Cryogenic optical systems for the rapid infrared imager/spectrometer (RIMAS)

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ABSTRACT

The Rapid Infrared Imager/Spectrometer (RIMAS) is designed to perform follow-up observations of transient astronomical sources at near infrared (NIR) wavelengths (0.9 - 2.4 microns). In particular, RIMAS will be used to perform photometric and spectroscopic observations of gamma-ray burst (GRB) afterglows to compliment the *Swift* satellite's science goals. Upon completion, RIMAS will be installed on Lowell Observatory's 4.3 meter Discovery Channel Telescope (DCT) located in Happy Jack, Arizona. The instrument's optical design includes a collimator lens assembly, a dichroic to divide the wavelength coverage into two optical arms (0.9 - 1.4 microns and 1.4 - 2.4 microns respectively), and a camera lens assembly for each optical arm. Because the wavelength coverage extends out to 2.4 microns, all optical elements are cooled to ~70 K. Filters and transmission gratings are located on wheels prior to each camera allowing the instrument to be quickly configured for photometry or spectroscopy. An athermal optomechanical design is being implemented to prevent lenses from loosing their room temperature alignment as the system is cooled. The thermal expansion of materials used in this design have been measured in the lab. Additionally, RIMAS has a guide camera consisting of four lenses to aid observers in passing light from target sources through spectroscopic slits. Efforts to align these optics are ongoing.

Keywords: optical design, near infrared, optomechanics, optical alignment, cryogenic systems, ground-based instrumentation, infrared spectroscopy

1. INTRODUCTION

The study of rapidly fading astronomical sources is aided by multi-band observations made within minutes of the initial detection while the targets are relatively bright. This is particularly true for gamma-ray bursts (GRBs) whose afterglow emission decays as a power-law in time. The Discovery Channel Telescope (DCT) has already demonstrated that it is capable of slewing to target positions and observing GRB afterglows within minutes of an alert from the *Swift* space telescope. In February of this year, GRB140215A was detected 2.7 minutes post-burst using the Large Monolithic Imager (LMI) on DCT[3]. This response time will be improved once an automated target of opportunity program is in place.

The addition of the Rapid Infrared Imager / Spectrometer (RIMAS) to the telescope will extend DCT's ability to observe transient sources to near-infrared (NIR, 0.9 – 2.4 μm) photometry and spectroscopy. RIMAS will be mounted on DCT's "instrument cube" along with LMI and three other instruments (Figure 1). Instruments are selected by inserting a fold mirror or dichroic into the beam inside the instrument cube. Since this only takes a few seconds, RIMAS will enable DCT to perform NIR photometry and spectroscopy as soon as it completes the slew to the target.

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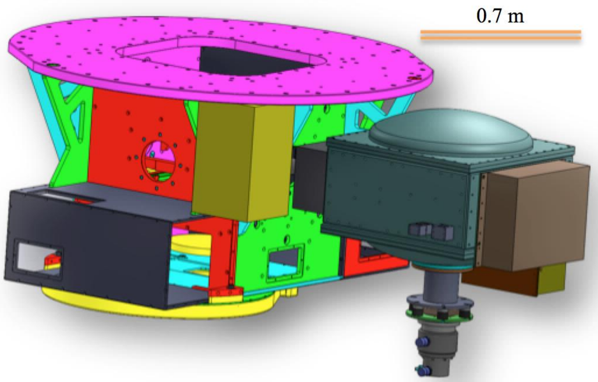

Figure 1. A CAD drawing of showing where RIMAS will be mounted on DCT's "instrument cube." Light from the telescope enters the cube from the top. LMI (not shown) would be located below the cube. Three additional instruments will be mounted on the remaining sides in the near future. Instruments are selected by inserting fold mirrors or dichroics into the beam-path. Using a dichroic will allow simultaneous use of LMI at visible wavelengths and RIMAS at NIR wavelengths.

2. GRB SCIENCE

Gamma-ray bursts (GRBs) are the most energetic transient events in the universe. All events in this category are characterized by an initial, short-lived burst of γ-rays. If the observed γ-ray intensities were emitted isotropically, the energy released would be 10^{50} erg $\lesssim E_{\mathrm{iso}} \lesssim 10^{54}$ erg[1,5]. For this reason, these sources are observable at very high cosmological redshifts ($z > 7$)[4,13].

Approximately 95% of bursts found by the *Swift* satellite have a detected X-ray afterglow. The spectral energy distribution (SED) of this emission follows a broken power-law, with observations of this emission out to radio wavelengths. These afterglows are thought to be the result of synchrotron emission produced by electrons accelerated by turbulent magnetic fields following shocks in the circum-burst medium (CBM)[10,11]. Following a burst, the afterglow emission decays in time as a power-law with a decay index ~ 1 with the peak emission wavelength increasing. Because afterglows have relatively simple SEDs, they are ideal for absorption and dust extinction studies[6]. Additionally, absorption lines should be observable in the brightest GRB afterglows to a cosmological redshift of ten[9].

Because of attenuation by dust and neutral hydrogen along the line of sight to the burst, the afterglow is often dark at visible wavelengths[5]. Observing such sources in the NIR increases the chance of a detection. Additionally, the afterglows' SEDs are brighter in the NIR than at visible wavelengths. RIMAS has been designed to increase the number of afterglow detections by performing rapid NIR photometry using a 4 meter class telescope. Depending on the magnitude of the detected afterglow, photometry will be followed up by either low resolution (R ~ 30) or moderate resolution (R ~ 4500) spectroscopy.

3. OPTICAL DESIGN OVERVIEW

The optical design for RIMAS is influenced by several factors. Refractive optics are used because of space limitations on DCT's instrument cube. Operating at NIR wavelengths, particularly at the long end of this coverage (~2.4 μm), requires that the optics be cryogenically cooled to reduce the thermal background. A guide camera imaging the field surrounding RIMAS's spectroscopic slits is also required to aid observers when using the spectroscopic modes. A more detailed description of the optical design is found in a previous publication[2].

3.1 Science optics

The design for the science optics is broken into three lens assemblies, one collimator and a camera for each of two optical arms. Each assembly is composed of five elements to minimize image aberrations. NIR light from DCT is directed to RIMAS by positioning a dichroic in the instrument cube (Figure 1). The beam is then passed through RIMAS's dewar window. After this point, all optics are cooled to ~70 K. Once the beam has been collimated a dichroic is used to divide the wavelength coverage into two optical arms, “YJ” (0.9 ~ 1.4 µm) and “HK” (1.4 ~ 2.4 µm). Before being refocused by the cameras, the beams are either filtered or dispersed by additional optics located on wheels. A Teledyne H2RG HgCdTe detector (2048×2048 pixels) is positioned at each arm’s focal plane. Figure 2 shows an overhead view of the optical and optomechanical design for the science optics.

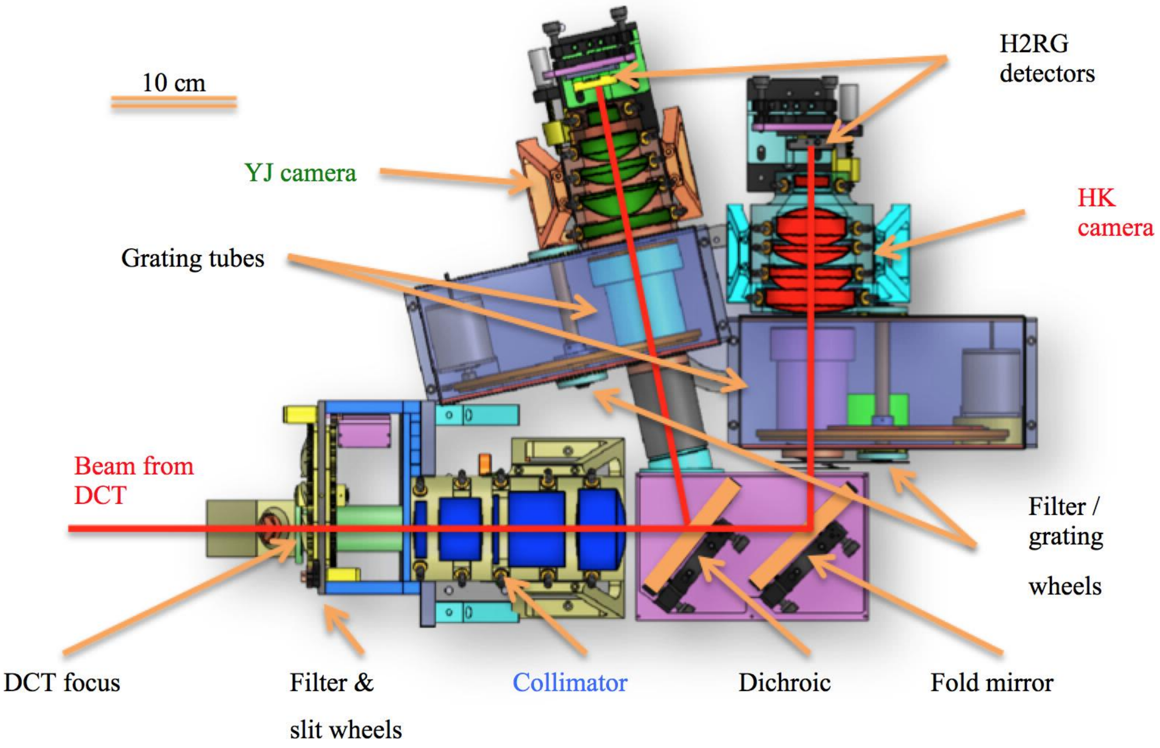

Figure 2. The drawing shows the layout of the optical and mechanical elements used in the RIMAS design. Light from the DCT first passes through the filter and slit wheels in the instrument’s “front module,” is collimated and continues until focused by either the “YJ-band” (0.9 – 1.4 µm) or “HK-band” (1.4 – 2.4 µm) camera. Filters or gratings are selected by rotating filter wheels located before each optical arm’s camera.

The optomechanical design accounts and compensates for the thermal contraction of the optical bench as well as all optical mounts. In particular, an athermal lens centering design will cause lenses to maintain their room temperature alignment[2]. This design uses high thermal contraction materials to compensate for the difference in contraction between lenses and their aluminum holders. As part of this effort, the thermal contraction of compensator materials were measured in the lab by imaging their change in length relative to fused silica as the samples were cooled to ~50 K. Sample images are shown on the left in Figure 3. In the second image the samples have been painted to simplify the analysis. The results were compared with past measurements by other groups. Typical results are presented on the right in Figure 3. Deviations from past results at 70 K are small enough that they are not relevant to this athermal design.

3.2 Spectroscopic slit-viewing optics

The surfaces surrounding RIMAS’s spectroscopic slits are tilted and polished to act as fold mirrors for light not passing through the slits to the science optics. Slits are mounted on a wheel, allowing users to select from various slit sizes. The reflected light then passes through a set of lens doublets to be imaged on a 256×256 pixels legacy indium antimonide (InSb) Spitzer IRCAM detector. Viewing these images will help observers to ensure light from their target is passed through the spectroscopic slit. A drawing of this design is presented in Figure 4.

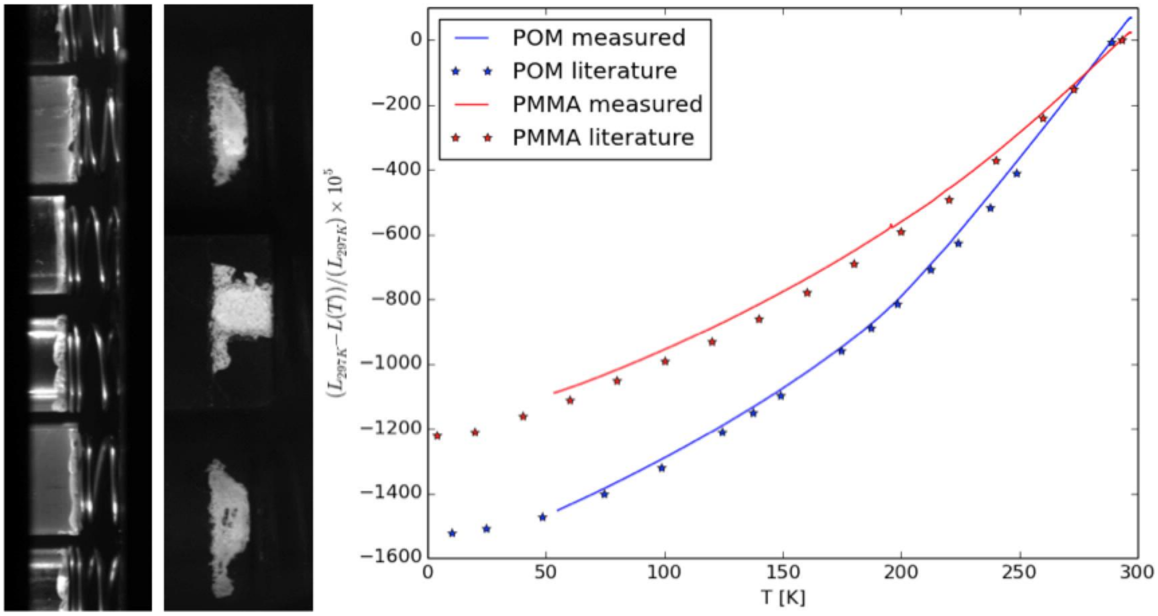

Figure 3. The thermal expansion of several materials used in RIMAS were measured down to ~60 K relative to room temperature in the lab. The measurements where done by imaging samples through the dewar window. Fused silica rods were used as references. Thermometers were attached at either end of the samples to check for temperature uniformity. (left) This image shows the original setup where samples where not painted. Springs are visible to the right. (center) Samples were painted flat black and white marks were added to the ends to increase contrast. This simplified the analysis. (right) Measured thermal expansion for two plastics is plotted along with past measurements taken by other groups[8,12]. Measured differences are not large enough to impact RIMAS's athermal lens holder design.

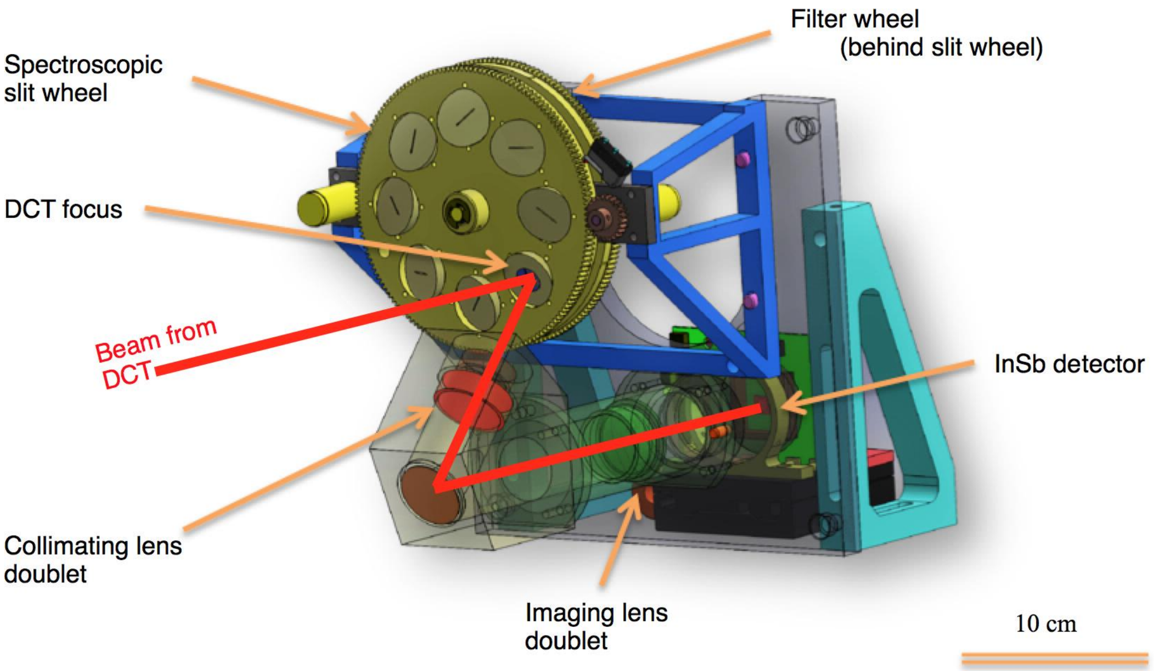

Figure 4. This drawing shows how the slit-viewing optics will image light not passing through spectroscopic slits. The mirror surface surrounding slits passes light through a lens double which provides some collimation. The light is then focused on an InSb detector by a second lens doublet. Doublets are used primarily to achromatize the design.

4. LENS ALIGNMENT

The slit-viewing optics are AR coated and currently being aligned using an alignment telescope equipped with a pip generator[7]. An alignment pip generator is a white light source which is made to diverge from the front of the telescope by using a small fold mirror (Figure 5). The reflection of this light from lens surfaces is then focused using the telescope into a "pip". The telescope is mounted on motorized stages which are operated using a joystick via a custom written LabVIEW program. A CCD mounted on the telescope is used by the alignment software to identify the centroid of a pip when it is focused by the user. Using a CCD allows for a more precise alignment than would be possible aligning pips by eye. Tip and tilt will be fixed by custom machined washers. Lenses will then be centered using the alignment telescope and pip generator.

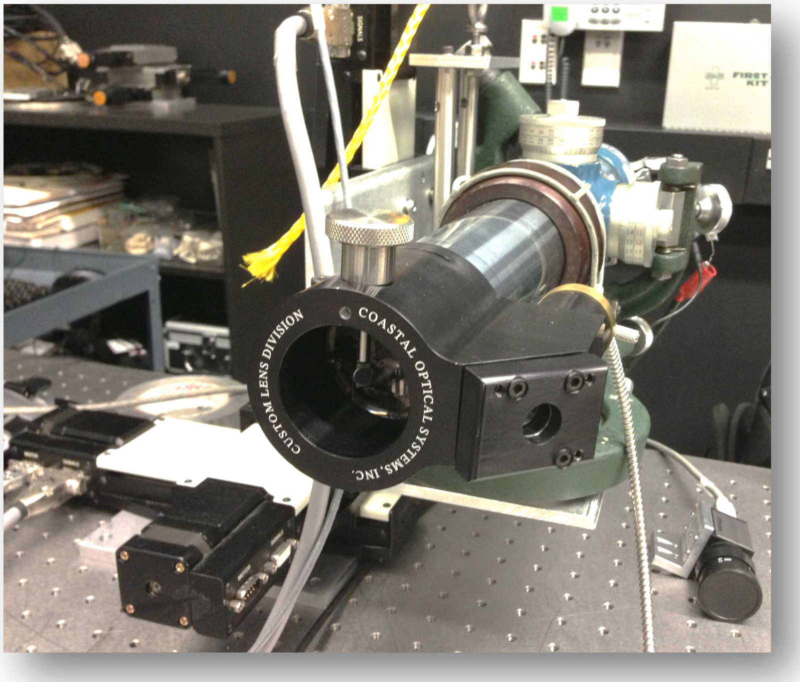

Figure 5. This image shows the pip generator mounted on the alignment telescope. The telescope is mounted on motorized stages which allow the user to reposition the telescope precisely and quickly.

5. STATUS

All lenses for both the science optics and slit-viewing camera have been received. The slit-viewing lenses are AR coated and will be aligned once the optomechanical assembly is received. It is expected that this secondary optical system will be completed by the end of this summer.

The metrological data delivered with the lenses were incomplete. This has delayed the AR coating and alignment of the primary optical system since the optomechanical design must be reoptimized to compensate for any parameters failing to meet the design specifications. The required measurements were completed in mid June; analysis and reoptimization are ongoing. The time to completion of this system is highly dependent on the scale of the required design changes, however it is expected that the lenses will be aligned in the next few months.

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