Near IR WFSing For Gemini

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I. Introduction

Understanding the processes of star formation is one of Gemini's key scientific goals. The early stages of star formation occur deep within obscuring clouds of gas and dust, whose extinction reduces the apparent brightness of objects in or behind the clouds at optical wavelengths, with a much smaller reduction at IR wavelengths. IR observations of the nearest regions of star formation, Rho Oph and Taurus, will be particularly important, because it will be in these regions that the highest spatial resolutions will be achieved.

The Gemini Project is assessing the availability of optical and near-IR reference stars in nearby SFR's. This work will be reported separately by Doug Simons. It clearly indicates that many key regions in Rho Oph and Taurus will have no candidate optical references stars to the limit of the HST GSC plate material (about 20.5 for the E-band Northern Hemisphere material and about 21.5 for the J-band southern Hemisphere material), while near-IR candidates abound.

In order to achieve the best spatial resolution, the Gemini telescopes will generally require observations of reference stars within the 3 arcmin FOV of the OIWFS and as close as possible to the science line-of-sight. For observations beyond 3 µm, t/t and fast focus corrections derived from the reference star observations will frequently be sufficient to provide near diffraction limited images. For shorter wavelengths, higher order AO corrections will generally be required in order to achieve near diffraction limited resolution. For all non-AO observations, the best images will be achieved with OIWFS t/t and ff corrections. For NGS AO observations, reference star observations for t/t, ff and higher order terms using the OIWFS and/or AOWFS are required, while for a Laser Beacon AO system, OIWFS observations of a reference star for t/t and fast focus correction are still required.

In addition to addressing the issue of adequate reference stars in nearby SFR'S, there are several other potential advantages associated with a near-IR OIWFS compared to R band or shorter wavelength WFSers. Mid-IR instruments operating at wavelengths longer than about 5µm may utilize window materials that are not transparent at optical wavelengths. The t/t and ff correction could be obtained from a near-IR OIWFS observing through a dichroic that splits off wavelengths shortward of, say, 3 µm. A near-IR OIWFS could address both the window transparency and reference star availability issues for mid-IR instruments. Other advantages of near-IR WFSing are a) somewhat better images, thus improving the centroiding for a given

SNR; b) much reduced differential atmospheric refraction between the reference star sensing wavelength and the science wavelengths; c) relative insensitivity to moonlight - IR observations are relatively insensitive to phase or position relative to the moon, provided adequate pointing and tracking information is available; and d) opens up the possibility of obtaining high quality thermal IR observations during morning twilight and for an hour or two after sunrise.

This memo briefly explores the relative performance of a near-IR vs R band OIWFS for t/t and ff.

II. Star Counts

The first order comparison is illustrated for the north galactic pole (NGP). Interstellar extinction will tend to redden at lower galactic latitudes, with the extreme case being star formation regions. If the prospects of a near-IR WFS look attractive at the NGP, then Gemini IR instrumentation could be equipped with such a device, for use over the whole sky, eliminating the need for an optical OIWFS for the IR instruments.

In order to achieve a 90% probability of finding a guide star brighter than some magnitude limit, m_{90}, in the 3 arcmin diameter FOV of the OIWFS, the average surface density of stars brighter than m_{90} has to be about 1170/deg^2. For Johnson's R band, using the Bahcall-Soneira galaxy model, m_{90}(R) = 18.8 mag. Using Martin Cohen's IR star model, m_{90}(J) = 17.3 mag, m_{90}(H) = 16.7 mag, and m_{90}(K) = 16.6 mag. The resulting photocurrent, assuming nominal bandpasses for the above bands, 80% detector QE and 50% throughput to the detector in all cases, is I_{90}(R) = 7200, I_{90}(J) = 13400, I_{90}(H) = 14000, I_{90}(K) = 7300 e/sec. Thus, near the NGP, for the same star density on the sky, and other parameters held constant, one would collect significantly more photoelectrons in J or H bands than in either K or R bands. A similar conclusion and very similar numbers were derived by P. Puxley and S. Ramsay. The effectiveness of J, H bands relative to R band will be further increased as one goes toward the galactic plane and grossly so going into dark clouds.

III. Sky Background

The zenith sky background in the above bands is about BG(R) = 20.3 mag/arcsec^2 for dark sky, 18.5 mag/arcsec^2 for a full moon 45° away from zenith, and 17.2 mag/arcsec^2 with full moon 10° away. The moonlit sky brightnesses were obtained using D. Simons' adaptation of Krisciunas and Schaefer's (1991, *PASP*, **103**, p1033) semi-empirical model determined for MK. BG(J) = 16.0 mag/arcsec^2 for dark sky and 15.9 for full moon, BG(H) = 14.5, and BG(K) = 14.3 mag/arcsec^2. The corresponding photocurrents from the sky background, using the same assumptions as above, are 1800(dark), 9500(full moon) in R band, and, 44,000, 106,000, and 61,000 e$^-$/sec/arcsec^2 at J, H and K respectively.

IV. Relative Centroiding Accuracy

There are many different options that could be evaluated, but this first order assessment is restricted to looking at a simple case of centroiding performance.

Centroiding accuracy is proportional to SNR/image size. The expected SNR at 90% sky coverage (SNR_{90}) is taken to be

$$SNR_{90} = \frac{I_{90}\delta t}{(I_{90}\delta t + I_{BG}\delta t + N_p N_r^2)^{1/2}}$$

For the nominal case, it is assumed that there are N_p = 12 pixels covering 3/4" dia area (4x4 minus the corners), and each pixel has N_r = 5 e^- read noise, and the integration time, δt, is 0.01 sec. The results are shown in the table below.

Thus if a read noise around 5 electrons can be achieved for a small format near-IR sensor, then there appears to be the potential for improved SNR for fast t/t and ff. In addition, there is some advantage in image size at near IR wavelengths. For a long exposure image whose shape is determined by a Kolmogorov turbulence spectrum, the FWHM is expected to decrease as $\lambda^{0.2}$. For a tip/tilt and ff corrected image, the decrease in image size with increasing wavelength will be faster, roughly estimated as $\lambda^{0.4}$. The centroiding precision for the nominal case, compared to that at R band is then error (R)/error(J) = 1.8, error(R)/error(H) = 1.7, error(R)/error(K) = 1.2. These differences could be very significant over much of the sky, and under many conditions.

Parameter	Band				Comment
	R	J	H	K	
$I_{90}\delta t$	72	134	140	73	electrons
$I_{BG}\delta t$	9	220	500	300	electrons
$N_p x N_r^2$	300	300	300	300	
SNR(nominal)	3.7	5.2	4.6	2.8	
SNR(FM, 45°)	3.4	5.2	4.6	2.8	
SNR(FM, 10°)	3.1	5.0	4.6	2.8	
SNR(noisy)	3.7	3.4	3.3	1.8	N_r(J,H,K)=10
SNR(fast)	0.80	1.4	1.35	0.75	δt=0.002 sec
SNR(2x2 SH)	1.0	1.8	1.7	0.9	4x4 subarrays

Table 1 - Calculated centroiding parameters are listed for various assumptions about sampling, noise, etc.

V. Daytime Observing

The sky background at wavelengths beyond 2.8 µm is essentially the same night or day. In addition, there are strong indications (mostly anecdotal) that atmospheric seeing is very good during morning twilight and for perhaps one or two hours after sunrise. At these wavelengths, near diffraction limited imaging can generally be achieved with t/t and ff correction only. Thus the key to excellent morning observing is pointing the telescope and having a reference star for t/t and ff correction. The K band is likely to be the best band for this purpose because the daytime sky background at MK is near a minimum at these wavelengths. Adapting D. Simons' moonlit sky background model for sunlit sky, the K band sky background for zenith pointing with the sun 1° above the horizon is estimated to be about 9.9 mag/arcsec^2. For the nominal case considered above, this sky background would result in about 1400 e^-/pix/0.01 sec, thus pixel saturation should not be a problem. In order to achieve a SNR of about 5, similar to the best in the above table, with this background, would require a 14.2 mag reference star in the K band. At the NGP, there is about a 40% probability of finding a star this bright or brighter in a 3 arcmin FOV. At galactic latitudes of 30° or less the probability would be greater than 90%. All such stars, over the whole sky, would be in the 2MASS catalog, with excellent positions (astrometric errors of less than 1 arcsec and tied to the Hipparcos reference frame). Thus a near-IR WFS for t/t and ff would provide an opportunity to exploit an additional 2 - 3 hours of observing time each night.

One key to the success of near-IR WFSing is the development of low noise, fast, small format IR arrays or the capability to sample subarrays fast with low read noise. Potential detector arrays include Ge photodiodes with wavelength cutoff near 1.7 µm, HgCdTe arrays with 2.5 µm cutoff and InSb. The operating temperatures for these arrays are low enough that they could be incorporated into the cryocooled dewars, which could reduce some mechanical flexure problems. A. Fowler is making a first order assessment of what can be achieved in the area of small format near IR arrays.

The implementation of a near-IR OIWFS in near-IR instrumentation is not straightforward; options include reflective off-slit viewing for nirs, selectable dichroics, e.g., H band to OIWFS when science observing in J band and J, or I+J when science observing at H or longer wavelengths. The most appropriate approach would have to be explored with the nirs and niri teams.