# SCIENCE PERSPECTIVE OF THE MID-INFRARED IMAGER PERFORMANCE REQUIREMENTS

DOUG SIMONS
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## 1.0 Overview and Facility Summary

The Gemini Telescopes are being built to exploit the unique infrared sites of Mauna Kea in Hawaii and Cerro Pachon in Chile. Beyond ~5 µm, using fast tip/tilt secondaries these 8 m telescopes will be essentially diffraction limited much of the time. In addition the use of protected silver coatings for both the primary and secondary mirrors and efficient in-situ mirror cleaning means the telescopes should be capable of delivering focal plane emissivities of ~2%. The baseline design for the Mauna Kea telescope also includes an adaptive optics system capable of feeding a 1-2 arcminute corrected field to near infrared instruments mounted at the f/16 Cassegrain focus. Fully exploiting the superb characteristics of the Gemini telescopes will require a new generation of instruments which will challenge both instrument designers and infrared array technologies. The baseline complement of infrared instruments includes a 1-5 µm imager, a 1-5 µm spectrometer, and a mid-infrared (8-25 µm) imager (see Table 1). Several optical instruments will also be built under the baseline instrumentation plan.

Accordingly, the purpose for this technical note is to highlight to prospective mid-infrared imager builders some of the unique aspects of the Gemini telescopes' design that drive imager performance requirements and to explain why these telescopes will be unique platforms for mid-infrared instrumentation. This technical note also serves to supplement other documentation supplied to prospective builders with aspects of the telescopes that impact the design and ultimate use of the facility mid-infrared imager. Unlike the rest of the Phase I Gemini instruments, the mid-infrared imager is intended to be transported periodically between Gemini North and South in order to use this powerful instrument across the entire sky.

| Class | Mauna Kea | Cerro Pachon |
|---|---|---|
| Facility | Near-Infrared Imager<br>Near-Infrared Spectrograph<br>Multi-Object Spectrograph | Multi-Object Spectrograph<br>High Resolution Optical Spectrograph<br>Mid-Infrared Imager (shared N/S) |
| Shared | Michelle (shared with UKIRT) | Phoenix (shared with CTIO/NOAO)<br>COB (commissioning camera) |

Table 1 - A list of the initial instruments available at both Gemini sites is shown, which includes both the facility and currently planned shared instruments for each site. Note that Phoenix and COB will be shared with CTIO, and the facility mid-infrared imager will be shared between Gemini North and South.

## 1.1 Telescope Enclosure and Structure

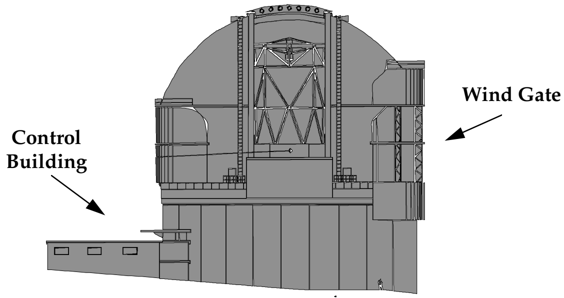


Figure 1 - The Gemini North enclosure is shown, as viewed from the east. It features a separate control building and large wind gates on the sides of the dome that will permit effective flushing of the interior.

Figure 1 shows an external view of the telescope enclosure currently under construction on Mauna Kea. Unlike many past observatories which include the support facilities (including computing, machine shop, storage, etc.) at the base of a cylinder with the observatory floor at the top, the Gemini observatories will have a telescope enclosure that is separated from the control building. This will minimize injecting unwanted heat into the dome interior, which can lead to degraded seeing. Perhaps the most distinctive aspects of the enclosure are the large wind gates located on each side of the dome. These structures are adjustable to control the amount of flushing the dome interior experiences. Under high wind conditions the gates will likely be closed in order to protect the telescope as well as minimize wind shake on the telescope structure. Overall the dome has minimal protrusions, yielding a clean aerodynamic profile that provides laminar flow into the enclosure under most ambient wind conditions. The dome surface will be painted with a special low emissivity paint to minimize absorption of solar radiation during the day. Under low wind conditions, high capacity internal air handling units will draw exterior air into the dome. Finally, in order to minimize thermal equalization time after the dome is opened in the evening, during the day the interior will be air conditioned to a temperature level that is typically within ~1° C rms of the beginning of each night's observations.

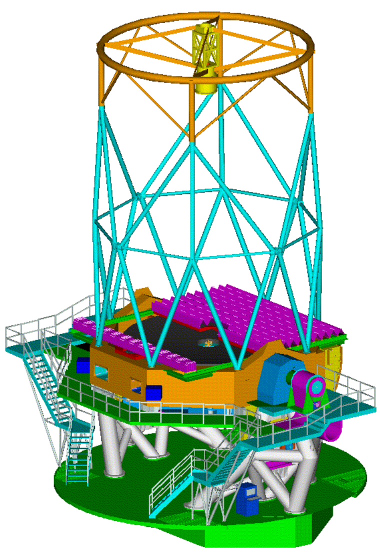

Figure 2 - The overall telescope structure is displayed. Of note is the exceptionally thin cross section of the truss system holding the secondary mirror in place, which helps minimize wind load and allows the structure to rapidly equilibrate with ambient temperature conditions.

Seen in Figure 2 is the complete telescope structure. The baseline design includes a removable top-end supporting an *f*/16 mirror capable of fast tip/tilt/focus adjustments. The structure suspending the secondary vanes has been light-weighted, which reduces its aerodynamic wind load characteristics and thermal response time to ambient conditions. The telescope elevation axis is located 20 m above the ground, which will place it above the ground seeing layer on Mauna Kea and Cerro Pachon most of the time. When combined with the fact that the primary mirror is located above the telescope elevation axis, it will be possible to effectively flush the air above the primary mirror under most wind conditions, thereby helping to reduce mirror/dome seeing.

For the mid-infrared imager these and other unique telescope and enclosure design features mean *the mid-infrared imager will be atmosphere and site limited, not dome or telescope limited, and will be used to explore the entire sky between Gemini North and South*.

## 1.2 High Performance Coatings and Mirror Cleaning Program

To date essentially all telescopes have used aluminum as a coating material for a number of reasons, including its durability and the relative ease with which high quality coatings can be applied without using exceptionally low vacuum pressures. Unfortunately the intrinsic emissivity of aluminum is too high to permit reaching an effective telescope emissivity of only ~2%, Gemini's goal. Gemini has therefore been engaged in a mirror coating development program in order to explore new techniques for depositing high performance reflective films over large areas. The net result of this activity has been the development of a protected silver coating that offers outstanding performance over a broad wavelength range. Results to date indicate that it should be possible to achieve a total telescope emissivity slightly over 2% if the coatings developed under laboratory conditions can be replicated within Gemini's 8 m coating chamber. The coating will be deposited using state-of-the-art sputtering techniques in a stainless steel chamber (to achieve the reduced base pressures needed for silver deposition). The measured 4 µm emissivity of these coatings is ~1%, approaching the theoretical maximum possible performance for a silver coating.

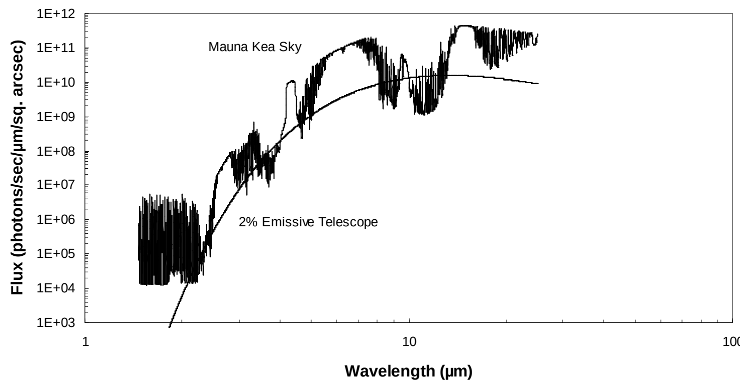


Figure 4 - A model of the infrared sky emission for a typical Mauna Kea night is shown. Strong OH line emission dominates at non-thermal wavelengths. Beyond ~3 µm a combination of molecular emission and thermal radiation determine the sky flux. Note that at ~10 µm where the emissivity of the sky is quite low, minimizing the telescope's contribution to the total background has a large impact on performance.

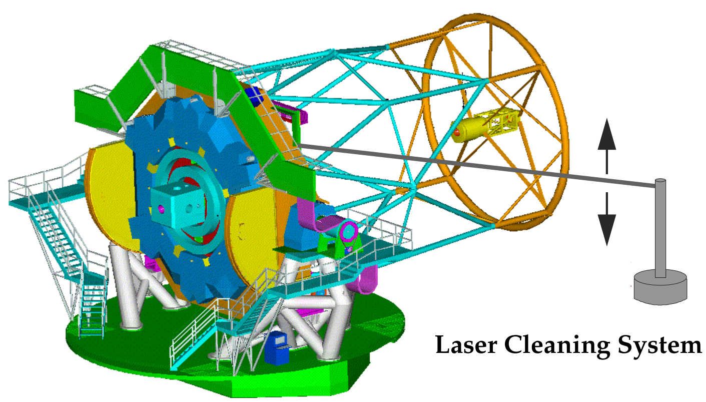


Figure 5 - The mirror cleaning system planned uses a pulsed laser that raster scans a beam across the primary mirror surface with the telescope pointed toward the horizon. The secondary mirror should also be cleaned by reflected radiation during this scanning procedure.

Figure 4 shows the scientific importance of having a telescope with low intrinsic emissivity. Depicted is a model of infrared sky radiation for a typical Mauna Kea sky (1 mm precipitable water vapor or PWV). The flux is a complex combination of molecular line emission and thermal radiation. Of particular importance is the scientifically interesting 10 µm window. In this region the exceptionally low atmospheric emissivity combined with the low emissivity of the telescope will lead to significantly enhanced sensitivity over what is possible with current generation ground based telescopes.

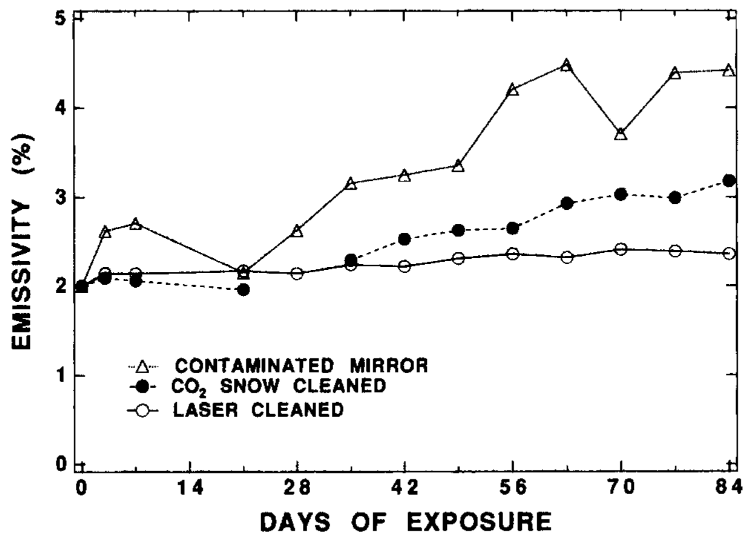


Figure 6 - A plot of measured emissivity over time after test samples have been exposed to the Mauna Kea environment and laser cleaned is shown. The laser cleaning technique, when performed on a regular basis, can very effectively preserve the low emissivity performance of the telescope, long after fresh coatings have been applied.

Maintaining such low emissivity implies a rigorous cleaning program. The baseline design for the Gemini telescopes includes the use of a laser mounted on the observatory floor. With the telescope pointed near the horizon, a gimbal mounted mirror will raster scan a pulsed laser beam across the primary mirror, removing through several physical mechanisms dust and molecular contamination from the mirror (see Figure 5). This process is expected to require ~6 hours to complete and tests made on samples exposed to Mauna Kea conditions indicate that such a cleaning exercise will be needed roughly once a week to maintain the Gemini emissivity specification. An additional benefit will be that the secondary mirror will intercept the once-reflected laser beam during the scanning procedure, cleaning it as well, though tests conducted at the IRTF suggest that such down-looking optics are not as susceptible to contamination as up-looking elements. The benefits of such an aggressive mirror cleaning program for thermal imaging are clear, since the dust and molecular contamination that normally inhibits telescope performance soon after clean coatings are applied can be substantially mitigated and the sensitivity of the mid-infrared imager can be preserved for long periods of time (see Figure 6).

## 1.3 Delivered Image Quality

The cornerstone behind the Gemini telescopes' design is high performance imaging. In the mid-infrared this is achieved through tip/tilt compensation at the secondary mirror and the use of a pair of peripheral field wavefront sensors that are incorporated into the acquisition and guiding unit. These sensors, which patrol a 14 arcminute field around the central 3 arcminute unvignetted science field, are used to:

- Periodically update the force matrix used to define the shape of the primary mirror through an array of actuators.

- Maintain precise telescope collimation and focus

- Provide relatively fast tip/tilt image compensation to help remove atmospheric image degradation and wind shake

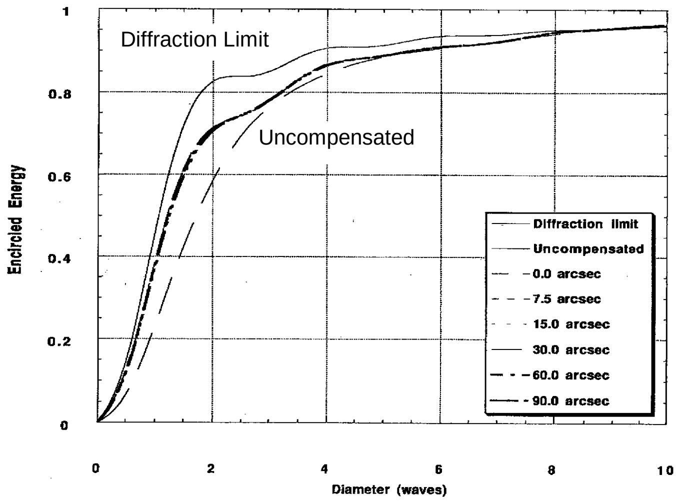


Figure 7 - Predicted 10 µm image quality is shown as a function of wavefront sensor off-axis distance for median Mauna Kea seeing conditions. Note that 2 waves is approximately equal to 0.5” at 10 µm.

With the use of low noise, small format CCDs the aforementioned peripheral wavefront sensors are expected to provide >99% sky coverage. Figure 7 shows the predicted image quality at 10 µm with and without tip/tilt compensation, using a wavefront sensor at a variety of offsets from the central target. This plot demonstrates that it will be important, even at long wavelengths, to maintain good tip/tilt compensation if a diffraction limited core in images is to be realized. The fact that delivered image quality is not a strong function of guide star offset is due simply to the large $r_0$ expected on Mauna Kea and Cerro Pachon at ~10 µm. Though recent KECK measurements indicate that tip/tilt errors may be relatively small across large baselines, for Gemini making such corrections will still be needed to correct for windshake even if the atmospheric component is smaller than anticipated in our models.

### 1.4 Environmental Sensitivity and Queue Scheduling

To date most telescopes have had a relatively limited dynamic range in terms of delivered image quality. Even telescopes on such outstanding sites like Mauna Kea typically only experience a factor of ~2 in FWHM of images. Such limited dynamic range is generally due to a combination of static aberrations in telescope optics and “dome seeing”, or wavefront degradation due to a significant air temperature gradient between the air in the dome and outside the dome. In the case of Gemini, delivered near-infrared and optical images will span nearly an order of magnitude in FWHM, due to active control of the optics and all of the aforementioned measures dedicated to reducing dome and mirror seeing. In terms of sensitivity, Figure 8 illustrates the range in exposure times required to achieve equivalent signal to noise ratios in an image of a point source. From this Figure it is clear that integration times can range by a factor of 5-10 at optical and near-infrared wavelengths, depending on (uncontrollable) natural seeing variations. For compact objects, where diffraction is a dominant component in defining image size (i.e., for the mid-infrared imager) the range in integration times is much lower. *Hence during essentially all seeing conditions the mid-infrared imager will make very efficient use of the telescope.*

All of this leads to the need to flexibly schedule the Gemini telescopes so that science programs can be matched with varying observing conditions. In the baseline operations model for both telescopes, early into the operations phase at least 50% of science programs will be scheduled for observing time through a queue that is coordinated by Gemini operations. Staff astronomers will be responsible for conducting these queued observations and will have the task of matching on a nightly basis science programs (that are of course compatible with the instruments currently mounted on the telescope) with observing conditions. Such an operational model dictates streamlined instrument and telescope control with observing programs being substantially "pre-programmed" in computer controlled sequences of telescope and instrument configurations, thereby leading to a much more efficient and responsive observing environment than is typically found in observatories today. The consequences of these operational and environmental considerations for the mid-infrared imager are that it will typically be located in the up-looking infrared optimized port and in a "standby" mode, ready to be called into service as changing conditions warrant, but may be used preferentially in times of poor seeing since even under worst-case seeing on Mauna Kea and Cerro Pachon the mid-infrared imager will theoretically deliver near diffraction limited images when used with the facility tip/tilt compensation systems on the telescopes.

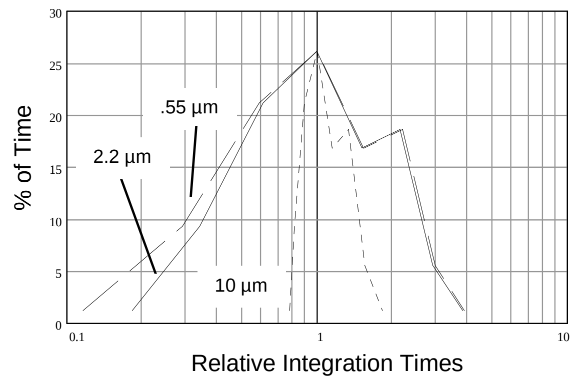

Figure 8 - Relative integration times for tip/tilt corrected imaging with Gemini are shown for three wavelengths. The natural seeing conditions assumed in the model were derived from Racine et al. (private communication). Large variations in exposure time will be required to achieve the same level of sensitivity with Gemini for non-thermal observations. At 10 µm though, sensitivity is nearly constant under all seeing conditions, being dominated by diffraction.

## 1.5 Secondary Mirror Chopping Performance

With the advent of large format thermal infrared arrays the need for chopping is less certain than it was when single element detectors were commonly in use. In any event, the tip/tilt mechanism incorporated into Gemini's f/16 secondary is also capable of supporting chopping. Furthermore, tip/tilt compensation can be supported on both sides of a chop cycle through the use of two reference stars, one centered in each peripheral wavefront sensor's field of view on each side of the chop cycle. The maximum chop throw possible with the secondary articulation mechanism is ±15" at 5 Hz, hence chopping sequences can be supported over distances comparable to the field of view of the mid infrared imager, with diffraction limited imaging supported on each end of the chop cycle.

## 2.0 Mid-Infrared Imager Performance Requirements

The basic design philosophy that was used to formulate the top-level performance requirements listed below is that the imager should be a relatively simple high throughput dedicated imager. Since the Gemini telescopes are being uniquely designed to provide an input focal plane of diffraction limited quality with exceptionally low background flux from the telescope, the science gains of even a relatively simple and low cost mid-infrared imager on Gemini should be large. The top level performance requirements and a brief discussion of each are presented in the remainder of this document.

υ *Wavelength range: 5-25 µm with an extension to 30 µm as a goal*

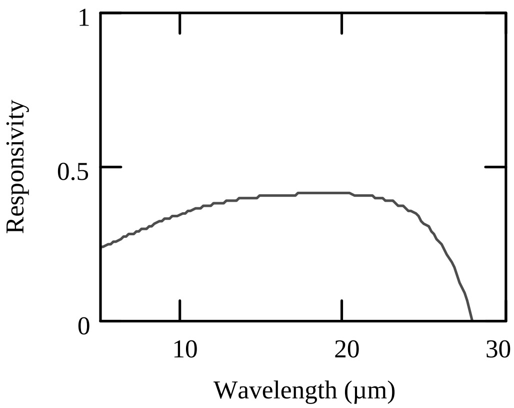


Figure 9 - A plot of achieved QE as a function of wavelength is shown for the IBC device described in Hoffmann et al. 1993, (SPIE, 1946, p449).

The wavelength range specified above is driven by the responsivity of available IBC arrays (see Figure 9) and the atmospheric transmission at the Gemini high altitude sites. Figure 10 shows a model of the zenith atmospheric transmission for Mauna Kea under typical 1 mm PWV conditions. Though the 20 µm window is heavily dominated by water vapor, it is nonetheless important that the Gemini mid-infrared imager be able to use this window since observations will be queue scheduled and the imager will be stationed for relatively long periods of time (months) at the infrared optimized port, *hence observations demanding rare ultra-low PWV conditions at both sites can be exploited effectively*.

The next generation of mid-infrared arrays is currently under development at sites including Rockwell and SBRC. These devices have ~70000 pixels (or nearly 4x more than previous generation devices) that are 50 µm across, nearly 100% fill factor,

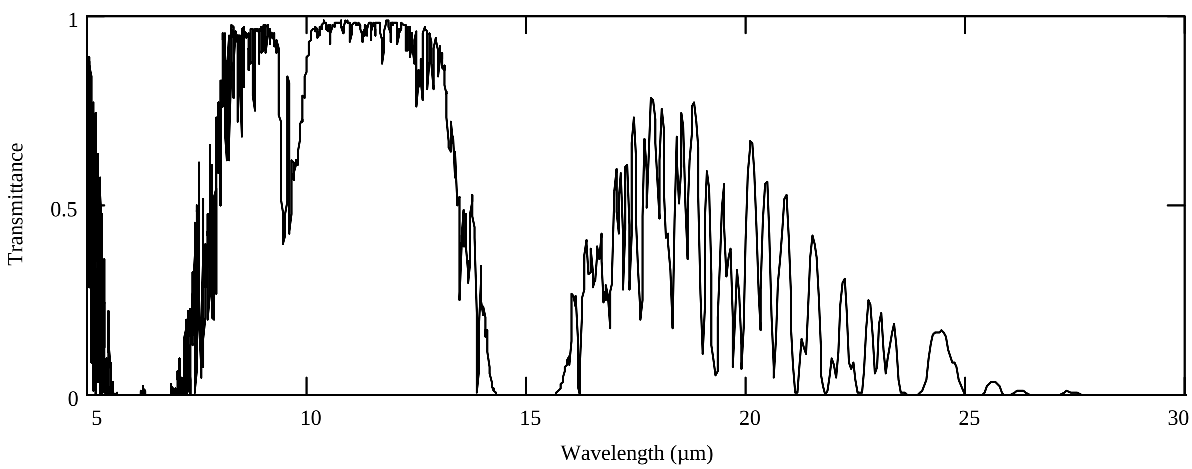


Figure 10 - A model atmospheric transmission curve for Mauna Kea under nominal 1 mm PWV conditions is shown for the wavelength range that is relevant for the mid-infrared imager. At such high altitude sites like Mauna Kea and Cerro Pachon, the atmospheric transparency is remarkably high in the 8-12 µm range. Water vapor will be particularly important in defining system performance at wavelengths exceeding ~15 µm and Gemini's unique queue scheduling system will be able to assure that observations requiring rare ultra-low PWV conditions can be completed.

at least ~350 Hz frame rates, roughly $2 \times 10^6$ e- full well, and are based upon Si:As IBC architectures. Overall these detectors represent significant advances over current technology and if ongoing development efforts are successful would be quite interesting for use in the Gemini mid-infrared imager.

ϖ *High Throughput*

The basic philosophy behind the imager is that it should be a relatively simple instrument (does not support a wide range of modes) that is dedicated to high throughput diffraction limited imaging so that maximum broadband sensitivity can be achieved, making the imager extremely competitive against similar instruments on other large telescopes.

ω *Plate Scale: ≤0.13 arcsec/pixel*

The intent behind the plate scale specification is simply that the imager must be able to critically sample a diffraction limited PSF at the short wavelength end of imager's sensitive range, which in practice will be determined by the atmosphere and cuts off at ~8 µm. The FWHM of a diffraction limited core at 8 µm is 0.25 arcsec, hence the requirement that it be sampled with at least two pixels which are ~0.13 arcsec in width. Again, since the input focal plane is expected to be diffraction limited most of the time, the mid-infrared imager optics must be of sufficient quality to relay such images onto the science array without significant degradation. Keeping with the philosophy of the mid-infrared imager being a simple low-cost instrument, there is no requirement for multiple plate scales.

ξ *Instrument Background: The imager's contribution to the total background signal should be <1% in the low emissivity atmospheric windows between 8 and 25 µm*

Minimizing the instrument's effective emissivity contribution to the telescope's is crucial if the theoretical performance gains possible on Gemini over other 8-10 m telescopes is to be achieved. All Gemini facility infrared instruments are required to keep their contribution to the background to <1% in order to preserve the intrinsically low emissivity nature of the telescope's delivered focal plane. This will require careful consideration in the areas of scattered and diffracted light along the optical path of the imager, including the window. Keeping the window clean from dust and molecular contaminants will also be important in the long term preservation of a low instrumental contribution to background radiation. As an example, a square millimeter of a 1% emissive surface at 0 °C emits $\sim 10^{13}$ photons/sec/sr into the 8-25 µm bandpass and reducing its temperature to that of $LN_2$ only reduces it to $\sim 10^{10}$ photons/sec/sr while reducing it to ~15 °K reduces it to <<1 photon/sec/sr, hence it will be important that the temperatures of all surfaces the science array sees be carefully baffled and sufficiently cold to achieve truly background limited performance.

ψ *Filters: Accommodation should be made to hold 20-30 cold filters*

Since the imager is expected to reside on the telescope for perhaps several months at a time, ready to be used on short “notice” as queued observations are executed, it will be important that a fairly large range of filters be available within the imager at any one time so the vacuum jacket does not have to be opened except on rare occasions. Some examples of filters that might be included range from broadband 8-13 µm and 17-25 µm filters to narrowband features covering various atomic and ionic lines.

Desirable options include:

υ *Dichroic feed to support near-infrared simultaneous wavefront sensing*

One of the top science goals for the Gemini telescopes will be to conduct cutting-edge research involving spectroscopy and imaging in obscured star formation regions. Targets like the molecular clouds in Orion, Taurus, and Ophiucus represent high priority science targets at mid-infrared wavelengths, where it is possible to penetrate through the dust enshrouding these objects and, since they are close-by, observe forming stellar systems, disks, and potentially substellar objects. With the heavy emphasis on the overall Gemini telescope design of low emissivity, high throughput, and high performance imaging, a quite natural scientific niche that Gemini stands to uniquely fill is dark cloud research.

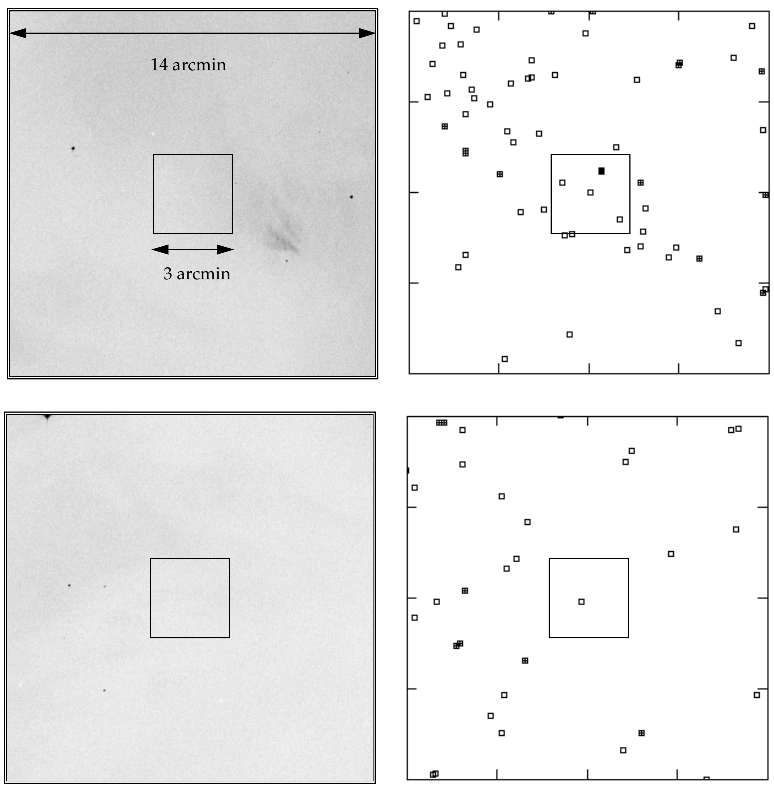


Figure 11 - Examples of typical embedded ρ Oph IRAS sources as viewed with the STScI digital catalog images (left) and corresponding J-band star charts derived from 2MASS scans (right) are shown. The full field of view is 14 arcmin and the size of the inner box is 3 arcmin. Filled boxes correspond to $J < 13$ mag sources. For the 3 arcmin field of view of the on-instrument wavefront sensors there will be significant problems finding adequate guide stars in these highly obscured areas unless near-infrared wavefront sensing is implemented.

An internal assessment of the availability of near-infrared guide stars (J, H, K) in ρ Oph and Taurus, using data provided from 2MASS and the Digital Sky Survey, indicates that adequate guide stars exist in these regions for the nominal 3 arcmin field of view of the Gemini on-instrument wavefront sensors. The details of this analysis are reported in a separate technical note (TN-PS-G0033). Accordingly the use of near-infrared wavefront sensors for tip/tilt/focus sensing (instead of the originally planned optical sensors) is under serious consideration for use with Gemini's other infrared instrumentation. Relying on such on-instrument sensors for measuring tip/tilt/focus is preferable to reliance upon the peripheral sensors since they reduce anisoplanatism and are mechanically coupled to the same cold structure housing the science array and therefore track flexure quite well. For the mid-infrared imager, while these gains would be valuable, the peripheral sensors can still be used for tip/tilt sensing since the isoplanatic patch size is so large at ~10 µm and in dark clouds frequently at least one reference star of sufficient optical brightness will be available using the peripheral sensors. Long term flexure drifts are not corrected with the use of the peripheral sensors. Thus, while there would be performance gains in dark clouds with the use of an on-instrument near-infrared wavefront sensor, such gains are not as large as those realized at near-infrared wavelengths and hence the use of an on-instrument sensor is listed as a desirable goal instead of a requirement.

ϖ *Optical design should support arrays that are at least twice the size of the initial array*

Given the steady increase in format that infrared arrays have exhibited over the past decade, and the long life that an instrument with as much scientific potential as a mid-infrared imager on an infrared optimized 8 m telescope will likely have, upgrading the imager with a larger format detector may be feasible over its lifetime. Accordingly, as a goal, the reimaging optics within the imager should support a field of view that is about twice the size dictated by the first generation of detectors, or ~2x256x0.13 or ~65 arcsec.

## 3.0 Theoretical Sensitivity

Table 2 lists predicted background flux levels for the mid-infrared imager. These values assume a QE curve like that described by Hoffmann et al. 1993 (SPIE, 1946, p449), 2% telescope emissivity, 0.13" pixels, a 60% total system throughput (top of the atmosphere to detector), 273 °K ambient temperature, and the previously mentioned emission model of Roche et al. These values be scaled to estimate background rates for other assumptions about throughput, pixel size, or filter bandpass. Note that the leading candidate IBC arrays for this application both support a maximum frame rate of at least 350 Hz with full wells of ~2-3x10$^{7}$ electrons. Accordingly, a bandpass encompassing the entire N band is theoretically possible, permitting high efficiency broadband imaging. Implied by this is the need for an array controller that can readout the array fast enough to support N-band imaging, fulfilling one of the key science drivers behind the instrument, namely high sensitivity broadband imaging.

| Bandpass | Wavelength | e-/sec/pixel |
|---|---|---|
| N | 8.0-12.8 | 3.9x10$^{8}$ |
| Q | 17.0-26.0 | 5.7x10$^{9}$ |

Table 2 - Predicted sky backgrounds for the input focal plane of mid-infrared imager on Gemini, assuming 0.13" pixels, 2% telescope emissivity, 273 °K ambient temperature, and applying the previously mentioned model of Mauna Kea sky emission.

Figure 12 shows the theoretical sensitivity of a mid-infrared imager on Gemini compared to that achieved on a more typical 4 m telescope. For the Gemini system a 3% telescope plus instrument emissivity is assumed as well as a diffraction limited PSF sampled by 0.13” pixels (the baseline design specifications). For the 4 m system a 15% telescope plus imager emissivity is assumed together with a diffraction limited PSF sampled by 0.3” arcsec pixels. In both cases flux is extracted only within the Airy disk. The point source sensitivity gains offered by the Gemini mid-infrared imager are impressive compared to what is possible on typical 4 m telescopes that have not been infrared optimized. No attempt has been made to adjust these model sensitivities for chopping or other noise sources, which would shift the plotted lines but not change the basic conclusion that a well designed, high throughput mid-infrared imager on a telescope like Gemini will vastly outperform any current system.

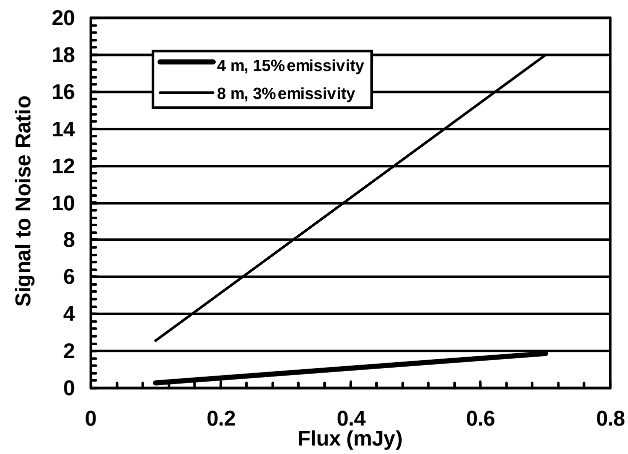


Figure 12 - A plot of theoretical point source sensitivity for the Gemini mid-infrared imager is shown compared to an imager on a 4 m telescope. The model assumes a 1 hour total integration time and a 10-12 µm bandpass.

## 4.0 Flat Fielding with the Gemini Facility Calibration Unit

Instrument calibration will typically be achieved with the use of a dedicated facility calibration unit (FCU), attached to one of the ports of the instrument support structure. At the time of this technical note, the functional requirements of the FCU are still under review. It is expected to provide flat fielding and wavelength calibration for GMOS and near infrared spectrograph, and provide flat fielding for the near-infrared imager. It works by injecting a uniformly illuminated beam which replicates the telescope pupil and f/ratio into the Cassegrain mounted science fold mirror, where it can be directed to any instrument. The eventual builder of the mid-infrared imager will be expected to communicate flat fielding specifications for the FCU to the Gemini Project Office so that, if required, mid-infrared imager calibration can be supported through that facility as well.