Simultaneous Infrared-Visible Imager/Spectrograph a Multi-Purpose Instrument for the Magdalena Ridge Observatory 2.4 m Telescope

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ABSTRACT

The Simultaneous Infrared-Visible Imager/Spectrograph (SIRVIS) is a planned multi-purpose instrument for the Magdalena Ridge Observatory 2.4 m telescope located west of Socorro, NM. The primary science drivers are asteroid studies, the rapid response to astrophysical transient phenomena and observations of artificial targets such as satellites. For asteroid science, the wavelength range 0.39-2.5 μm gives the most mineralogically diagnostic information on surface compositions using standard filters and low-resolution, R ~ 200, spectroscopy. For transients, the telescope's rapid 10° /second slew rate will facilitate acquisition of data on any target within one minute of receipt of notice. For artificial targets, simultaneous two-color imaging will assist in unique determinations and overall condition monitoring. SIRVIS has two channels, a cryogenic NIR channel covering 0.85-2.5 μm at 0.27 arcsec/pixel, and an ambient temperature-pressure visible channel covering 0.39-1.0 μm at 0.15 arcsec/pixel. The beam is split by a cryogenic, red-pass dichroic mirror located between the telescope focal plane and the respective collimators. Both channels use refractive optics. The instrument is being designed to initially phase in the visible channel, then the NIR channel, and readily accommodate upgrades. For sky subtraction, the telescope is nodded between 30-60 second NIR integrations. Long visible integrations are made possible by shifting the CCD charge in sync with the nod.

Keywords: Infrared, Visible, Imager, Spectrograph, Magdalena Ridge Observatory

1. INTRODUCTION

The Simultaneous Infrared-Visible Imager/Spectrograph (SIRVIS) is a planned multi-purpose instrument for the Magdalena Ridge Observatory (MRO) 2.4 m telescope. SIRVIS is capable of serving the astronomical and defense communities with great versatility. SIRVIS will offer simultaneous near-infrared (NIR) and visible imaging or spectroscopy with wavelength coverage from 0.39 to 2.5 μm through the use of two channels. This capability is necessary to obtain colors of fast moving, or rapidly varying targets, as there is no second chance to re-observe. Fast moving targets include aircraft, missiles, artificial satellites and near-Earth objects. Rapidly varying targets include gamma-ray bursts, cataclysmic variable stars and fast-rotating asteroids. The telescope's swift 10° $second^{-1}$ slew rate will allow it to center on any target and acquire data within one minute of receipt of notice. SIRVIS will increase the productivity of many observer as both their visible and NIR observational needs are served simultaneously. The use of the two channels eliminates the need to swap instruments to provide full wavelength coverage. Furthermore, color calibration will benefit since the observations are obtained through the same airmass. We present here the preliminary optical design, operating modes and estimated performance.

Magdalena Ridge Observatory is located at an altitude of 3,230 m, about 28 km west of Socorro, New Mexico. The MRO Interferometer and Langmuir Laboratory for Atmospheric Research are located along the same ridgeline. From the 2.4 m site, the Very Large Array is visible to the west. White Sands Missile Range and the New Mexico Spaceport are to the east and southest. Site seeing measurements gave values better than 1.0 arcseconds 49% of the time[1]. Skies as dark as 22.1 mag $arcsecond^{-2}$ have been measured in a broad visible bandpass. If a useable night is defined as one that is clear for at least half a night, there is at least 70% useable nights except for February and the July-August monsoon season[2].

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The telescope's alt-az mount is capable of tracking targets at up to 10° s^{-1} along both axes, and has a 2° look-down capability. Telescope fabrication is by EOS Technologies, Inc., Tucson, AZ. The optics are an f/8.77 modified Ritchey-Chrétien design. The telescope focal plane is located 325 mm behind the Nasmyth instrument port flange. There is a circular unvignetted field of view of 16 arcminute in diameter, though corrector lenses are required to obtain good image quality over this field. A vignetted field extends out to 18 arcminutes. Commissioning begins in September 2006 using a 4K × 4K CCD, with an f/7.5 focal reducer added shortly thereafter.

SIRVIS serves three scientific functions:

1) Photometry to measure the brightness of a target in selected filters.
* Simultaneous visible and NIR photometry to derive colors.
* Atmospheric extinction corrections are simplified as both channels observe simultaneously through the same airmass.
* Targets as faint as V (0.55 μm) ≈ 20 and J (1.25 μm) ≈ 18 magnitude can be detected in 1 second images.
* 2% photometry can be performed on these same targets in 10 minute long images.

2) Spectroscopy for surface material characterization and temperature measurements.
* The visible and NIR spectra offer continuous coverage from 0.39-2.5 μm.
* Overlap in the ~ 0.85-1.00 μm range simplifies cross-calibration of the visible and NIR spectra.
* Low resolution spectra maximizes sensitivity to faint targets, or shortens exposures of brighter targets.
* R~200 (R is $\lambda/\Delta\lambda$) spectroscopy is sufficient to identify the mineral content of small bodies or surface materials of artificial satellites.
* Can measure the black body temperature of warm and hot targets.

3) Astrometry to measure the exact position and motion of targets.
* The low, <0.1%, geometric distortion simplifies the measurement of a target's position with respect to reference objects in the same field.
* Relative astrometry accurate to <0.1 arcseconds across either field.

SIRVIS achieves its versatility by employing both visible and near-infrared science channels. The visible and NIR channels cover the wavelength ranges 0.39-1.00 μm and 0.85-2.50 μm, respectively. In imaging mode, simultaneous two color images can be obtained using standard filter sets. In spectroscopy mode, a slit is inserted into the telescope focal plane and grisms into the collimated beam of each channel. To match the telescope's swift slew rate, changing between observing modes will occur in only a few seconds. SIRVIS will be mounted on the MRO 2.4 m Nasmyth port derotator. SIRVIS will fit within a 1 × 1 × 1.1 m box and is estimated to weigh approximately 230 kg. Its design will readily accomodate upgrades. Specifications for each channel are given in the table below.

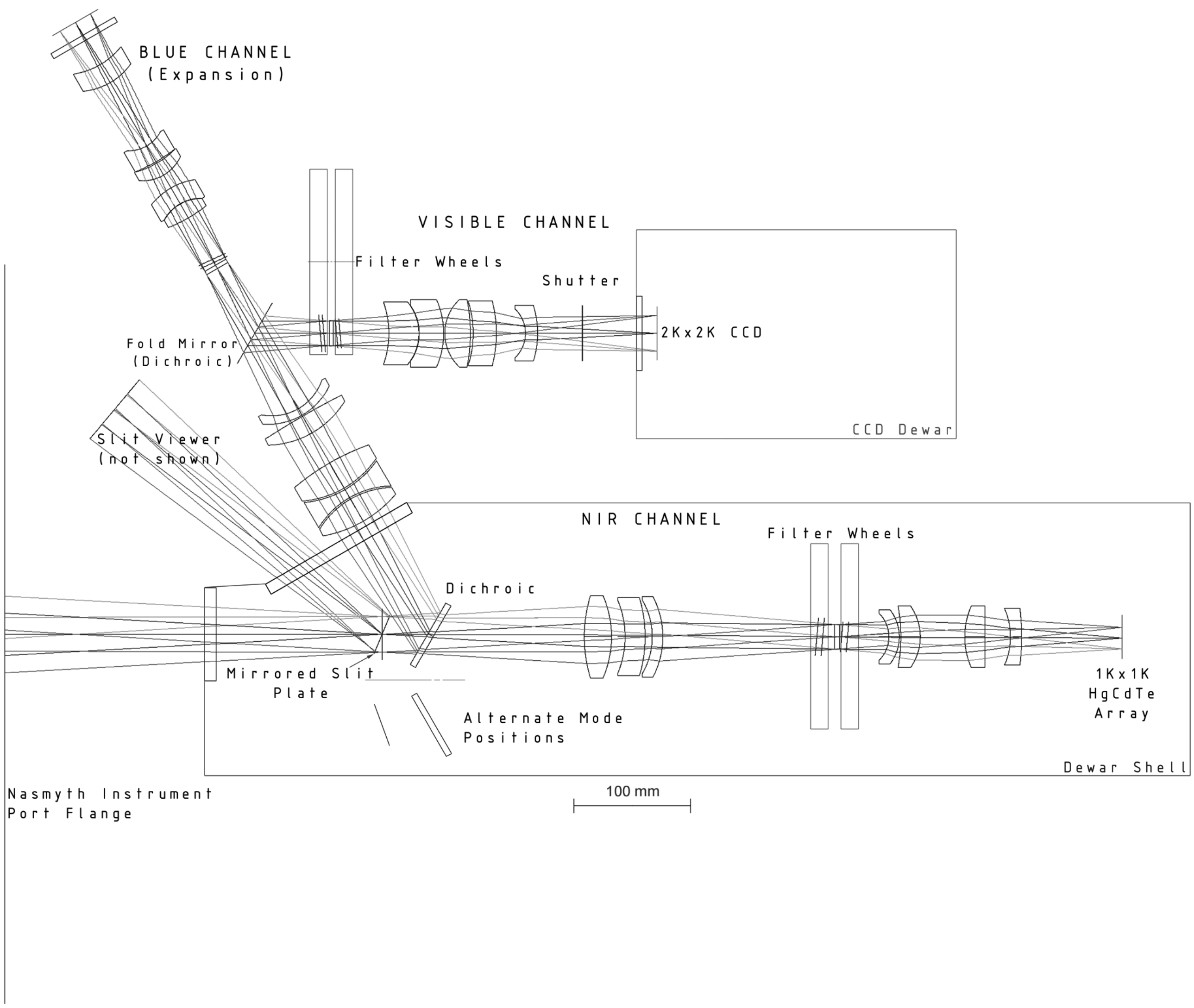
SIRVIS Channel Characteristics

	Visible	***NIR***
Detector	2K × 2K CCD	1024 × 1024 HgCdTe
Wavelength Coverage (μm)	0.39-1.00	0.85-2.50
Field of View (arcminutes)	5.0 × 5.0	4.7 × 4.7
Pixel Scale (arcseconds $pixel^{-1}$)	0.15	0.27
Pixel Size (μm)	15	18
Effective f/#	f/8.8	f/5.7
Pupil Diameter	21	21
Minimum Filter Diameter (mm)	25	25

A number of existing and proposed instruments provide simultaneous visible and NIR coverage. The REM-IR camera[3] is a dual channel system for Gamma Ray Burst follow-up observations. ANDICAM[3] is a two channel, high photometric precision imager. UCLA two optical-NIR imaging system[5] is a simple imager that combines a CCD and NIR detector using a warm dichroic mirror. TRISPEC[6] is a three channel design, one visible and two NIR channels in an all-cryogenic layout. X-shooter[7] will use two visible and one NIR channel to provide coverage from 0.30-2.5 µm for the VLT. SIRVIS combines some of the best features of these designs to provide MRO 2.4 m users with both imaging and spectroscopy.

2. OPTICAL LAYOUT

Our design principle is to combine a conventional ambient-temperature visible channel and a cryogenic NIR channel in an simple way. Each channel is optimized for stand-alone operations. Simultaneous use of the two channels is facilitated by an insertable cold, red-pass dichroic mirror (see figure). The dichroic mirror is located within the NIR channel Dewar, behind the telescope focus. This ensures that both channels view the same area of the sky, which especially important when performing slit spectroscopy. The telescope focal plane is located within the Dewar to permit the use of a cold field stop and slits. A cold ($T < 120$ K) slit and dichroic mirror minimizes the instrument thermal contamination entering the NIR channel.



SIRVIS optical layout. The telescope Nasmyth port is to the left. The slit viewer optics are not shown. The blue channel is an expansion option.

We chose an ambient temperature visible channel for several reasons. Conventional visible filters can be used, and readily exchanged. This is particularly important with custom, narrow-band filter sets such as those used for comet research. Use of such filters within a cryogenic environment could result wavelength shifts, and possible damage to the filters, not to mention the time delay required to thermal cycle the Dewar to exchange filters. Ambient temperature visible optics can be designed using existing index of refraction and thermal expansion data. Cryogenic index of refraction data has been published for only a limited number of materials[5]. The lenses can be fabricated with standard anti-reflection coatings. An in-line visible channel can be fabricated in-house (using vendor supplied lens assemblies) and commissioned before the cryogenic NIR channel is completed. Two disadvantages of our design is slightly lower visible throughput by the addition of two windows and a thermal blocking filter, and more flexure between the two channels.

The visible channel is folded into the shape of the letter "Z". The dichroic mirror reflects the visible through a 60° angle. The beam exits the NIR channel Dewar through an IR blocking filter and exit window. The IR blocking filter reduces the heat flux into the Dewar. The visible collimator is located immediately outside the exit window. A fold mirror is located in the collimated beam to bring the optical axis back to being parallel the rotational axis of the Nasymth port. A Lyot stop may be located at the pupil image. The filter wheels are located before and after the pupil image. Grisms are mounted only in the rear filter wheel. The camera optics provides over 80 mm between the last camera lens and the image plane. A fast-acting shutter is located in this space. This spacing will also allow SIRVIS to accommodate a variety of expansion options and CCD Dewars. The fold mirror permits the use of a standard CCD Dewar with a window centered on one face, and the LN_2 fill/vent on the opposite face. The visible channel is enclosed in a light-tight cover that is purged with dry N_2 to prevent condensation, and exclude dust and moths.

The NIR beam lies along the rotational axis of the Nasmyth port. The NIR beam passes through the dichroic mirror substrate. Like the visible channel, the NIR optics use a collimator and a camera lens assemblies. The filter wheels are located either side of the Lyot stop. The optical design provides over 85 mm between the last camera lens and the image plane. Plans are to use a 1K × 1K HgCdTe focal plane array with 18 μm pixels. Depending upon the final design, the NIR optical bench may double as one side of the LN_2 reservoir.

2.1 Lens assemblies

Both channels use lens assemblies with all spherical surfaces to deliver ~80% encircled energy in 2 pixels diameter spots at all wavelengths across most of the field without the need to refocus. The geometric distortion is less than 0.1% in both channels. With the possible addition of a NUV/blue channel in mind, the materials for the visible collimator were selected to cover the 0.33 to 1.0 μm. The materials are, in order, CaF2, S-LAL7, S-FSL5, CaF2, S-LAL18. The visible camera is a five lens design of CaF_2, S-LAL18, CaF_2, SF5 and S-LAL18. The glass selection allows operations down to 0.39 μm. The NIR channel collimator uses three lenses of BaF_2, IR grade fused silica and ZnSe. The NIR camera is a four lens design of ZnSe, BaF_2, CaF_2 and IR grade fused silica. The NIR channel is nearly telecentric, thus there is only a minor change in plate scale with focal changes. Further optimization may alter the materials, or eliminate a lens. An aspheric surface may be used if it can eliminate a lens, or notably improve performance at a minimal additional cost. The optical designs are developed in Zemax-EE®.

2.2 Dichroic mirror

The dichroic mirror mounted is on a rotatable wheel located between the telescope focus and the NIR collimator. This wheel may hold dichroic mirror(s), a 50/50 beamspitter, a full mirror and a substrate. 60 mm diameter substrates are required to avoid vignetting. A dichroic mirror maximizes the throughput to each channel but, introduces a color term in the spectral overlap region between ~0.85 and 1.00 μm. A selection of dichroics would allow observers to pick a cutoff wavelength to best match their observational requirements. An atmospheric absorption band near 1.14 μm provides a convenient location for a cut-off wavelength that would place the SDSS (Sloan Digital Sky Survey) z' and Cousins I_c bandpasses into the visible channel. A cutoff wavelength near 0.88 μm would better utilize the NIR array's short wavelength sensitivity. A beam splitter divides the light equally to both channels (*i.e.* no color term, thus simplifying cross-calibration) but at the cost of a 50% loss in throughput to each channel. The full mirror maximizes the throughput for visible channel use only. The AR coated substrate is for straight-through NIR operations only, with the best possible throughput and image quality. A substrate of equivalent optical path length to the dichroic is required to avoid excessive NIR collimator focus travel.

The dichroic mirror substrate is an optical flat located in a divergent beam. This introduces astigmatism into the NIR images. In SIRVIS, the astigmatism is reduced in two ways. First, the dichroic is tilted at a 30° angle to the beam, not the traditional 45°. Second, the back surface of the dichroic substrate is wedged by about 0.7°. Although the astigmatism is reduced, it is not eliminated, and the NIR point spread function is no longer radially symmetric about the center of the field. The substrate does introduce an asymmetric grid distortion pattern at the few pixel level.

2.3 Spectroscopy

Our primary science driver of asteroid studies require low-resolution, R ~ 100-200, single-order spectroscopy. Later medium, R ~ 2000 capability may be added. The selection of grisms are mounted in the rear filter wheel of each channel. Most spectroscopy is performed using one of several slits ranging from ~0.5 to ~3 arcseconds in width. These are mounted on the slit wheel located in the telescope focal plane. The slit wheel also contains an open slot for imaging or slitless spectroscopy. For visible bright, NIR faint targets it is possible to perform slitless visible spectroscopy, and NIR imaging.

There is a third, non-science slit viewing channel for target identification and tracking that is used only during slit spectroscopy. Each slit is cut into a 35 mm diameter mirrored plate that is tilted 20° to the incoming beam. Light not passing through the slit is reflected off-axis and then focused onto a sensitive, high-frame rate camera. The final configuration of the slit viewer is to be determined. One possible configuration is an ambient temperature camera mounted outside the NIR Dewar. Alternatively, the slit viewer could be configured as a cryogenic channel, and use either a visible or NIR focal plane array.

3. MECHANICAL

3.1 Moving mechanisms

To achieve SIRIVIS's versatility requires many moving mechanisms. There are a total of six wheels. #1 is the slit wheel located at the telescope focal plane. #2 is the dichroic wheel located behind the telescope focus. The dichroic is shared between the visible and NIR channels. Wheels #3-4 are the NIR channel forward and rear filter wheels. #5-6 are the visible channel forward and rear filter wheels. Wheels #1-4 are located in the NIR channel Dewar and are LN_2 cooled. Wheels #5-6 are at ambient temperature.

The filter wheels are located in the collimated beam on either side of the pupil stops. The number of slots available in each wheel is to be determined. The current plan has a five slot slit wheel, five slot dichroic wheel, and ten slot filter wheels. Using ten-slots filter wheels would allow up to seventeen filters, with up to nine for grisms (in the rear filter wheels only) per channel. Each filter wheel must have an open slot, and one wheel in the NIR channel requires a blank for dark frames – no shutter is required in the NIR channel.

Three more moving mechanisms are needed. A 50 mm clear aperture shutter is used in the visible channel immediately infront of the CCD Dewar. To correct for changes in focus, both collimators are each mounted on a linear stage.

3.2 Dealing with atmospheric refraction

Atmospheric dispersion will separate the 0.39 and 2.5 μm images by approximately 1 and 3 arcseconds at 40° and 60° zenith angle, respectively. For imaging, the atmospheric dispersion will generate an astrometric offset between visible and NIR channels. For spectroscopy, the atmospheric dispersion is comparable to the width of the slits, thus would result in light loss if the slit were near perpendicular to dispersion. For spectroscopy of point sources, the position angle of the slit is not important. We propose to orient the slit parallel to the atmospheric dispersion (*i.e.* vertically at the Nasmyth port) and locking the derotator. In this way, the atmospheric dispersion acts as a cross-disperser that can be compensated for during data reduction. There are several additional advantages to a vertical slit; telescope nodding is only along the elevation axis, and instrument flexure is not changing. There are currently no plans for an atmospheric dispersion corrector, though the design does not exclude it as the future addition.

3. EXPANSION OPTIONS

The SIRVIS optical layout offers great flexibility for expansion. For occultations and satellite tracking, the frame rate of the 4K × 4K CCD is too slow, even with windowing. Instead, a dedicated visible detector capable of frame rates in excess of 100 second^{-1} is required. One option is to temporarily remove the CCD Dewar and replace it with the other detector - a time consuming process. Another option is to insert a 45° mirror into the visible channel between the camera optics and the CCD. The mirror would direct the beam to a high frame rate detector. The latter option would permit changing to tracking mode within seconds. The NIR array is inherently high frame rate, especially when the array is windowed.

The addition of a dedicated blue channel would broaden visible wavelength coverage, and add a third simultaneous color. The visible camera optics are limited to operations longward of 0.39 μm by the use of SF-5. High-index SF-5 glass is used to achieve the good image quality and low distortion in a five-element camera design. With the thought of sharing the visible collimator with a blue channel addition in mind, the visible collimator is design to operate over 0.33-1.00 μm through careful selection of materials. The blue channel would be optimized over 0.33-0.55 μm to cover the SDSS *u′g′* and Johnson-Morgan *UB* bandpasses. The blue channel camera optics would be added behind the visible channel collimator. Blue-pass dichroic mirrors would replace the fold mirror. To use both the SDSS and Johnson-Morgan filter sets requires two blue-pass dichroic mirrors. A cut-off wavelength of 0.55 μm falls between the *g′* and *r′*, and *B* and R_c filters, but is near the center of *V*. A cut-off wavelength of 0.43 μm falls between the *U* and *V* filters, but falls within the *g′* and *B* bandpasses.

The addition of a blue channel would require new filter wheel, camera optics and a blue-sensitive CCD. To generate sufficient clearance between the blue channel detector and Nasymth port flange, a fold mirror may be placed behind the dichroic. This fold mirror would place the optical axis of the blue camera parallel to the plane of the Nasmyth port flange.

4. SKY SUBTRACTION

One of the complicating factors in simultaneous NIR and visible imaging is the discrepancy in the sky constant times. For adequate NIR sky subtraction, the duration of the integrations is limited to a maximum of about one minute by variations in the JHK_S sky levels. After this time, the telescope or secondary mirror must be nodded five to tens of arcseconds off target to start another integration, or series of integrations. High signal to noise visible integrations, though, may require several tens of minutes. The simplest compromise is to obtain repeated, one minute CCD integrations and just accept under-exposed images with an increase in read noise.

We propose a more optimal solution that would minimize CCD read noise without moving optics. The bi-directional vertical charge shifting capability of certain CCDs can be utilized to shift the charge to remain beneath the optical image through multiple nods. During a nod, the CCD is clocked to shift the charge in either direction along a column depending upon the direction and size of the nod. This is akin to the nod-shuffle technique descibed in Cuillandre, *et al.*[8] and Glazebrook, Bland-Hawthorn[9]. For this to work, the CCD is oriented with the columns parallel to the slit. Further aiding this technique is the optic's low geometric distortion which will eliminate blurring between nodes as the plate scale remains constant across the array.

The steps for the visible channel integration:

1) Start the series of integration in both channels.
2) After about a minute:
    a) Closed the visible channel shutter.
    b) Nod the telescope in a direction parallel to the CCD columns.
    c) Clock the CCD to place the charge beneath the nodded position of the target on the chip. The charge at the top or bottom of the chip which is readout can either be discarded, or used to monitor the progress of the integration.
    d) Open the visible channel shutter to continue the integration.
3) Repeat #2 as often as necessary to obtain adequate S/N in the visible channel exposure.
4) Stop the series of integrations in both channels and readout images.

A shutter is used in the visible channel to avoid the need to program the CCD clocking rate to match the telescope acceleration profile during each nod. The NIR array is reset between integrations. Between each nod, the NIR channel obtains either a single one minute exposure, or multiple shorter exposures.

The charge shifting technique works best for point or compact sources. Objects that subtend several arcminutes would fill too much of the chip. These extended targets would require repeated, short CCD exposures. Disadvantages of charge shifting are the loss in field shifted off the CCD, greater charge transfer losses, difficulties in determining the effective mid-integration times, and a more complicated flat fielding process.

5. SUMMARY

The Simultaneous Infrared-Visible Imager/Spectrograph is a planned, multi-purpose, two-channel instrument for the Magdalena Ridge Observatory 2.4 m telescope. It will service astronomical and defense observers with imaging or spectroscopy covering 0.39 to 2.5 μm. The fields of view for the infrared and visible channels are 4.7 and 5.0 arcminute, respectively. The pixel scales of 0.27 and 0.15 arcsecond, respectively will Nyquist sample the natural seeing at the site. These properties are necessary to provide simultaneous two-color imaging, or broad-band spectroscopy for asteroid and astrophysical studies or tracking of artificial targets.

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