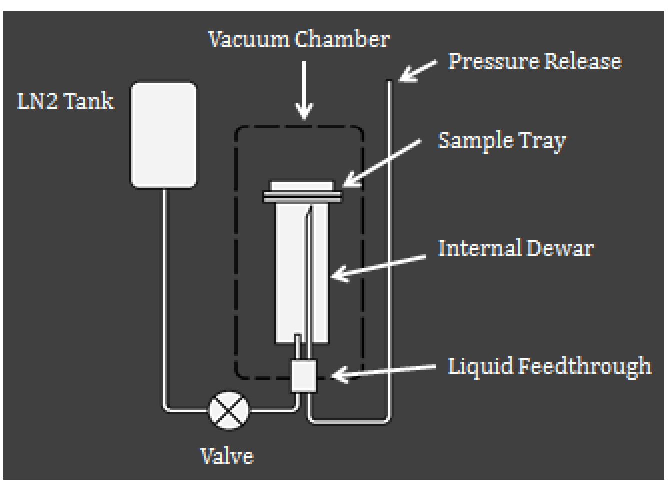

Figure 6. Gravity feed. *This schematic shows the internal dewar setup.*

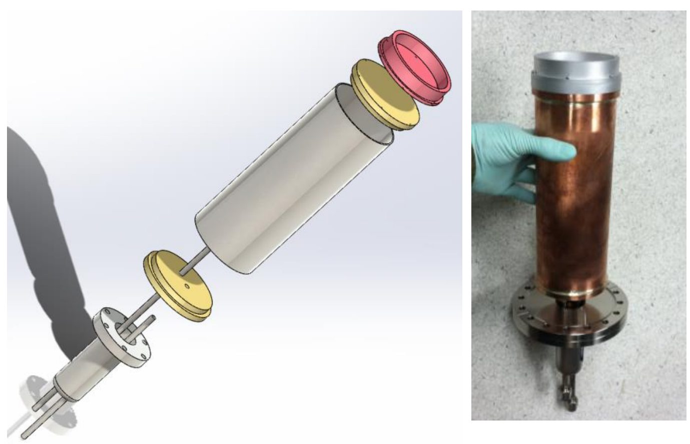

Figure 7. Internal dewar: exploded view and photograph. *This shows how the dewar is constructed: one copper pipe with 2 copper end caps silver soldered to it, and an aluminum sample container on top. The fluid feedthrough is silver soldered to the bottom copper cap.*

The mirror setup (Figure 8) mounts to the cross face opposite the chamber door (Figure 9). All of the parts are made from aluminum 6101. It was designed using Solidworks and then machined by FirstCut. The assembly is designed to move the mirror in six degrees of freedom (DOF) for optical alignment. Four threaded rods shown attached in the corners provide a stage for linear translation in two dimensions (DOF 1, 2) (Figure 10). These rods pass through the connecting piece (red part in figure 10), and the piece that connects the assembly to the cross. They can be manually adjusted and held in place by hex machine nuts. Attached to the cross-shaped piece are a back frame, a front frame, and a mirror holder. The front frame has a track milled out which fits the mirror holder, allowing it to be rotated and then held in place by tightening the screws (DOF 3) (Figure 11). Additionally, the cross-shaped piece has four 2-56 screws that fit through oversized holes on the front and back frame. This allows for changes in the angle of the mirror holder (DOF 4, 5) (Figure 12), and movement of the whole mirror assembly along the optical axis toward and away from the spectrometer (DOF 6). All of these features allow the mirror assembly to have a fully adjustable position. The mirror holder is compatible with both a 50mm protected gold flat mirror, which will be glued to the front of the mirror holder, and a 60° parabolic off-axis protected gold concave mirror. Both mirrors are from Edmund Optics[9].

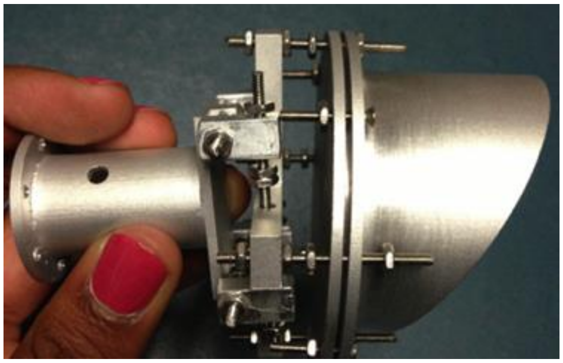

Figure 8. Final mirror assembly.

Figure 9. Exploded CAD view of the mirror assembly.

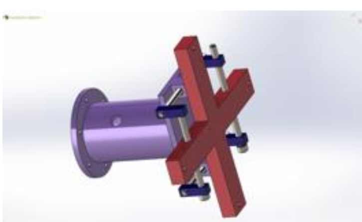

Figure 10. DOF 1, 2.

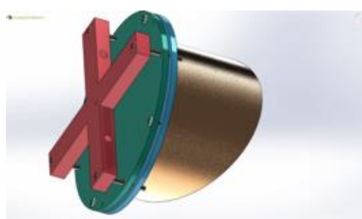

Figure 11. DOF 3.

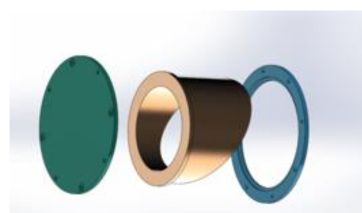

Figure 12. DOF 4, 5.

III. Calibration Device

A calibration device (Figure 13) was designed to emit blackbody radiation at temperatures of 150-350K via interchangeable apertures in order to provide spectral and radiometric calibration capability. The device must be able to calibrate the CIRIS by entering its field of view before measurement and then move away during measurement of other targets. In addition to this, the device must fit within the dimensions of the thermal vacuum chamber so that it will not interfere with any other components. The calibration device apparatus was designed using Solidworks and then machined by FirstCut. Minor adjustments were made manually after receiving the parts to meet the physical constraints of the thermal vacuum chamber.

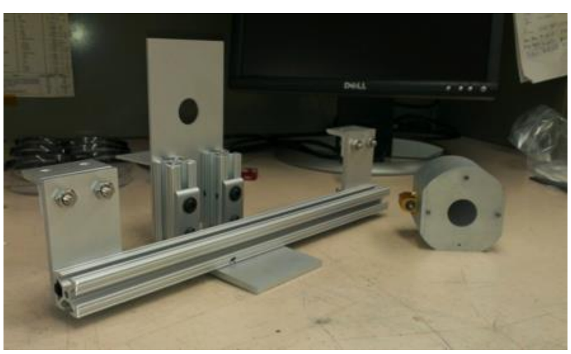

Figure 13. Components of the calibration device.

The calibration source is a conical cavity (Figure 14) within a cylindrical aluminum piece. The conical shape has an opening diameter of 4.82cm and extends 4.82cm into the cylinder. The end of the cone was slightly rounded to facilitate machinability. The opening of the cavity is attached to an aperture plate 0.5cm thick and identical in profile to the cavity face, with an aperture hole of 2.54cm in diameter. The inner surface of the cavity is coated with Avian Black-S coating from Avian Technologies. This coating has a low reflectivity through the mid-infrared spectrum, and the cavity has a conical shape. Therefore, the emissivity of the blackbody calibration source is very close to 1, which is necessary for accurate calibration[10]. In addition to this, the aperture (Figure 14) limits the power emitted from the blackbody to the spectrometer to a known value for radiometric calibration purposes. The bottom and sides of the cavity were flattened for the attachment of ceramic standoffs and resistive heaters (Figure 14). Two #4-40 tapped holes on each of the two sides allow for the attachment of two 25 ohm resistors and an additional three #4-40 tapped holes in the front provide mounting for the attachment of the aperture cover plate. Four #6-32 tapped holes on the bottom face provide mount points for the ceramic standoffs. An additional #4-40 tapped hole on one of the sides provides mounting for the attachment of a thermometer, which ensures that the cavity is at the constant heated temperature. A vent hole of .24cm in diameter was added for every tapped hole, connecting the bottom of the tapped hole to a different side of the device, to ensure that no air would be trapped between the end of the screw and the bottom of the hole, which would cause virtual leaks under vacuum.

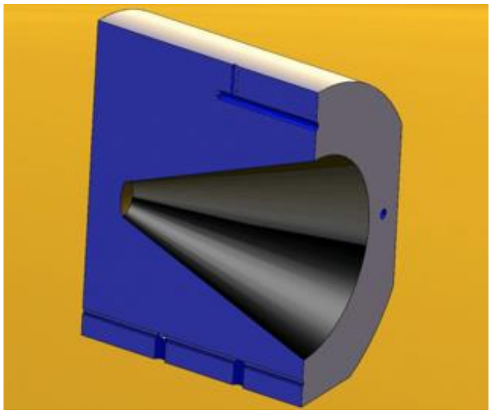

Figure 14. Cross section of conical cavity.

The cavity piece is connected to the rest of the device (Figure 15) by two ceramic standoffs that have a diameter of 0.635cm and a height of 1.27cm using set screws. Four holes were made on the bottom of the cavity piece in a triangular formation so that in the case that two standoffs would not be enough to support the entire cavity piece, the setup can be altered to have three standoffs. Ceramic was chosen as the material for these standoffs so that there would be minimal thermal conductivity between the cavity piece and the rest of the device. #6-32 screws were used to attach the bottom of the standoffs to an angle bracket. Four #6 clearance holes were made in the same formation

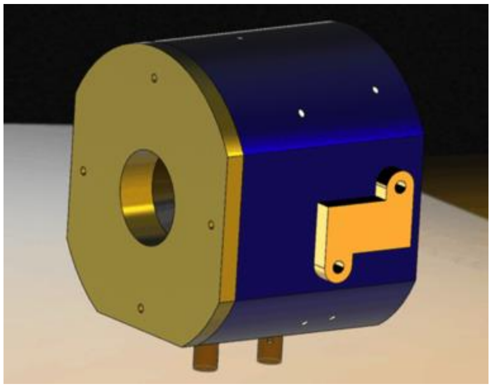

Figure 15. Cavity component with aperture and resistor.

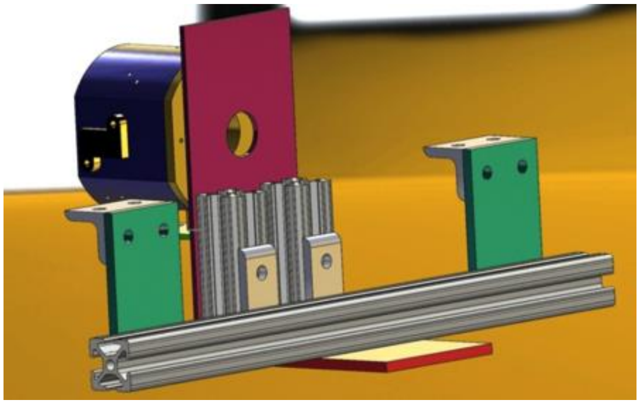

Figure 16. CAD Model of whole calibration device.

as the holes for the ceramic standoffs on the bottom of the cavity for attachment to the angle bracket. The vertical portion of the bracket has three #6 clearance holes for attachment to a separate aperture plate. This aperture plate is a 0.254cm x 7.62cm x 15.875cm vertical piece with a 2.22cm diameter aperture concentric to the aperture of the cavity cover. 0.635cm clearance holes are located on the bottom corners so that it can be attached to two 7.62cm long pieces of 10 series 80-20 aluminum. These 80-20 pieces enable vertical adjustment of the cavity piece. An 80-20 custom 1 x 2 vertical angled bracket is attached on the opposite side of each 7.62cm 80-20 piece for attachment to a 7.62cm wide plate. Two holes are made so that the plate can be attached to a 33.02cm piece of 80-20. This point of attachment is used for horizontal adjustment. A plate and an 80-20 custom 2 x 2 horizontal angled bracket are attached on both sides of the 80-20 piece so that it can be mounted to the bottom of the cold shroud.

IV. External Optics

Light is emitted from a blackbody radiator (different from the blackbody source used for calibration) and travels through an external optical setup before entering the six way cross and the thermal vacuum chamber (Figure 17). Light enters the six-way cross through a conflat flange with a 10.16cm ZnSe viewport attached to the top opening of the six way cross. The light is in the mid-infrared spectrum and emitted using an Electro Optical Industries Model WS163 blackbody radiator[11]. This model of a blackbody radiator was chosen because it can produce infrared light at the target of approximately the same irradiance as the light from the Sun that reaches Jupiter. The light reaches a convex lens within a Lens Tube Slip Ring mount from Thor Labs[12] with a diameter of 5.08cm that is located 8.255cm away. The lens mount is vertically and horizontally adjustable to allow it to move towards and away from the blackbody source and is attached to an 80-20 aluminum piece so that the lens can be positioned to be concentric to the light output. The light that is emitted from the blackbody source is collimated after being transmitted through the convex lens. The mount is attached to a 60mm elliptical turning mirror mount from Thor Labs that directs the light towards the viewport and into the chamber[13]. A support tower was built with 80-20 aluminum so that the blackbody radiator and all corresponding optical components are held in the correct position for the light to enter the six-way cross.

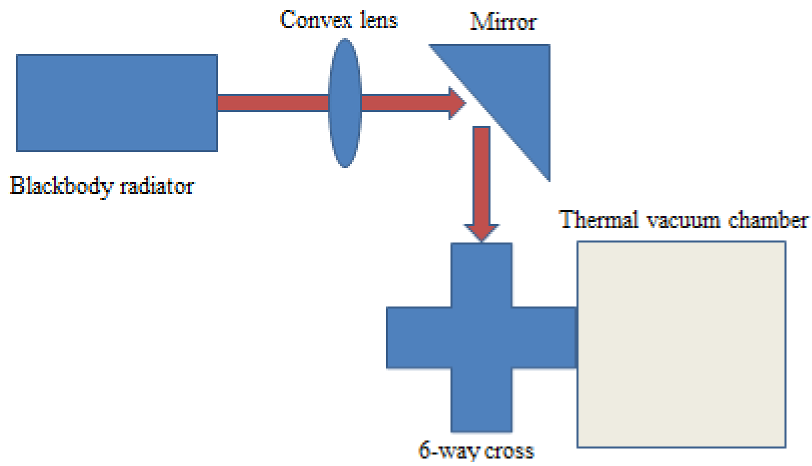

Figure 17. Diagram of external testing setup.

V. Testing

Preliminary testing shows the basic functionality of the cold sample dewar system for use as a stand-alone testing apparatus with a warm spectrometer. The setup shown in Figure 17 shows the sample apparatus setup with a benchtop version of the CIRIS spectrometer. In this test, we use the flat mirror configuration without collimating optics between the target and spectrometer. The ZnSe window is used to allow light to pass from the chamber to the spectrometer, which is mounted with its inlet right against the glass.

In this test, the sample is illuminated by a small IR lamp with a parabolic reflector, as shown in Figure 17. This light source consists of a Spectral Products ASB-IR-12K [14] blackbody filament with parabolic reflector contained in a 2.54cm diameter x 7.62cm long optical tube. This assembly rests on top of the upper ZnSe window and illuminates the target with a spot size approximately the size of the sample tray. The small red dewar is used to cool the detector. This provides similar irradiance as the large blackbody radiatior described above, but is not calibrated. The emissivity curve provided by the manufacturer is shown in Figure 19. This small source is portable and convenient for preliminary testing, and is powered using a 6V DC power supply.

Figure 18. Sample apparatus setup with benchtop version of CIRIS spectrometer.

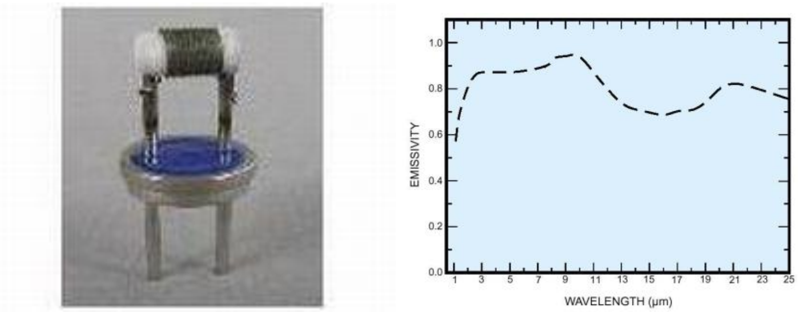

Figure 19. compact IR emitter used for preliminary testing and spectral emissivity plot[14].

Using the gravity-fed liquid nitrogen system, the sample tray reaches a measured minimum temperature of 105K without additional radiation shielding inside the chamber. This temperature could likely be reduced by the use of a radiation shield to block radiation from the warm chamber walls surrounding the dewar, but is sufficient for Europa surface studies, which varies between 100K and 130K[15]. For the test, a sintered gold reflectance standard of broadband unity reflectance was placed in the sample tray and thermally coupled to the tray using using Dow Corning 340 heat sink compound. The chamber was evacuated and the target cooled to 107K. Spectra were collected with the lamp operating at 4, 8, and 12W.

After collecting reflectance standard data, the dewar was allowed to return to room temperature, the chamber vented, and the standard removed. After cleaning the heat sink compound from the sample tray, the tray was filled approximately 7 mm deep with water. The water sample was frozen by filling the dewar with LN2 before pumping vacuum. As soon as the sample solidified, which took approximately 10 minutes, the chamber was pumped down to vacuum conditions. This order of operations minimizes the amount of evaporated water reaching the vacuum pump

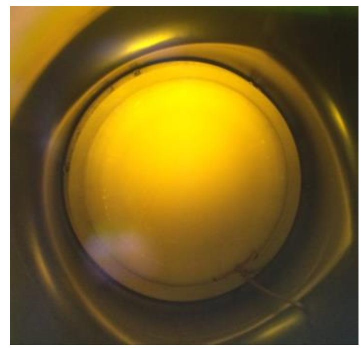

Figure 20. Frozen ice sample in dewar. Photo taken through ZnSe window in top of 6-way

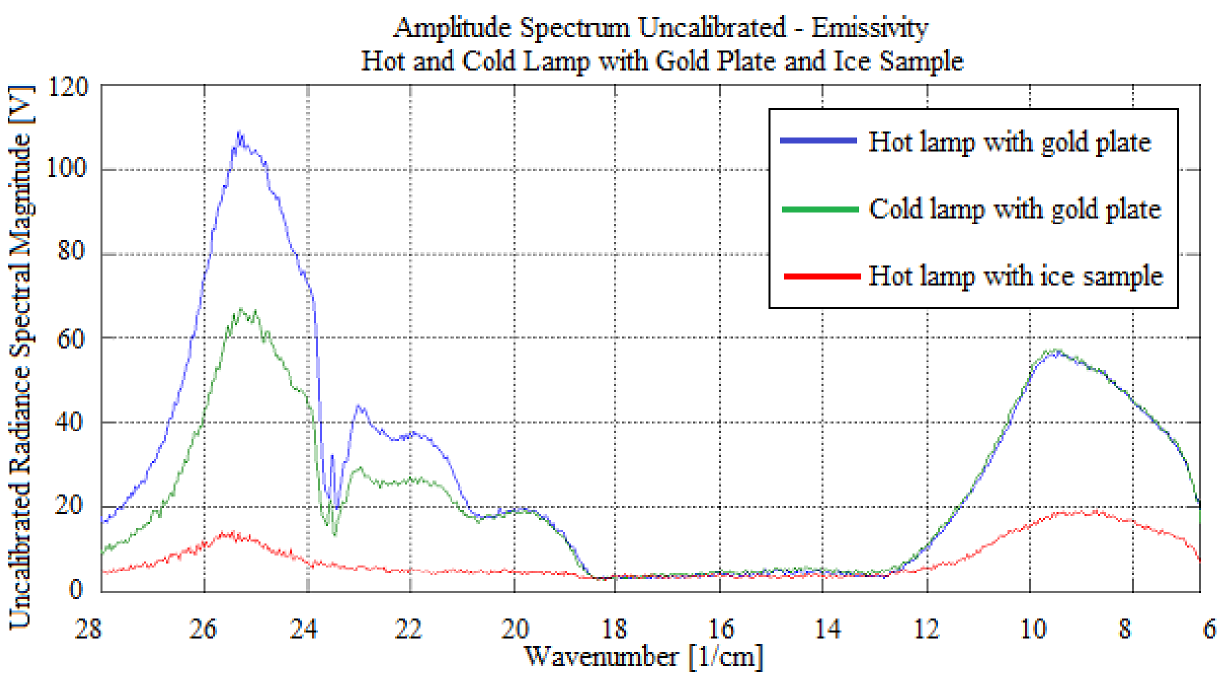

Figure 21. Preliminary spectral data from ice target and gold reflectance standard with 4W and 12W lamp power levels.

or deposited elsewhere in the chamber. Because the sample dewar is the coldest object in the chamber, any sublimated water vapor will tend to condense back onto the dewar/ sample tray. Spectra of the ice target were collected using the same geometry and illumination conditions as the reflectance standard. Figure 20 shows a photograph of the frozen ice target, taken through the top ZnSe window.

Figure 21 shows a plot of the uncalibrated signal magnitude vs. wavenumber measured by the spectrometer for the gold reflectance standard at 4 and 12W lamp power and the ice sample at 12W. Signal-to-noise is poor in the $1800cm^{-1}$ to $1500cm^{-1}$ due to low sensitivity of the lab detector used in that range.

This test used no collimating optics between the spectrometer input and the target, resulting in a large field of view. Because of this, significant radiation from the warm chamber walls reached the spectrometer, and severely increased the background signal levels. Further testing will use collimating optics and the parabolic mirror to allow the spectrometer to capture only light from the cold target. This should increase signal-to noise dramatically and allow testing of different optical designs for the spectrometer and input and output optics.

VI. Summary and Future Work

The goal of this project was to produce and test a cold target and calibration testing apparatus for the CIRIS for further testing of the spectrometer in a simulated environment of Europa. Testing of various samples such as ice or soil is necessary to ensure that the CIRIS can accurately measure the surface of potentially inhabited worlds. Preliminary testing has demonstrated the basic functionality of the design, and test spectra have been collected from an icy target at a minimum temperature of 107K. During the time frames associated with the tests (approximately 15 minutes to freeze the sample, and 4 hours at cryogenic temperatures), we observed no apparent change in appearance of the icy target or buildup on surrounding surfaces associated with evaporation or sublimation of the water in the vacuum chamber. We thus expect stable results for future testing of ice targets, during which we hope to identify impurities within the ice associated with various biomarkers which may be present on icy worlds. Upcoming tests will incorporate collimating optics and cold shrouding to increase signal-to-noise to representative spacecraft levels

Acknowledgments

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