On the Comparative Performance of an 8m NGST and a Ground Based 8m Optical/IR Telescope

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Abstract. The potential 1-20μm imaging and spectroscopic sensitivity of a cooled 8m NGST in space is compared to that of a 8m ground-based telescope. For $\lambda \geq 2.5\mu$m an 8m NGST may achieve a signal-to-noise ratio (SNR) advantage in the range 100 to 1000 for both imaging observations and for spectroscopic observations up to R=1000. In the 1 to 2.5μm regime an 8m NGST may achieve a SNR advantage for imaging of $\sim$10, while for spectroscopic observations the SNR advantage is expected to be substantially less and could approach unity for R$\geq$1000.

1. Introduction

The NGST science drivers dictate a telescope of 4m diameter or larger and imaging and spectroscopic capability optimized for the 1-5μm range and extending over the 0.6 to 20μm wavelength range with image quality at least as good as that of HST. While contemplating in more detail the design parameters of the NGST telescope and its instrumentation capabilities, it is essential to anticipate the likely state of ground-based astronomical observational capability at the time of the launch of NGST, expected to be no sooner than 2007.

Currently, ground-based astronomy is undergoing a fundamental revolution throughout the world. Shortly after the beginning of the 21st century, well before the launch of NGST, at least a dozen 8m class optical/IR ground-based telescopes will be in operation. A recent assessment of plans in this area is compiled in SPIE Volume 2871 (ed Ardeberg, 1996). These include Keck I and II telescopes (10m diameter, in operation on Mauna Kea, HI), Hobby-Eberly telescope (9.2m effective diameter, first light in mid 1996 on Mt. Fowlkes, TX), Subaru telescope (8.2m, first light mid 1998 on Mauna Kea, HI), VLT telescopes (four - 8m diameter telescopes, first light mid 1998 on Paranal, Chile), Gemini -North and -South (8m diameter, first light at the end of 1998 on Mauna Kea, HI, and mid 2001 on Cerro Pachon, Chile), the LBT telescope (2x8.4m dia, first light 2001 for a single optical train, 1 to 2 years later for the combined beam, on Mt Graham, AZ), and the Spanish GTC Project (10m diameter, first light planned for 2002, on La Palma).

Many of these telescopes are located on excellent sites for IR observations, with low water vapor and very good seeing. Spectroscopic instrumentation with resolutions ranging up to at least 100,000 at optical and IR wavelengths are planned and/or under development for these telescopes, including 2-d spectroscopy, multi-slit and wide field multi-object spectroscopic capability in the

1-5μm range. One can reasonably expect that these telescopes will continue to be equipped with state of the art instrumentation and detector arrays, covering the whole range of optical/IR wavelengths accessible from the ground.

Given the pace of Adaptive Optics applications in ground-based astronomy, one can also confidently predict that many of these telescopes will be equipped with Adaptive Optics systems based on Laser beacons, capable of providing near diffraction limited images at 1μm and longward, over most of the sky. Thus it is very likely that by the time NGST is launched, these ground-based 8m class observatories will be undertaking what can be done from the ground, exploiting Adaptive Optics, the most advanced detector arrays, and the most advanced technologies for high throughput, high resolution, multi-object spectroscopy covering a wide range of spectral resolutions.

It is essential to understand how the NGST will build on the investigations to be carried out with this collection of ground-based telescopes and how the parameters of the NGST telescope, e.g. collecting area and image quality, and instrumentation, e.g. wavelength coverage, field of view and spectral resolution should be optimized for scientific return given the likely activities of this unprecedented armada of very large ground-based optical/IR telescopes.

The obvious advantage of NGST compared to ground-based optical/IR telescopes is freedom from the effects of the earth's atmosphere. Absorption by molecules in the earth's atmosphere precludes astronomical observations from the ground over about 25% of 1-5μm regime and roughly 33% over the 1-25μm regime while the NGST would have unobstructed access to the whole wavelength range. This unobscured access will be important for many astronomical problems, but is probably not compelling by itself.

Turbulence in the atmosphere distorts the wavefront passing through, leading to rapidly varying degradation of the images of external sources while, for NGST, any degradation of diffraction limited performance will be the result of distortions in the telescope and instruments plus pointing/tracking errors. With the rapid development of Adaptive Optics, it is anticipated that ground-based telescopes in the 8m class will be capable of nearly diffraction limited image quality for wavelengths longward of 1μm. Achieving significantly better images at these wavelengths with NGST is likely to be a major cost driver.

Airglow emission from the earth's upper atmosphere, due primarily to rotation/vibration OH lines, dominants the dark sky backgound in the 0.6 to 2.3μm range for good ground-based astronomical sites. At longer wavelengths, thermal emission from molecules in the lower atmosphere and from the ambient temperature telescope itself dominates over all other backgrounds.

Outside the earth's atmosphere, the sky backgound over this spectral range is the result of scattering by and emission from interplanetary dust grains and astronomical sources. The NGST telescope and instruments will be cooled so their contribution to the IR background shortward of 25μm is negligible. It is in this area that NGST's fundamental advantage is anticipated, allowing the NGST to detect and study sources too faint to be seen from the ground. The remainder of this paper examines the comparative sensitivity performance of large ground-based telescopes and NGST. The comparison is illustrative rather than exhaustive, with several simplifying assumptions and arbitrary choices for parameters.

2. Sensitivity Comparison

We choose to simplify the sensitivity comparison in a variety of ways;

- Focus on 1-5μm spectral region, the optimized core of NGST wavelength coverage, with extension to longer wavelengths.
- Illustrate the comparison in the atmospheric "windows", where the effect of the atmosphere on telecope sensitivity is minimized. These atmospheric windows are assigned nominal properties based on modeling and observations. No attempt is made to model details within a window.
- Compare Signal to Noise Ratios (SNR) for the detection of point sources with a range of assumptions concerning spectral resolution (R = 5 (Imaging), 100, 1000, 10,000) and detector performance that are judged to be scientifically interesting possibilities for NGST, and technically reasonable.
- In order to include the effect of photon statistics for the source itself, the SNR comparison is made for a point source of flux density that achieves a SNR = 10 with a total integration time of 10,000 sec for the NGST assumptions.
- Assume that the array pixels convert photons into photoelectrons with unity gain, and that all the photon sources obey Poisson statistics. Then the SNR of an observation with exposure time t is given by (see e.g. Gillett, 1987):

$$SNR = I_s \cdot t/N(t)$$

where $I_s = 1.5 \cdot 10^7 \cdot A_c \cdot q_e \cdot T_a \cdot T_t \cdot T_i \cdot 1/R \cdot f_v \cdot f$ electrons/sec is the signal photocurrent, with A_c as the telescope collecting area in meters^2, T_a, T_t, T_i are the atmosphere, telescope and instrument transmission respectively, q_e is the detector quantum efficiency, R is the spectral resolution $\lambda/\Delta\lambda$, f_v is the source strength in Jansky's, and f is the fraction of source photons collected. The measurement noise is given by:

$$N(t) = (I_s \cdot t + I_{bg} \cdot t + n \cdot I_{dc} \cdot t + n \cdot N_r^2)^{1/2}$$

$I_{bg} = 1.5 \cdot 10^7 \cdot A_c \cdot q_e \cdot T_t \cdot T_i \cdot 1/R \cdot \beta_\nu \cdot \Omega$ electron/s is the background photocurrent, where β_ν is the sky background surface brightness in Jansky's per square arcsec, Ω is solid angle in square arcsec that encloses the fraction f of the point source flux, n is the number of pixels required to cover Ω, while I_{dc} and N_r are the detector dark current and read noise per pixel.

We assume that k observations with exposure time t can be combined with the resultant SNR given by $SNR(k \cdot t) = SNR(t) \cdot k^{0.5}$.

The values for parameters used in the comparison are discussed briefly below.

2.1. Telescope size/Collecting area (A_c) and throughput (T_i, T_a, T_t)

Calculation are based on the collecting area of one 8m diameter ground-based telescope with a small central obscuration. It should be noted that several ground-based observatories are planning to combine 2 or more 8m telescopes (e.g. Keck, LBT, VLT).

We also assume that the NGST has the same collecting area even though the NGST concepts range from 4m to 8m diameter. There is clear advantage in SNR for increased collecting area, and an optimistic version of NGST has been adopted for this illustration. The product of telescope and instrument transmission is taken to be 0.5 for both the ground-based telescope and NGST. The atmospheric transmission is taken as 0.95 and applies only to the ground-based telescope.

2.2. Image Size (Ω)

For the 8m ground-based telescope, the imaging performance is assumed to be consistent with a moderately good Adaptive Optics capability, roughly corresponding to a Strehl Ratio of 0.8 at K and less at H and J and diffraction limited at L and beyond.

For the NGST is is assumed that it delivers the same image size as the 8m ground-based telescope. Significant deviations from a circular aperture, i.e. petals and or large central obscuration will reduce the concentration of energy within the central core of the diffraction pattern. In addition, for smaller NGST diameter than 8m, the diffraction limited solid angle will increase inversely proportional to the diameter squared.

In all cases, it is assumed that the image area is covered by four pixels in order to achieve spatial resolution roughly commensurate with the image quality. The parameters adopted are a beam size of 0.01 square arcsec and f=0.7 for $\lambda < 3.5\mu$m and beam size $0.01\cdot(\lambda/3.5\mu\mathrm{m})$ square arcsec with f=0.5 for $\lambda \geq 3.5\mu$m.

2.3. Background (β_ν)

For the 8m ground-based telescope, several sources of background photons are important in this wavelength regime. Beyond 2.3μm the background for a ground-based telescope is overwhelmingly dominated by thermal emission from the telescope and atmosphere (see Figure 1). The telescope contribution is taken to be at an ambient temperature greybody of 0 deg C with emissivity of 3%, and the atmospheric contribution is calculated for a high altitude site like MK with 1mm precipitable water vapor at an ambient temperature at ground level of 0 deg C.

Shortward of 2.3μm OH airglow emission becomes significant and is the dominant source of background emission in the H and J bands. This background is concentrated in a relatively small number of very narrow lines. For imaging observations with broad band filters and low resolution spectroscopy, the lines are averaged to produced the background, however at higher spectral resolution, most of the spectral elements will be OH-line free.

For the R=100 and 1000 comparisons, two options are evaluated:

- The OH lines are averaged to produce the background, and

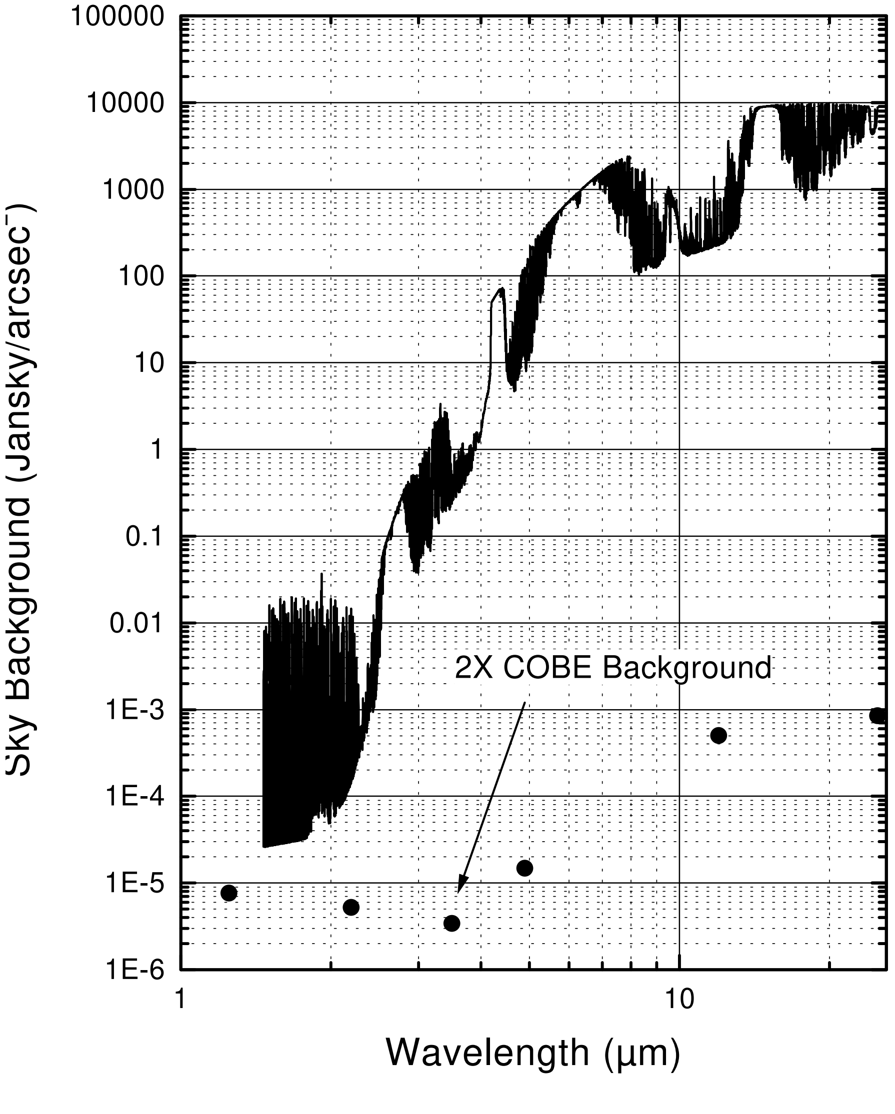

Figure 1. Typical IR background emission for a low backgound ground-based telescope at a good, high altitude site like Mauna Kea. Thermal emission from the telescope and atmosphere dominate the background beyond 2.3μm, while OH airglow lines dominate at the shorter IR wavelengths. Also shown is 2x the minimum sky background from space as measured by COBE.

- The observations are carried out at a resolution of 5000, and pixels contaminated by OH emission are deleted from the spectrum, with the remaining spectral elements combined to achieve an effective spectral resolution of 100 or 1000 (see e.g. Herbst, 1994). It is assumed that 10% of the pixels are lost because of contamination by OH lines, and that the recombined spectra have SNR given by $\mathrm{SNR(R)} = \mathrm{SNR(5000)}\cdot(5000/\mathrm{R})^{0.5}$. The technique achieves a substantially reduced background for the spectroscopic observations: however, the resulting sensitivity is more dependent on detector performance, and for the same array size, spectral coverage is reduced.

For the NGST, the sky background is taken to be 2x the minimum sky background observed by COBE (Hauser, 1994). The NGST telescope is assumed to be passively cooled to near 30K, thus contributing essentially no background in the wavelength range considered here.

The backgrounds in the 1-3μm regime are summarized in Figure 2. In addition the photocurrent generated by these backgrounds for the 8m telescope parameters adopted here is also indicated for spectroscopic observations. The photocurrents are extremely low, less than 0.01e/sec/pixel at R=1000, leading to a critical dependence of NGST (and the ground-based telescope) sensitivity on detector properties.

2.4. Detector Performance ($\mathbf{I}_d$, $\mathbf{N}_r$, $\mathbf{q}_e$)

It is assumed that the arrays for both NGST and the ground-based telescope have the same performance even though experience has shown that generally ground-based facilities can more rapidly deploy advanced technology of this type. Two cases are considered here: 1) Photon noise limited performance; except for the quantum efficiency, the detectors are perfect, i.e. dark current and read noise are negligibly small, and 2) Extrapolation of current performance; in this case the adopted read noise and dark current are improvements beyond the current state-of-the-art for InSb arrays operating over the 1-5.5μm range. For wavelengths longward of 5.5μm, the assumptions are significant improvements compared to current low temperature performance of Si:As IBC arrays. Parameters adopted for these two cases are listed in Table 1.

Wavelength range	1μm	to	5.5μm	5.5μm	to	25μm
Parameter	I_d	N_r	q_e	I_d	N_r	q_e
Photon noise limited	0	0	80%	0	0	40%
Extrapolation of current performance	0.02 e/sec	4e	80%	10 e/sec	30e	40%

Table 1. Assumed array characteristics.

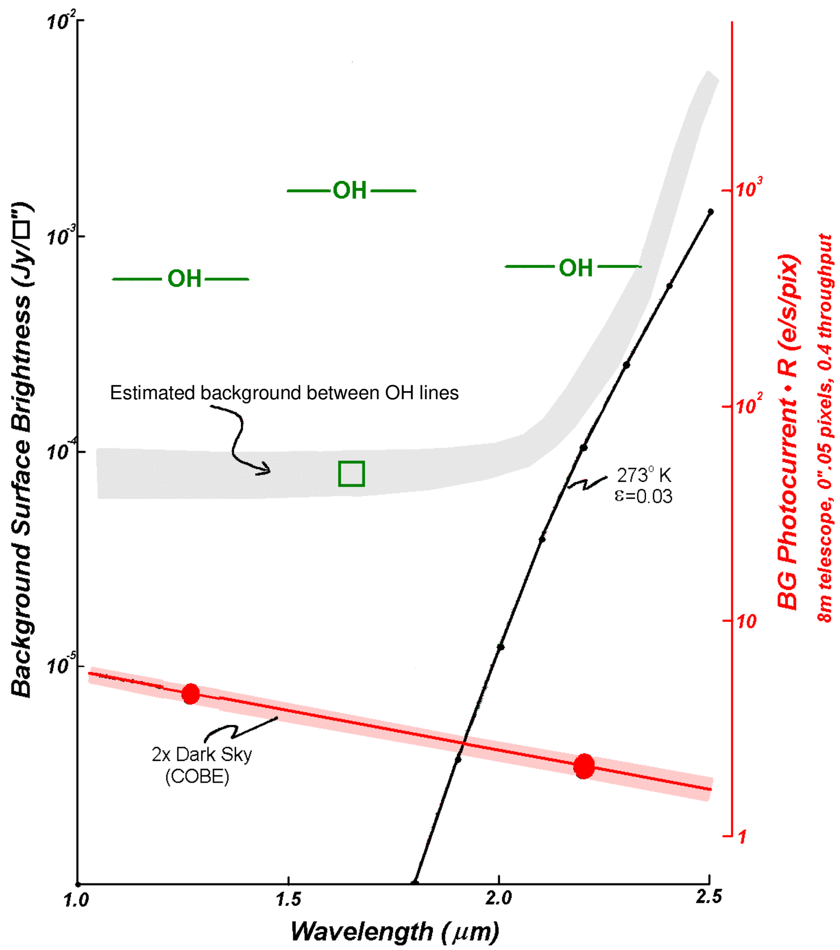

Figure 2. Near IR sky background surface brightness. Also indicated is the corresponding background photocurrent for the assumed 8m telescope parameters. References:
Minimum sky background measured by COBE - Hauser (1994)
OH line emission and Background between the OH lines - Maihara, et al (1993)

2.5. Integration Time (t)

The maximum single exposure time is taken to be 1000 sec for NGST, assumed to be limited by the effects of charged particle hits on the detector. Variable Cosmic Ray fluxes are the space equivalent of "weather", and are expected to be highly variable. For the ground-based telescope, shielded from much of the cosmic ray fluence, the maximum single exposure integration time is taken as 4000 sec. The SNR comparison is evaluated at SNR = 10 and total integration time of 10,000 sec, i.e. ten 1000 sec exposures on NGST and 2.5 4000 sec exposures for the ground-based 8 m telescope.

3. Discussion

The results of this illustrative comparison are shown in Figures 3 and 4. Figure 3 shows the sensitivity vs wavelength for imaging and R=1000 spectroscopy for both the NGST and 8m ground-based models. Figure 4 shows the relative SNR for NGST compared to the 8m ground-based telescope, for R=5, 100, 1000, and 10000, respectively.

For wavelengths longer than 2.5μm, an 8m NGST will have a SNR advantage compared to ground-based 8m class telescopes in excess of a factor of 10 and approaching a factor of 1000 at all spectral resolutions. This spectral regime is currently being probed from space with a cooled telescope by ISO, and will be explored to levels beyond ground-based sensitivities by SIRTF, but NGST retains a huge performance advantage compared to either of these space missions, because as its much larger collecting area and improved diffraction limited image quality. An 8m NGST would be unsurpassed scientifically in this regime. Because of the low background photon flux in space, detector performance becomes the dominant noise source for R$\geq$100.

In the 1-2.5μm range the NGST sensitivity advantage compared to the ground-based 8m telescope is substantially reduced due to the very rapid decrease in thermal emission from the atmosphere and ambient temperature telescope in the 2-3μm regime. For broad band imaging the 8m NGST has a SNR advantage of about a factor of 10 as a result of the $\sim$100x lower background in space compared to the OH line emission in this spectral region. If the extrapolated detector performance can be obtained, NGST imaging observations are likely to be background limited. Under background limited conditions, the SNR is roughly proportional to $(A_c/\Omega)^{1/2}$; thus, a smaller NGST telescope or poorer imaging performance would lead to a reduced SNR advantage for 1-2.5μm imaging.

Detector performance will be a major issue for spectroscopic observations with R$\geq$100 because of the very low photocurrents anticipated in this spectral regime for both ground-based and space-based telescopes. Because of the very low backgrounds, depending on assumptions as to relative image quality, maximum integration times, and collecting area, it is possible that ground-based facilities may have a SNR advantage compared to NGST for spectroscopic observations in this wavelength range. Under detector noise limited conditions, the SNR is proportional to A_c, thus the size of the NGST telescope will be critical to its spectroscopic performance compared to ground-based telescopes.

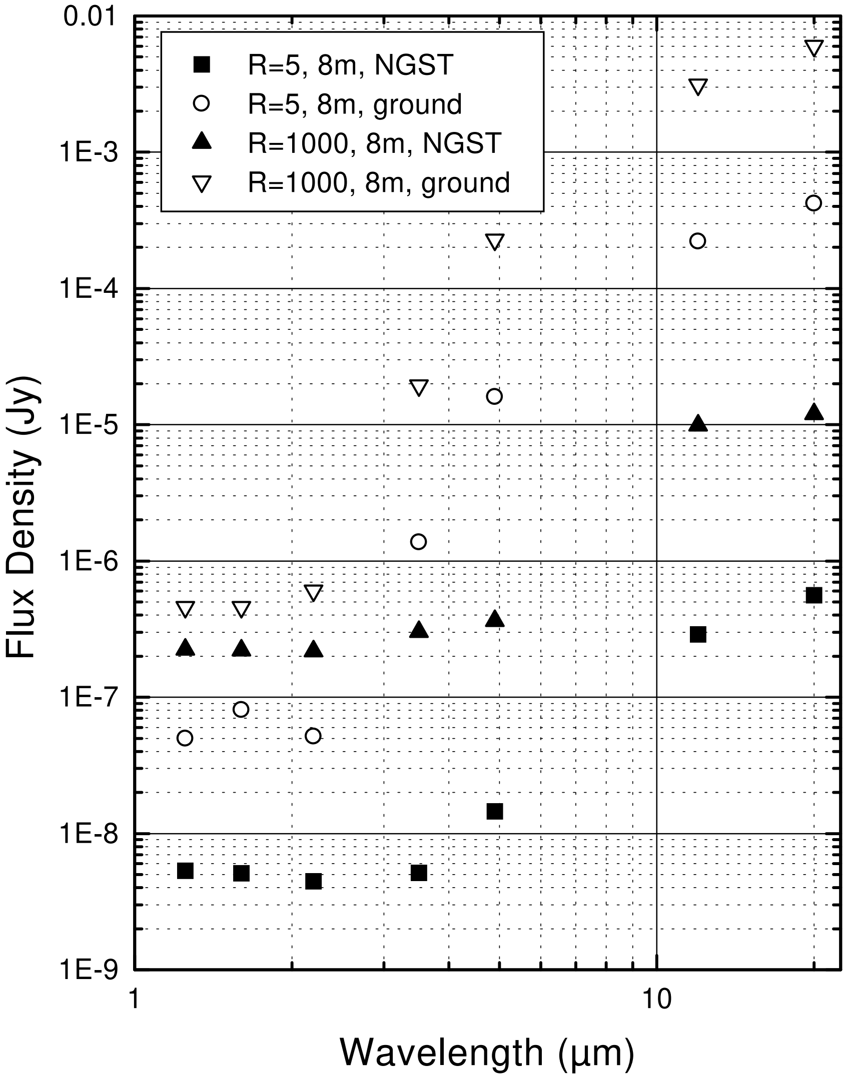

Figure 3. Point source sensitivity for the NGST and 8m ground-based telescope models for SNR=10 with 10,000 sec total exposure time for the parameters discussed in the text and assuming the extrapolated detector performance.

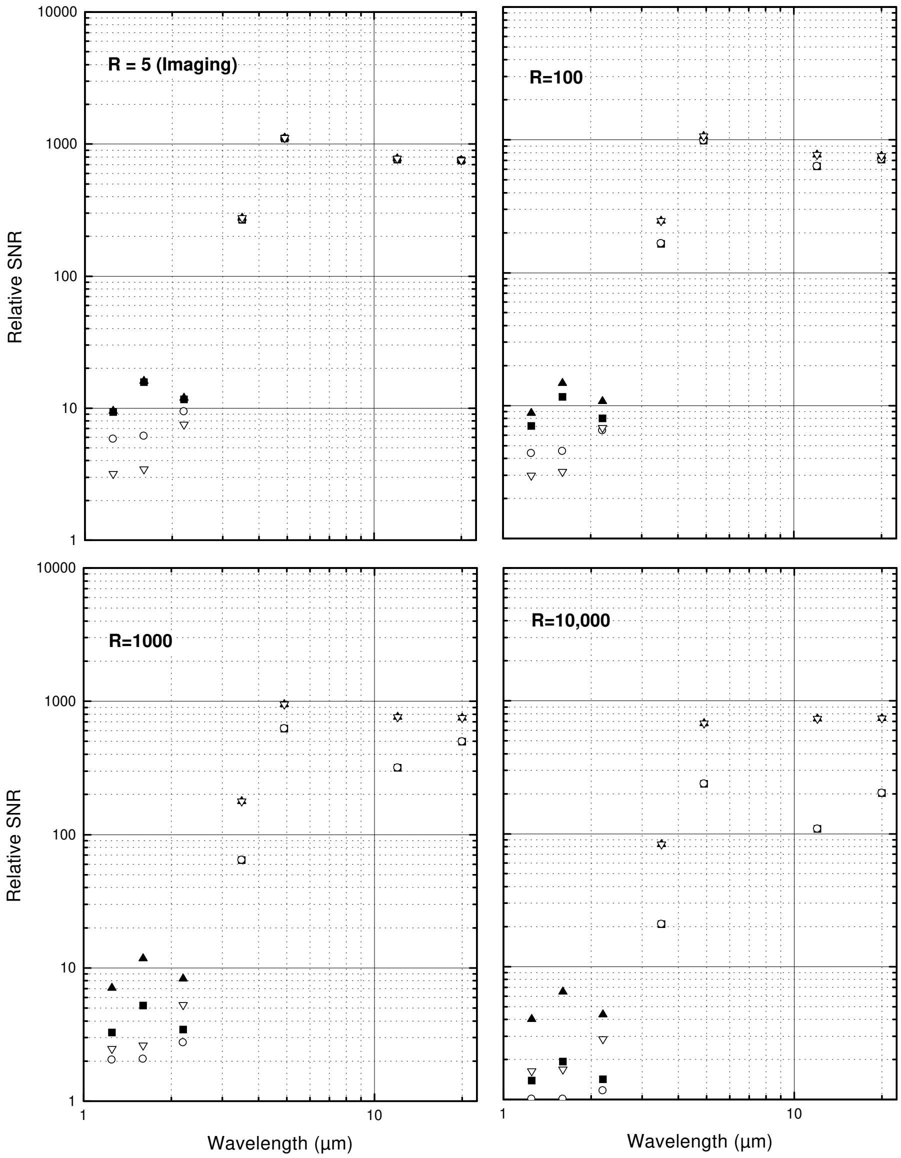

Figure 4. Relative point source SNR of an 8m NGST compared to 8m ground-based telescope for R=5 (imaging), 100, 1000, and 10,000.
Solid square - extrapolated detector performance, averaging OH lines
Solid triangle - photon noise limited performance, averaging OH lines
Open circle - extrapolated detector performance, between OH lines
Open triangle - photon noise limited performance, between OH lines

Source photon noise is a significant factor for NGST observations shortward of 5μm at R$\geq$100 and SNR$\geq$10.

References

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