Design Trade Space : FTS/FP/Grating – Based Spectrometers[1]

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1. Comparison of Point Source Sensitivities

[1] Draft: 12/26/98

1. COMPARISON OF POINT SOURCE SENSITIVITIES

Summary:

The potential point source sensitivity of three spectrometer concepts (Fourier transform spectrometer, Fabry-Perot/filter, and a grating) was considered in four cases: [1] full 1-5 micron spectrum, NGST goal detectors, [2]single line observation, NGST goal detectors, [3] full 1-5 micron spectrum, current detectors, and [4] single line observation, current detectors. Spectral resolutions of 50, 100, 1,000, and 10,000 were considered in each case. The Zodiacal background model of Thompson (1989) was used throughout.

Noise equivalent flux density (NEFD) plots denoting SN = 10 in 10^5 s evaluated at 2.5 microns were calculated for each case. The instrument concepts can be ranked by relative sensitivity as follows:

Case	Highest	Intermediate	Lowest
1	Grating	FTS	FP
2	Grating≈FP	…	FTS
3	Grating	FTS	FP
4	Grating≈FP	…	FTS

The distinction between highest and lowest varies from factors of 2 to several orders of magnitude in sensitivity among the various cases.

We note that relative sensitivity is only one dimension of comparison. This analysis does not address technical readiness and risk, operations complexity, observing efficiency and source count issues, and cost issues surrounding specific instrument concepts involving these three methodologies.

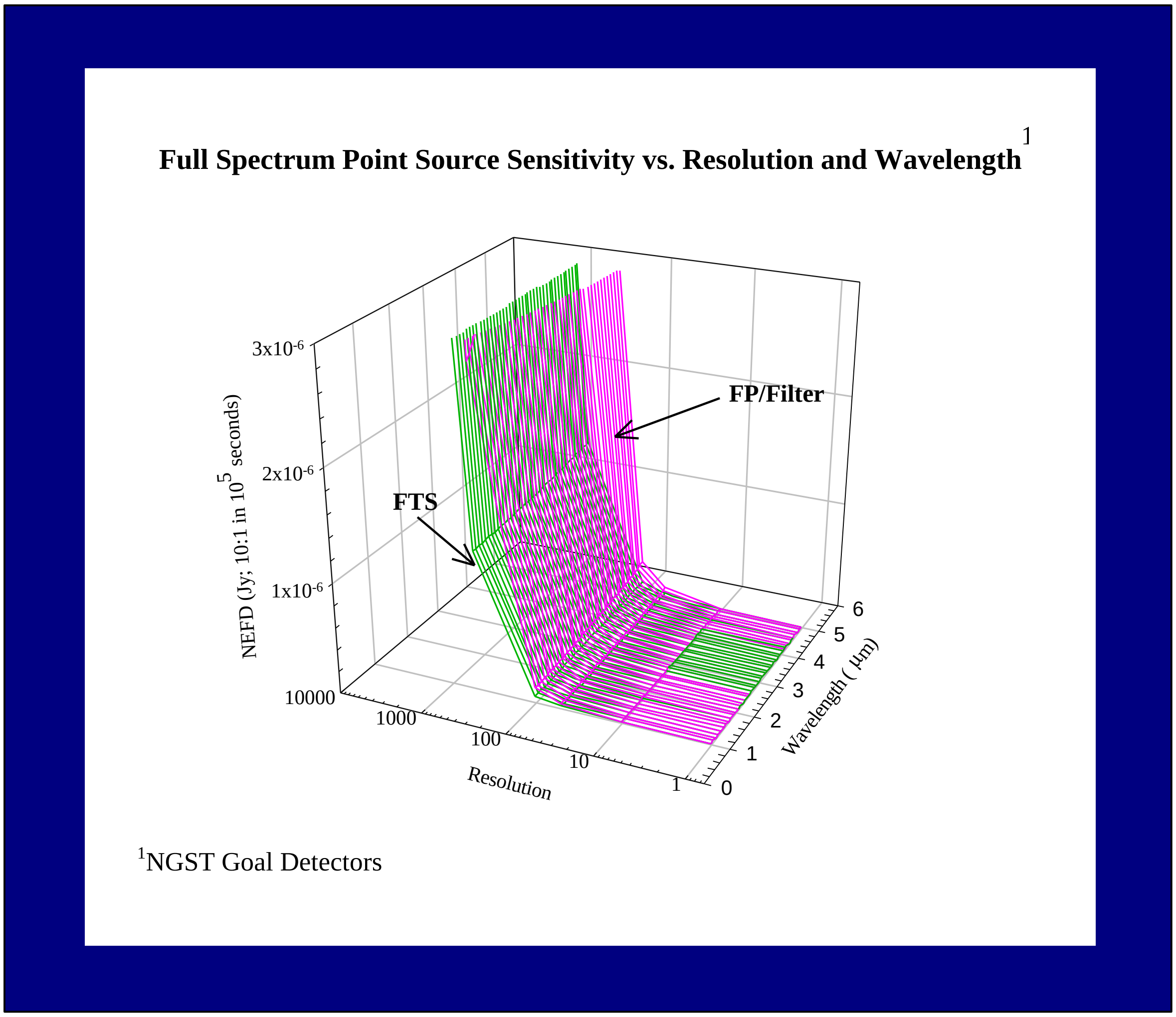

Figure 1: Point source sensitivity to obtain a full 1-5 μm data cube using an FTS and a Fabry-Perot (or broad/narrow-band filter) as a function of wavelength and spectral resolution. Flux density is given for a signal to noise ratio of 10 and a total integration time available to obtain the whole spectrum of 10^5 seconds. As can be seen, at low resolution, when the noise is dominated by the background shot noise in the Fabry-Perot/Filter case, the sensitivity of the FP/filter system is equal to that of the FTS. For the Fabry-Perot system, as the spectral resolution is increased, the background flux reaching the detector is reduced and the noise becomes dominated by detector noise. At these resolutions, the FTS is more sensitive. This cross over point occurs at a resolution of ~40 at 2 μm assuming NGST goal detector properties (see p. 16). With current detectors, the FTS is more sensitive than a FP/filter at R>10. Note that these cross over resolutions will become even lower using updated zodiacal background models (Stiavelli 1998) which predict lower background levels at 2 μm.

Assumptions:

For the Fabry-Perot, integration time is split evenly between the number of spectral channels contained within the spectrum at each resolution. Nyquist sampling is assumed for both cases, and the throughput is assumed to be the same. NGST goal detector parameters are assumed in this plot.

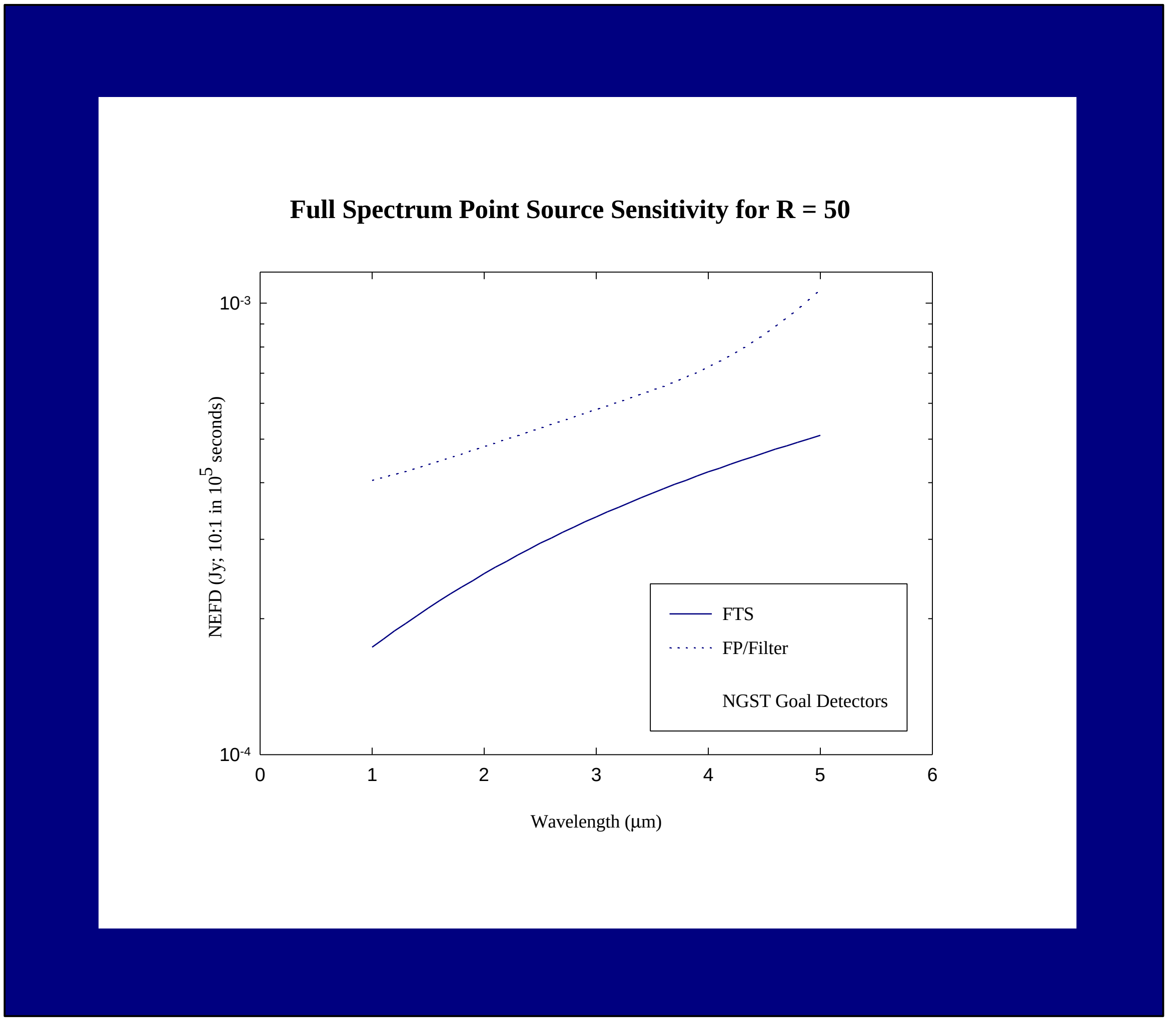

Figure 2: Point source sensitivity for obtaining full 1-5 µm spectrum for an FTS and FP/filter vs. wavelength for R=50. Integration time and signal to noise is same as for previous figure. As can be seen, even for resolutions as low as ~ 50, the detectors in the FP/filter case become detector noise limited, and the FP/filter system becomes less sensitive by a factor of ~ 2.5. Note that for an FTS, the sensitivity gets worse with wavelength at low resolution. At low resolution, the source flux is small, and the background signal dominates the noise. Since the background signal is multiplied by the number of pixels in the point spread function, and this number goes up with wavelength for diffraction limited performance, the sensitivity gets worse with wavelength for an FTS. At higher resolutions, the source photons dominate the noise term, and the sensitivity per spectral channel for an FTS is independent of wavelength. Note that the detectors in an FTS system are always photon noise limited regardless of whether goal or current detectors are used..

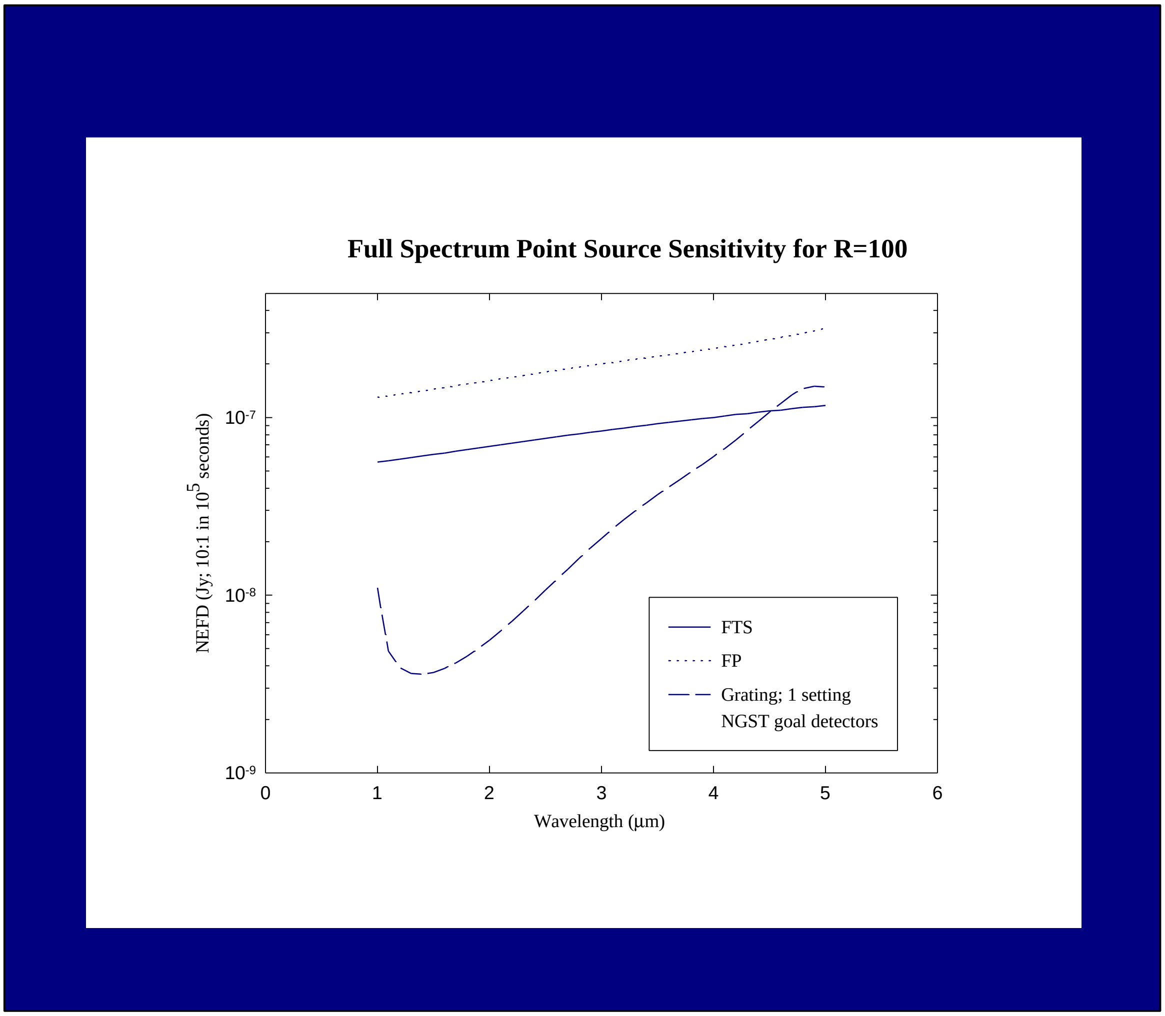

Figure 3: Point source sensitivity to obtain full spectrum for an FTS, FP, and grating vs. wavelength for R=100. Here we assume that we use only one grating. The assumptions about the grating follow below. As can be seen, the grating system is the most sensitive for a point source. At longer wavelengths, the noise is higher in the grating system because both the zodiacal background and the number of pixels in the point spread function go up, and the grating efficiency gets worse. The grating efficiency curve is given below. Note that for an FP and an FTS, the resolution is constant with wavelength. For a grating, the bandwidth is constant with wavelength (for one grating, one setting) and the resolution varies. Here R varies from 100 to 500.

Assumptions About Grating: Case A: R=100

- 1 grating can cover whole spectrum
- Band average efficiency is ~50%
- Grating density: 2.96 lines/mm
- Incidence angle: 8.74°
- Nominal blaze angle: -0.143°

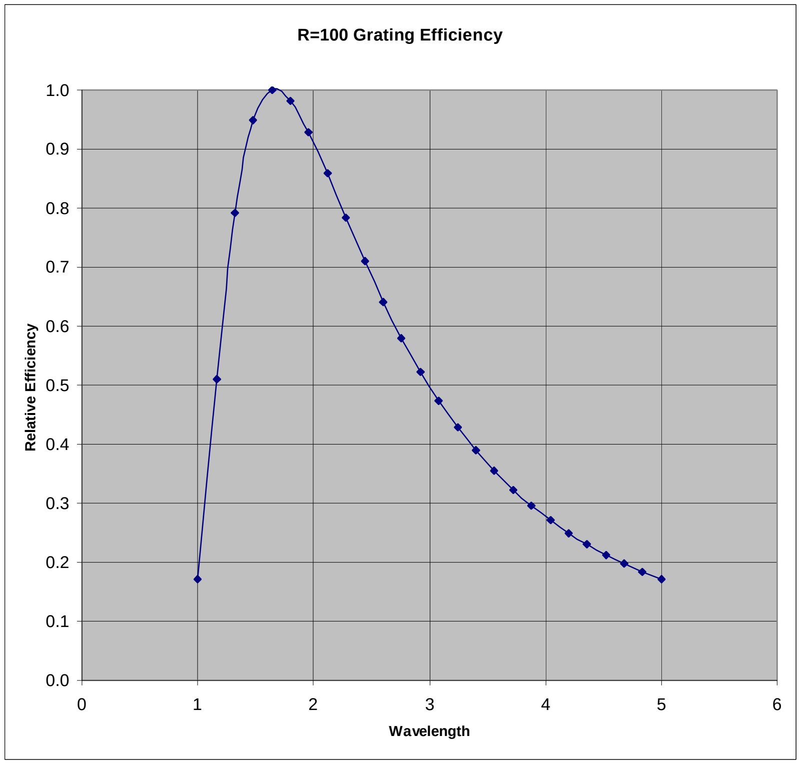

Figure 4: Grating efficiency vs. wavelength for one fixed grating covering 1-5 microns with 133 spectral resolution elements (266 pixels/detector row for MOS slit mask concept). . With one grating, the band average efficiency is 50%, but, as can be seen, it drops sharply to 17% on either end of the spectrum.

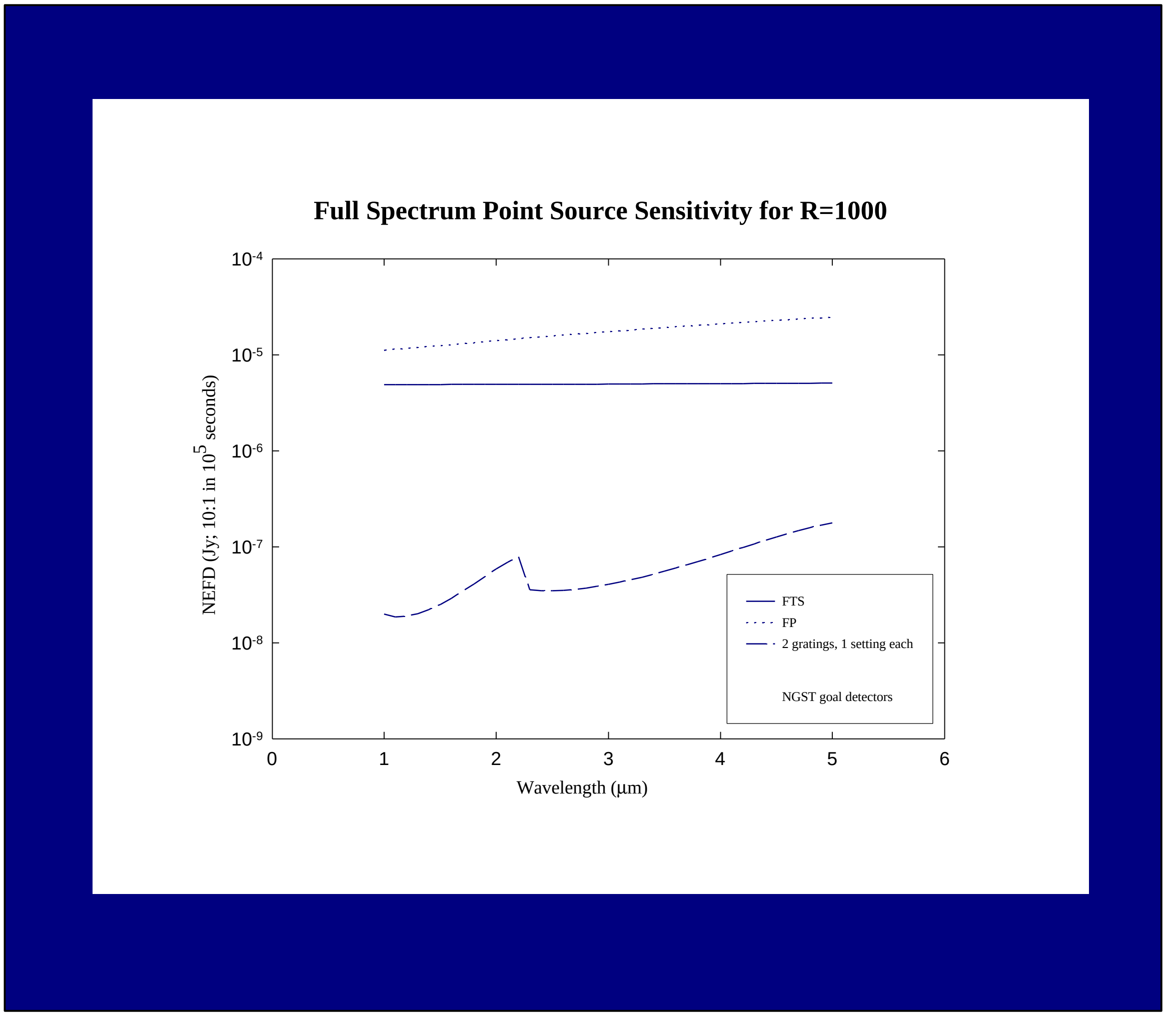

Figure 5: Full spectrum point source sensitivity vs. wavelength for an FTS, FP, and grating for R=1000. Here we assume that we use 2 gratings, with one setting each. The assumptions about the grating follow below. As can be seen, the grating system is the most sensitive for a point source at this resolution. Note that the sensitivity is flat for an FTS system at this resolution. This is because the detectors become source flux dominated at this resolution. The resolution for the grating system varies from ~ 640 to ~1400.

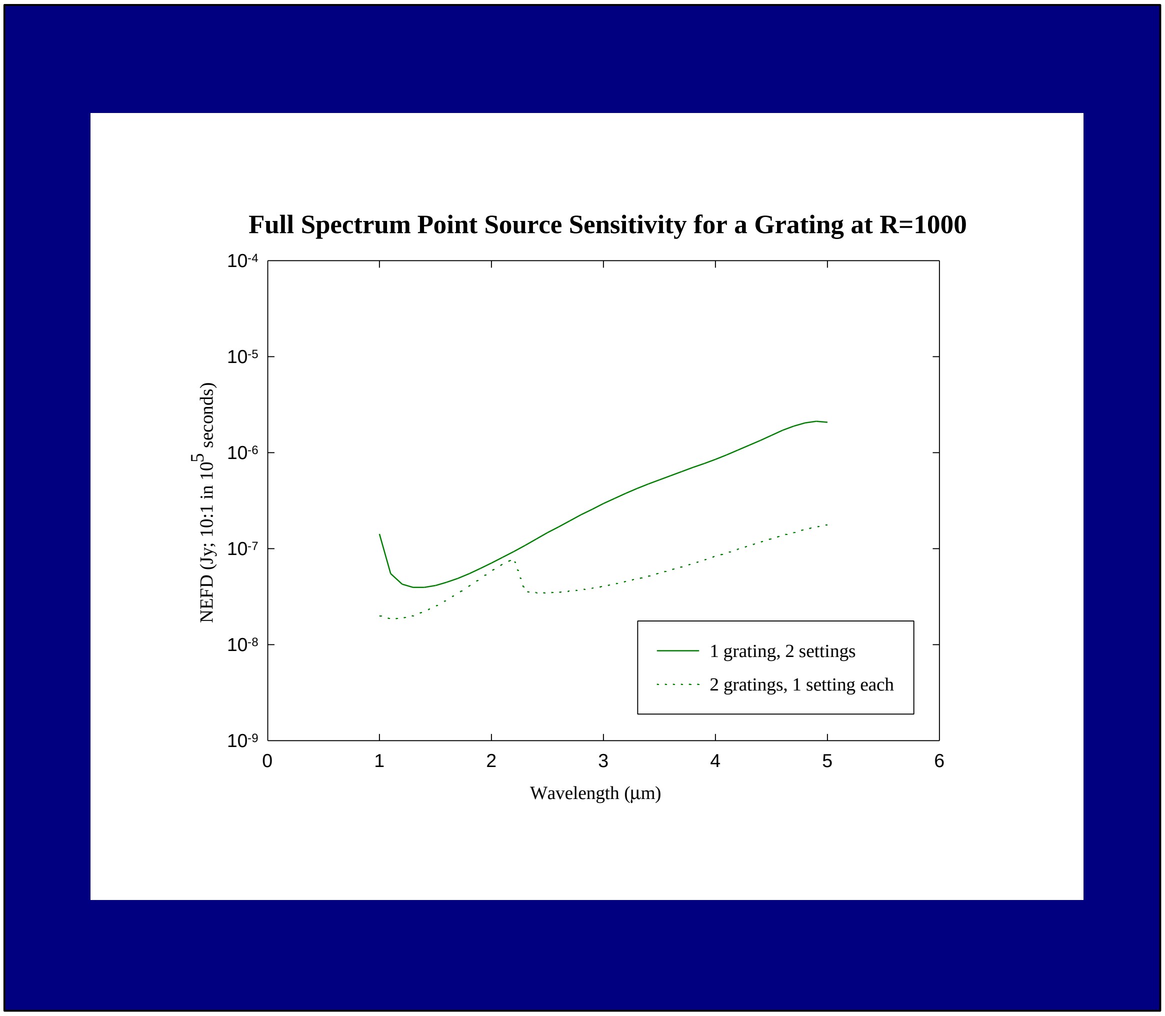

Figure 6: Sensitivity comparison of a one grating system and a two grating system for R=1000. The parameters for the gratings follow. As can be seen, the two grating system achieves greater sensitivity across the whole band.

Assumptions About Grating: Case B: R=1000

1) 1 Grating

- 1 grating can cover whole spectrum with 2 settings
- Band average efficiency is ~50%
- Grating density: 29.4 lines/mm
- Incidence angle: 7.924°,5.587°
- Nominal blaze angle: -1.42°
- Total integration time is divided evenly over the two settings (half time each)

The grating efficiency function is similar to that shown in Figure 4.

2) 2 Gratings

- 2 gratings can cover whole spectrum with 1 setting each
- Band average efficiency is ~83%
- Grating density: 54.5 lines/mm , 24.4 lines/mm
- Incidence angle: 6.43967°,6.43984°
- Nominal blaze angle: -2.183°,-2.186°
- Total integration time is divided evenly over the two settings (half time each)

The grating efficiency function is shown below.

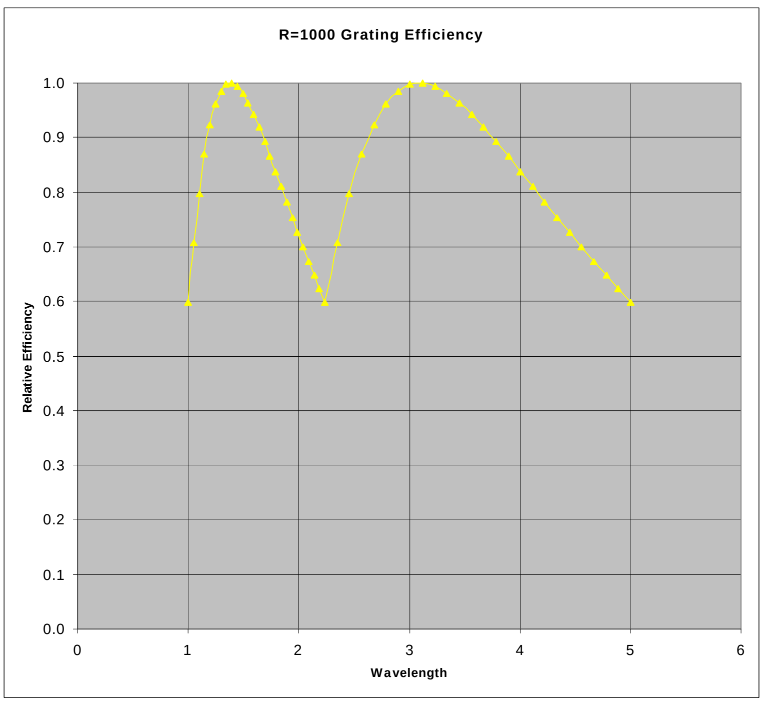

Figure 7: Grating efficiency function for R=1000 case, 2 gratings.

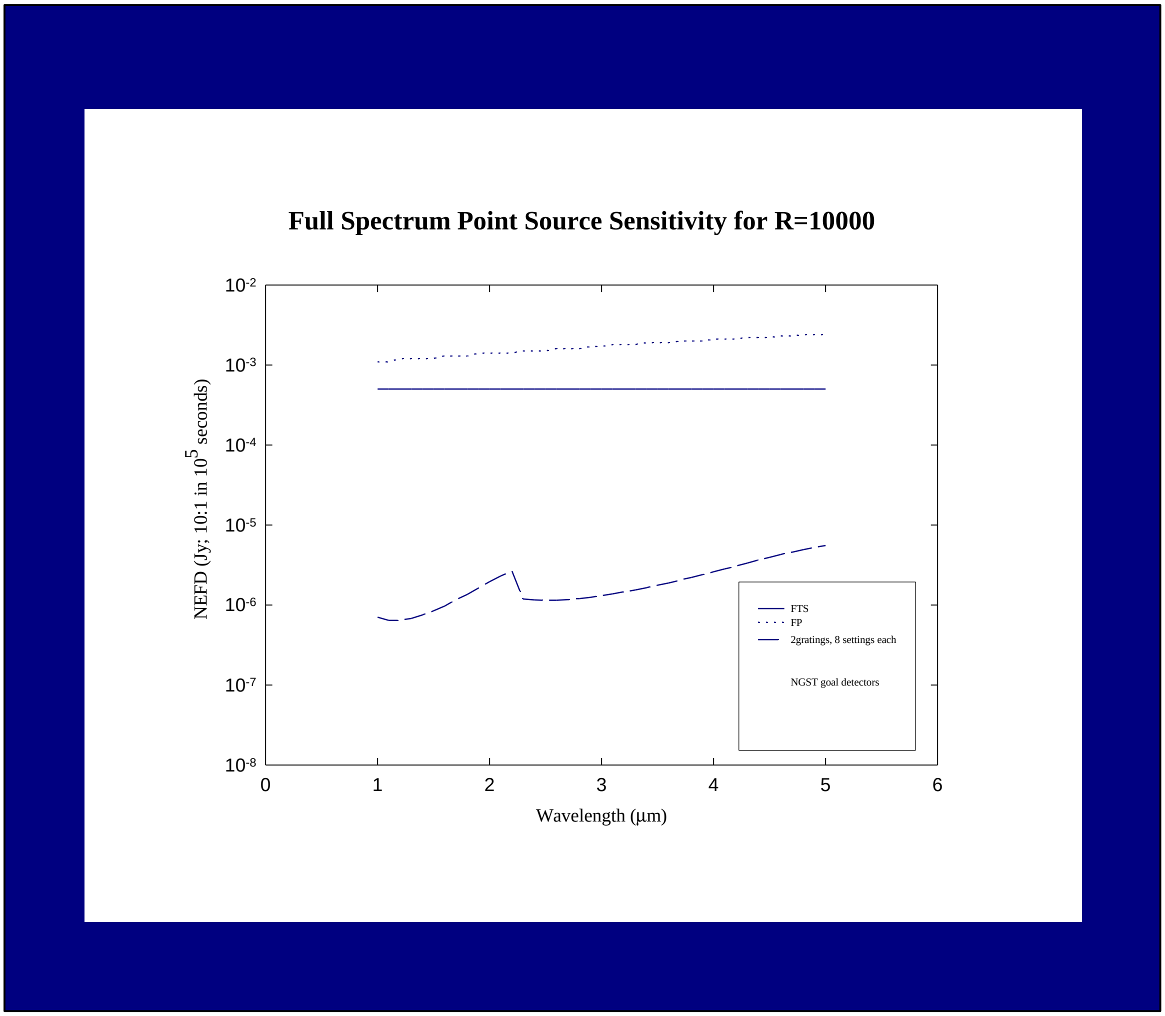

Figure 8: Full spectrum point source sensitivity vs. wavelength for an FTS, FP, and grating for R=10000. Here we assume that we use 2 gratings, with 8 settings each. The assumptions about the grating follow below. As can be seen, the grating system is the most sensitive for a point source, and the effect is most dramatic at high resolutions. The resolution for the grating system varies from ~ 6,400 to ~14,000.

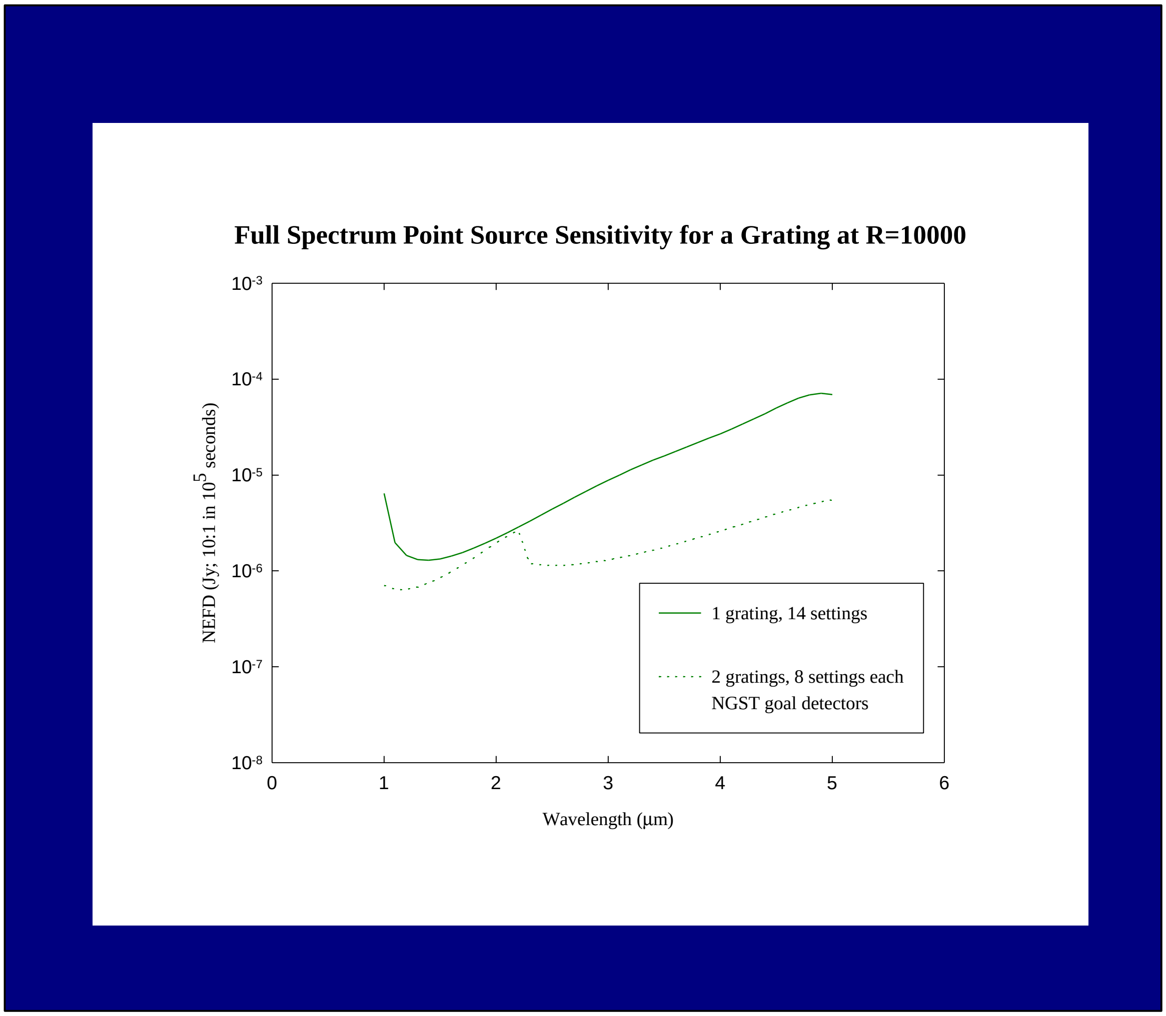

Figure 9: Comparison of sensitivity for a one grating system and a two grating system for R=10,000. The parameters for the gratings are given below. Note that the total integration time is always divided evenly into the total number of settings when calculating sensitivity. The difference in bandwidth vs. wavelength in the cases where there are several grating settings or gratings is also incorporated into the calculation.

Assumptions About Grating: Case C: R=10,000

1) 1 Grating

- 1 grating can cover whole spectrum with 14 settings
- Band average efficiency is ~50%
- Grating density: 24.4 lines mm^{-1}
- Incidence angle: 14 values
- Nominal blaze angle: -12.122°
- Total integration time is divided evenly over the 14 settings

The grating efficiency function is similar to that shown in Figure 4.

2) 2 Gratings

- 2 gratings can cover whole spectrum with 8 setting each
- Band average efficiency is ~84%
- Grating density: 48.6 lines mm^{-1} , 20.84 lines mm^{-1}
- Incidence angle: 8 different values for each grating
- Nominal blaze angle:**-**19.2277°,-19.2313°
- Total integration time is divided evenly over the 16 settings

The grating efficiency function is shown below.

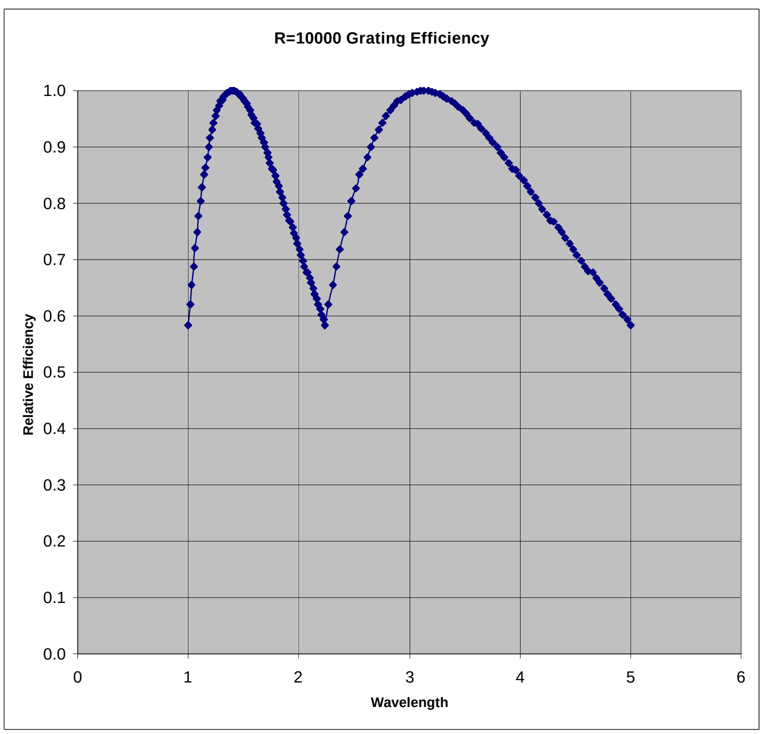

Figure 10: Grating efficiency function for R=10,000 case, 2 gratings.

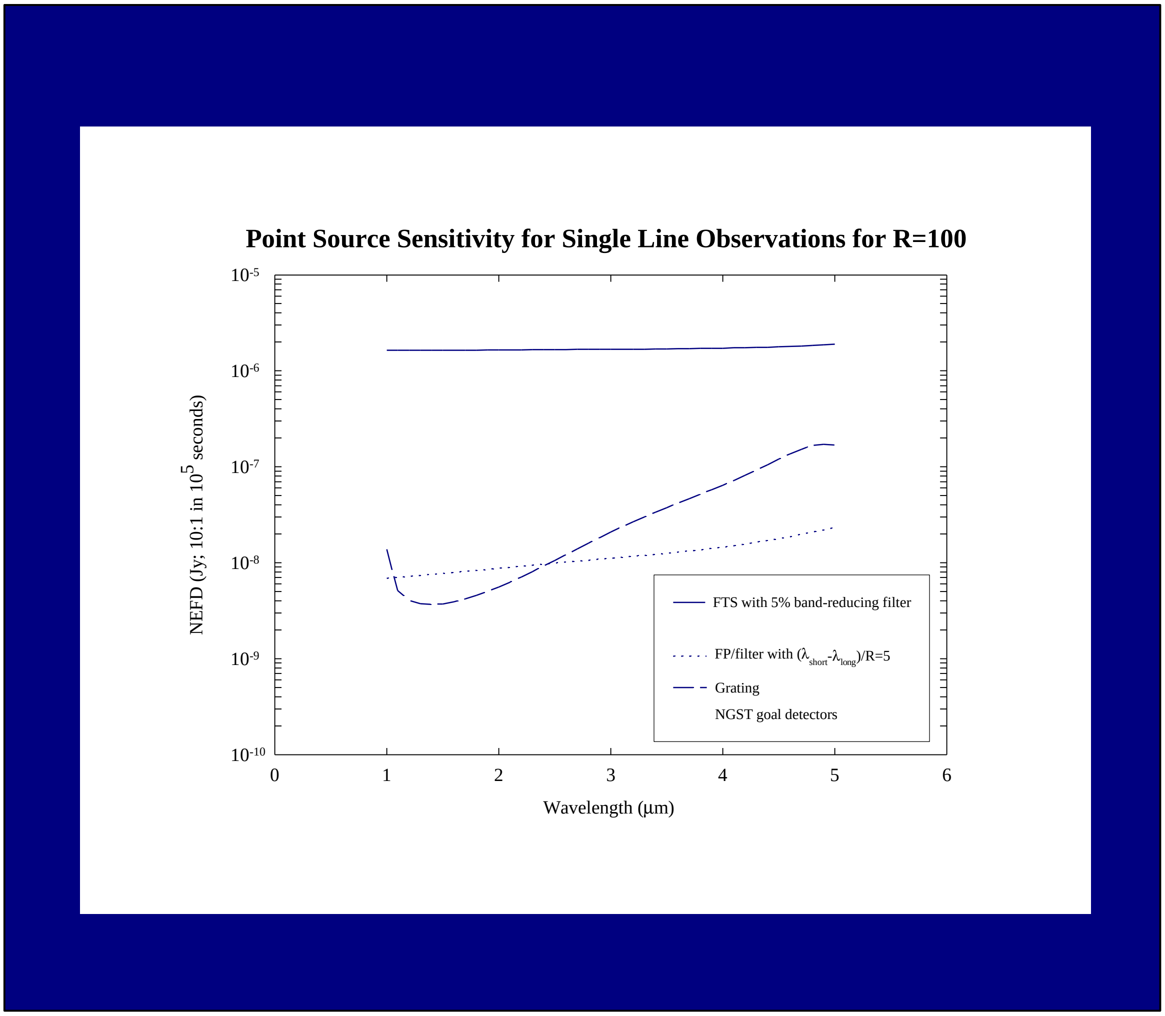

Figure 11: The point source sensitivity for single line observations with an FTS. FP/filter, and grating as a function of wavelength for R=100. The wavelength coverage for the FP/filter system is assumed to be 5 resolution elements. A 5% band-reducing filter is assumed to accompany the FTS. For the FTS, Nyquist sampling is assumed again. NGST goal detectors are assumed for the above plot.

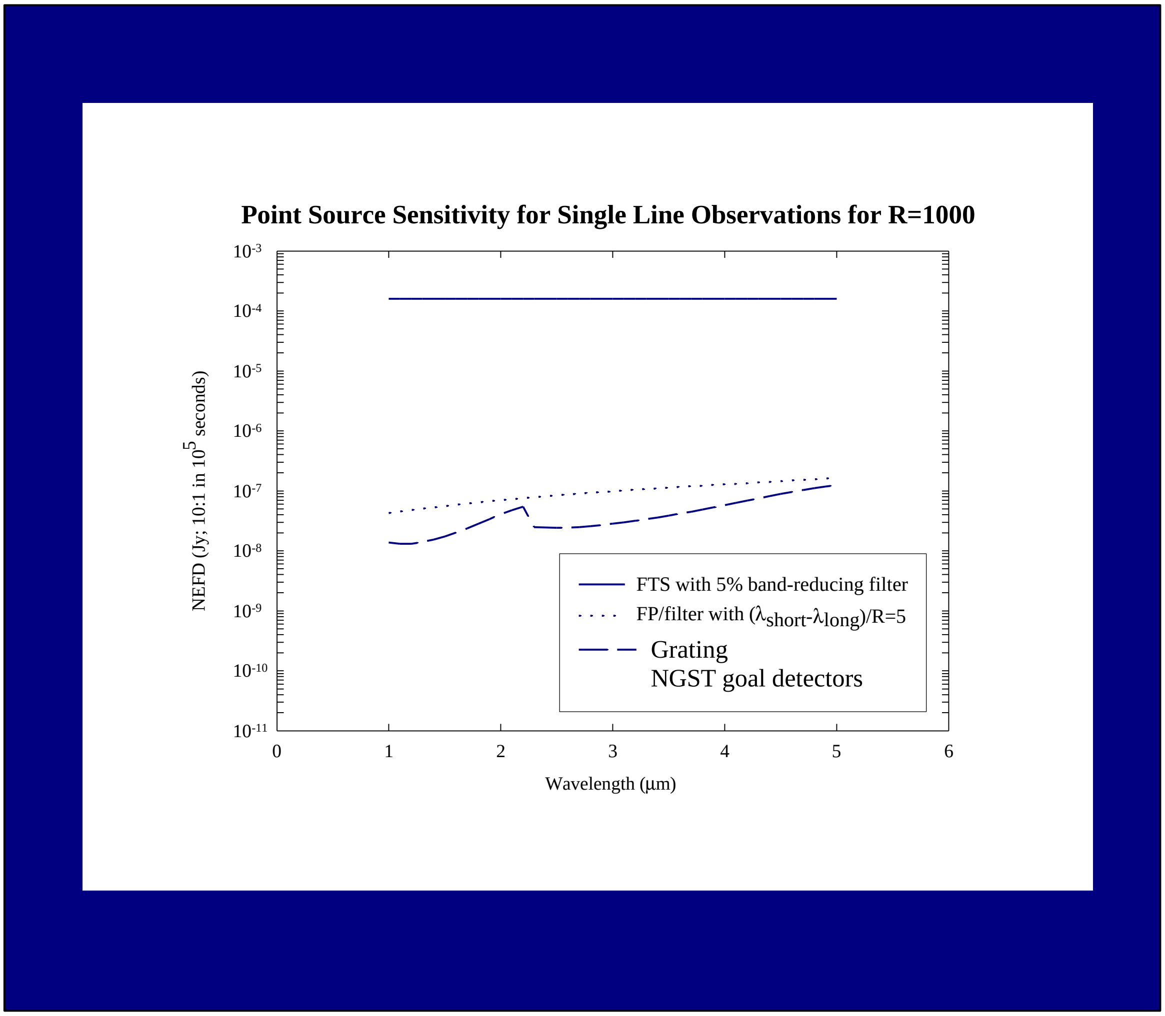

Figure 12: The point source sensitivity for single line observations with an FTS, FP, and grating, as a function of wavelength for R=1000. Again, a five spectral resolution element wavelength coverage is assumed for the FP, and a 5% band-reducing filter is assumed to accompany the FTS. Note that for the FTS, Nyquist sampling is assumed again. One setting for the grating is assumed since only one line is desired.

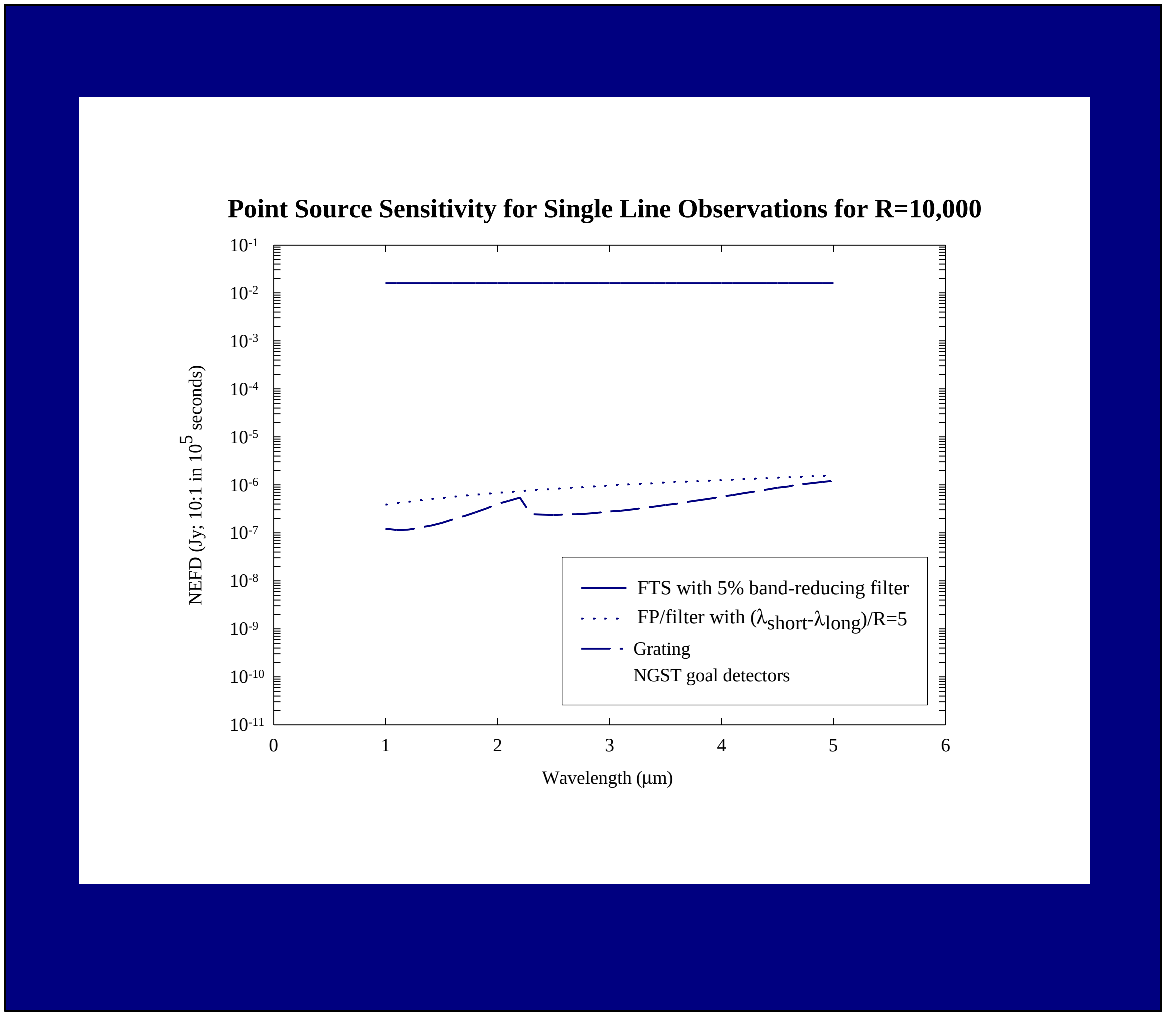

Figure 13: The point source sensitivity for single line observations with an FTS, FP, and grating as a function of wavelength for R=10,000. Again, a five spectral resolution element wavelength coverage is assumed for the FP, and a 5% band-reducing filter is assumed to accompany the FTS. Note that for the FTS, Nyquist sampling is assumed again. One setting for the grating is assumed since only one line is desired.

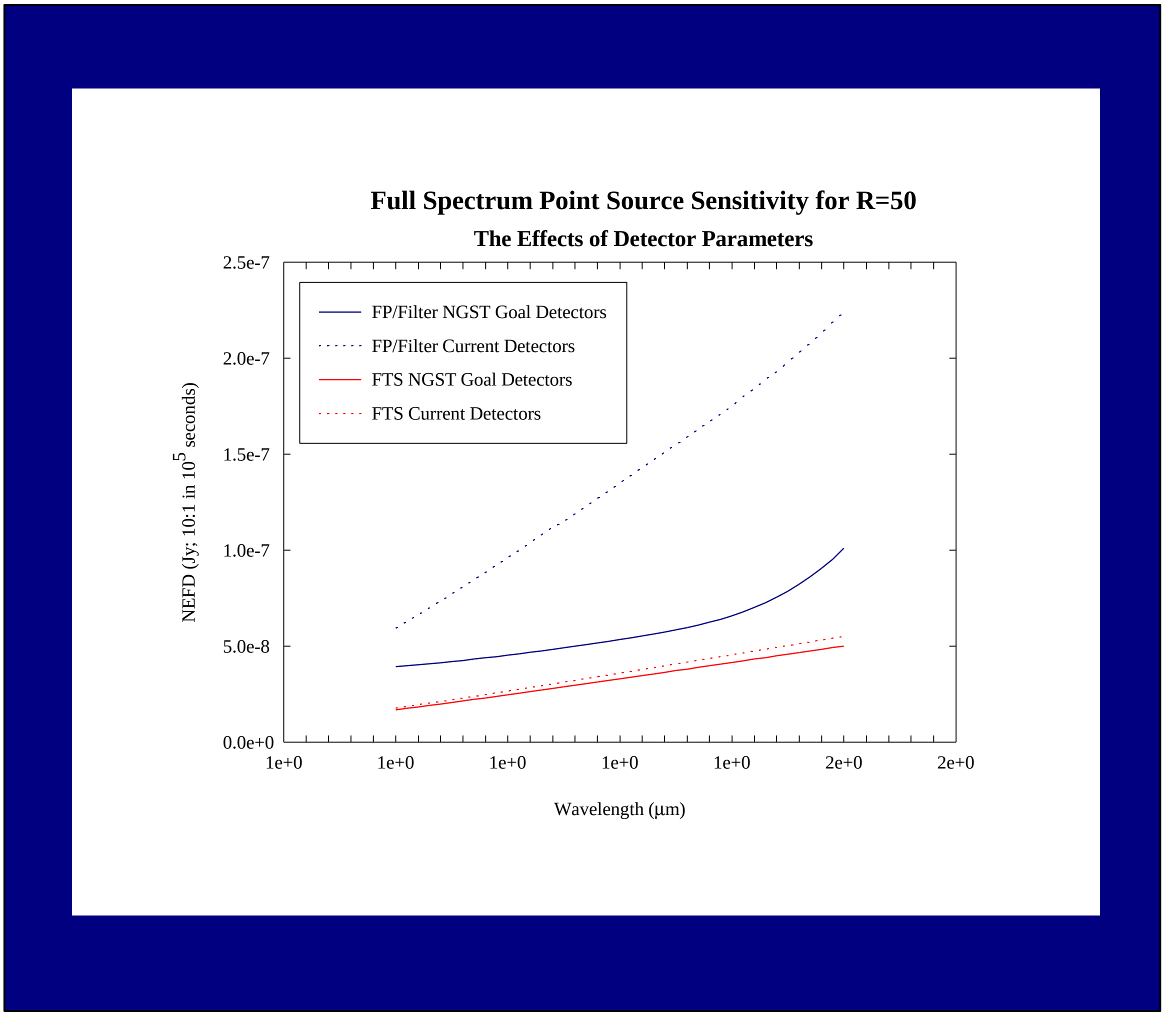

Figure 14: The effects of detector noise on sensitivities of the FP/filter- and FTS-based systems vs. wavelength for spectral resolution R=50. The sensitivity is for obtaining a full 1-5 µm spectrum at the indicated signal to noise ratio and integration time. Note that even at R=50, the detectors are detector noise limited in the FP/filter system, and the sensitivity is severely affected by the detector properties. The FTS is always background limited , so detector parameters do not affect the resulting sensitivity. For these calculations, goal detectors and current detectors are characterized by:

Case	QE	Read Noise (e-)	Dark Current (e-/s)
NGST Goal	0.8	3	0.02
Current	0.8	15	0.1

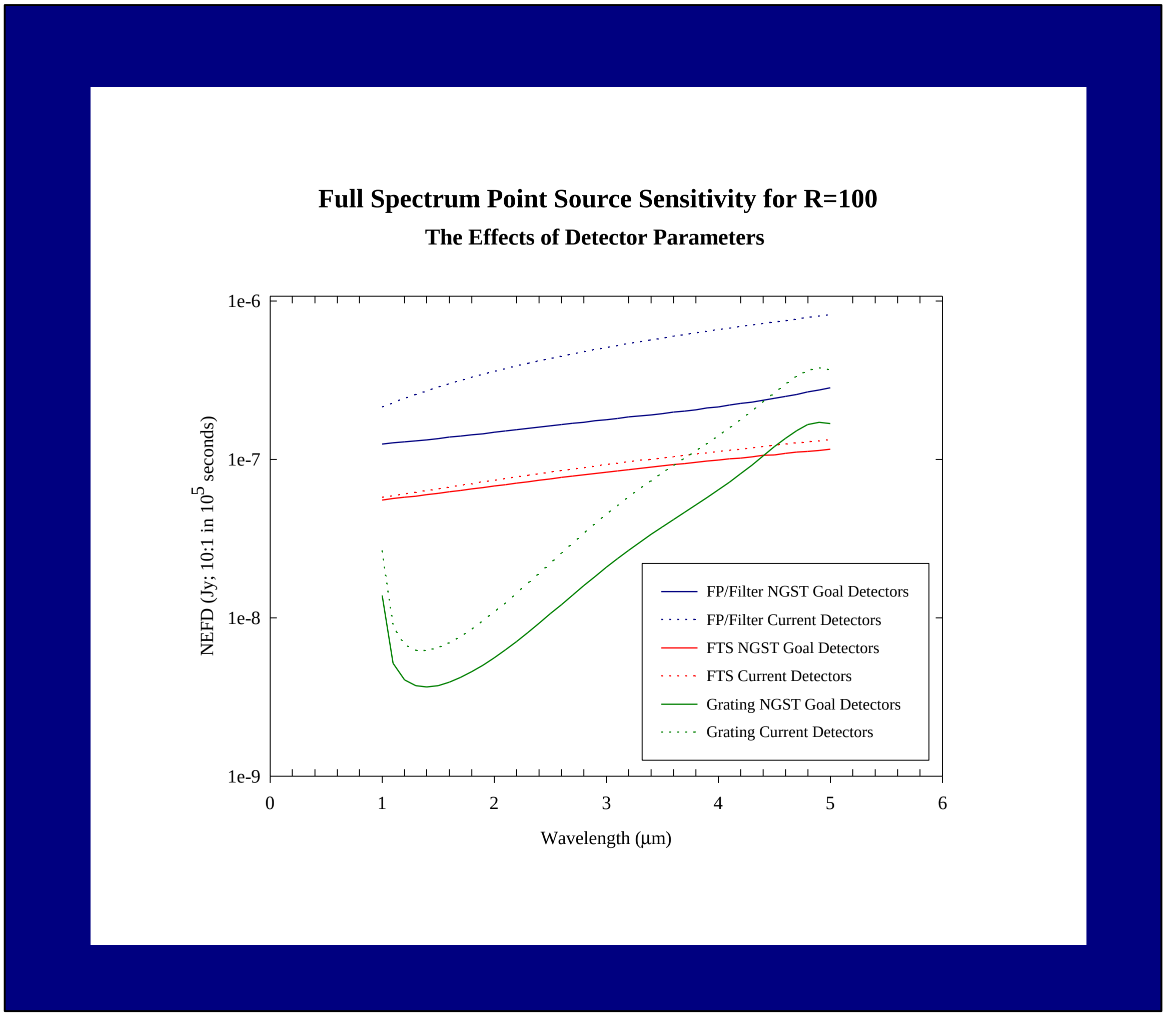

Figure 15: The effects of detector noise on sensitivities of the FP/filter and FTS vs. wavelength for R=100. The point source sensitivity is for obtaining the full spectrum at the indicated signal to noise ratio and integration time. Note that if we used current detectors, the grating sensitivity for the assumed is equal to the FTS' sensitivity at 3 microns. For NGST goal detectors, the sensitivity is equal at ~ 4.5 microns.

Case	QE	Read Noise (e-)	Dark Current (e-/s)
NGST Goal	0.8	3	0.02
Current	0.8	15	0.1

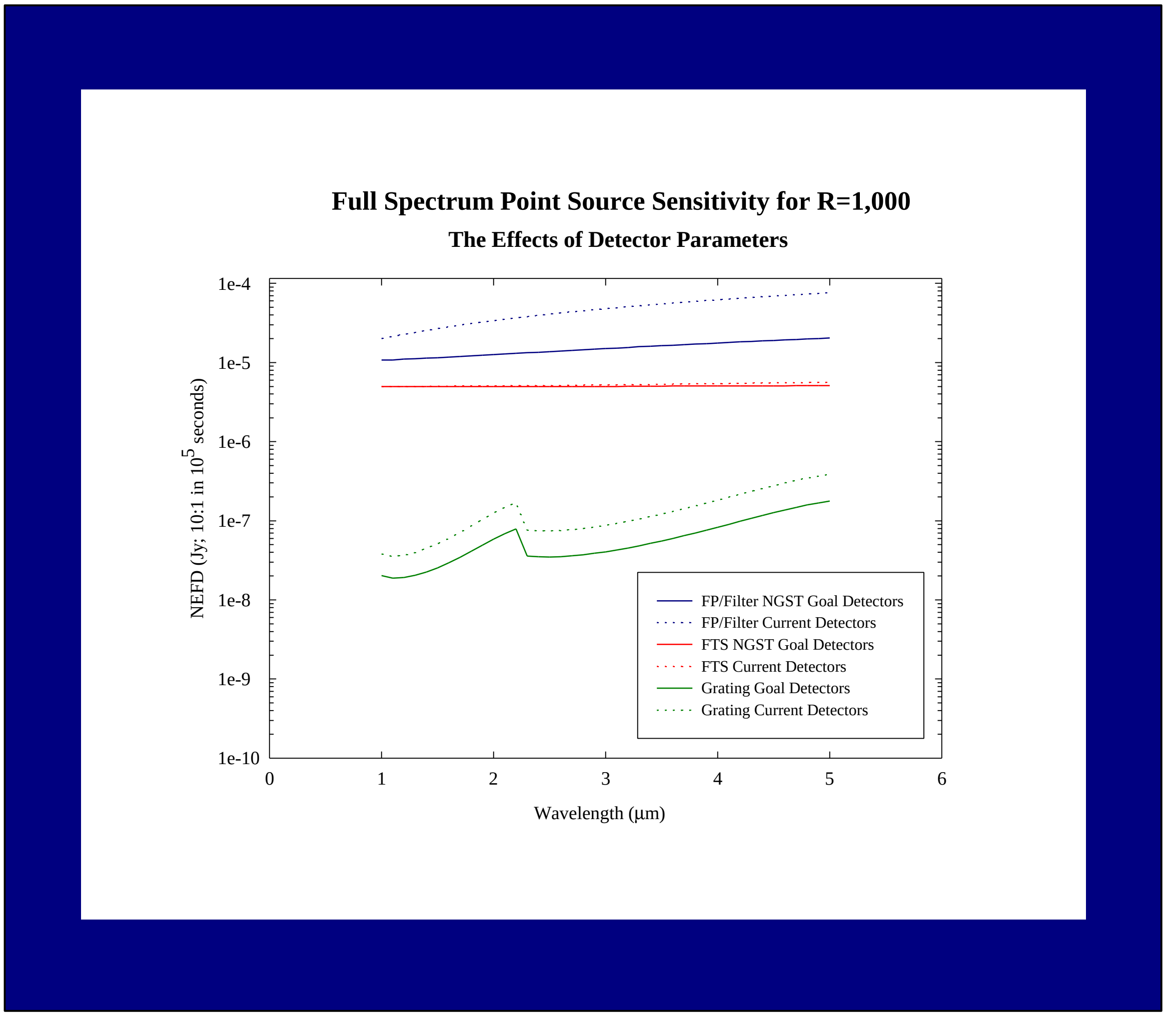

Figure 16: The effects of detector noise on full spectrum sensitivities with the FP/filter and FTS vs. wavelength for R=1000. Note that if we used current detectors, the grating sensitivity gets worse by a factor of ~ 2.

Case	**QE**	**Read Noise (e-)**	**Dark Current (e-/s)**
NGST Goal	0.8	3	0.02
Current	0.8	15	0.1

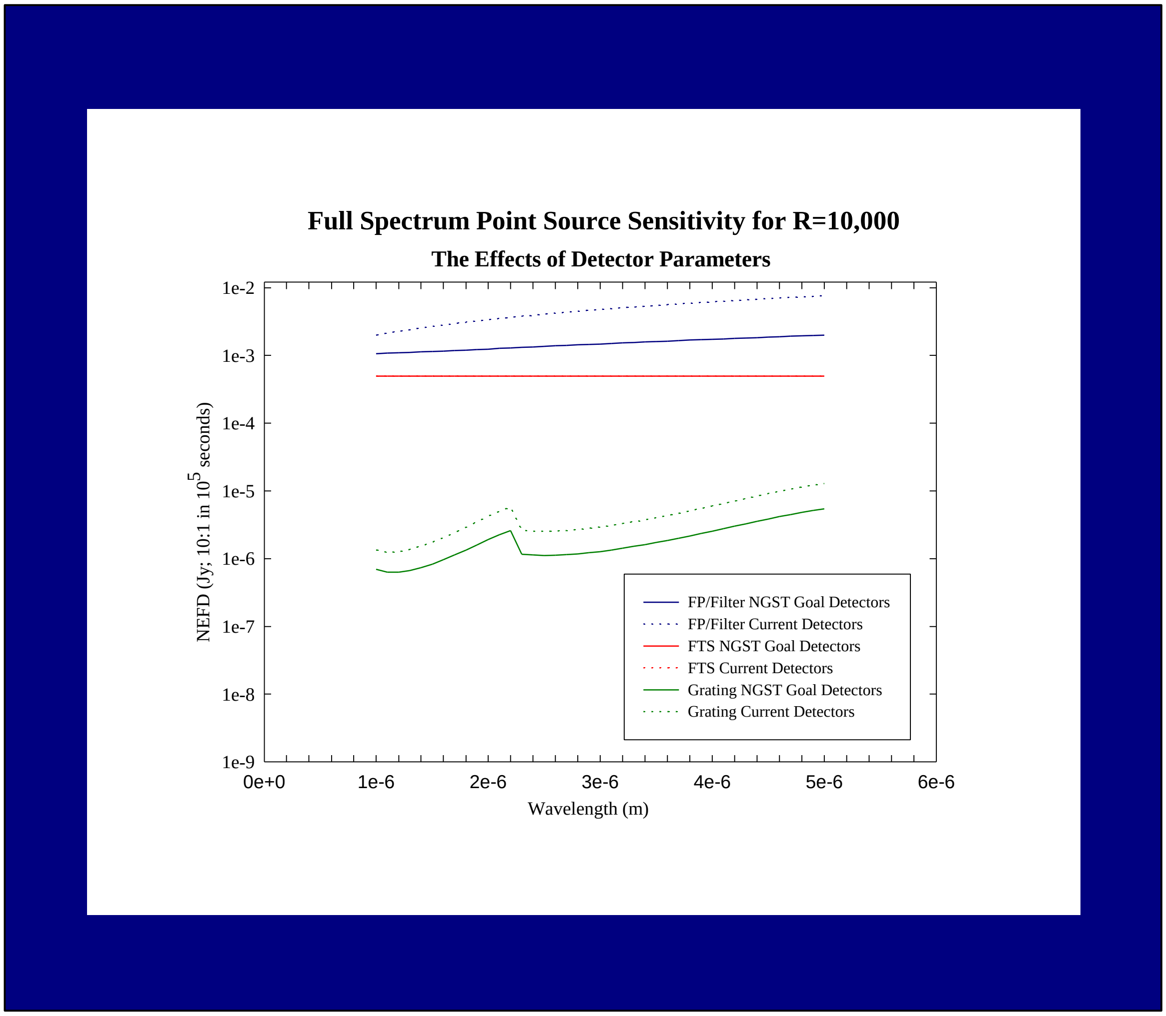

Figure 17: The effects of detector noise on full spectrum sensitivities with the FP, grating and FTS vs. wavelength for R=10,000. Note that if we used current detectors, the grating sensitivity gets worse by a factor of ~ 2.5.

Case	QE	Read Noise (e-)	Dark Current (e-/s)
NGST Goal	0.8	3	0.02
Current	0.8	15	0.1

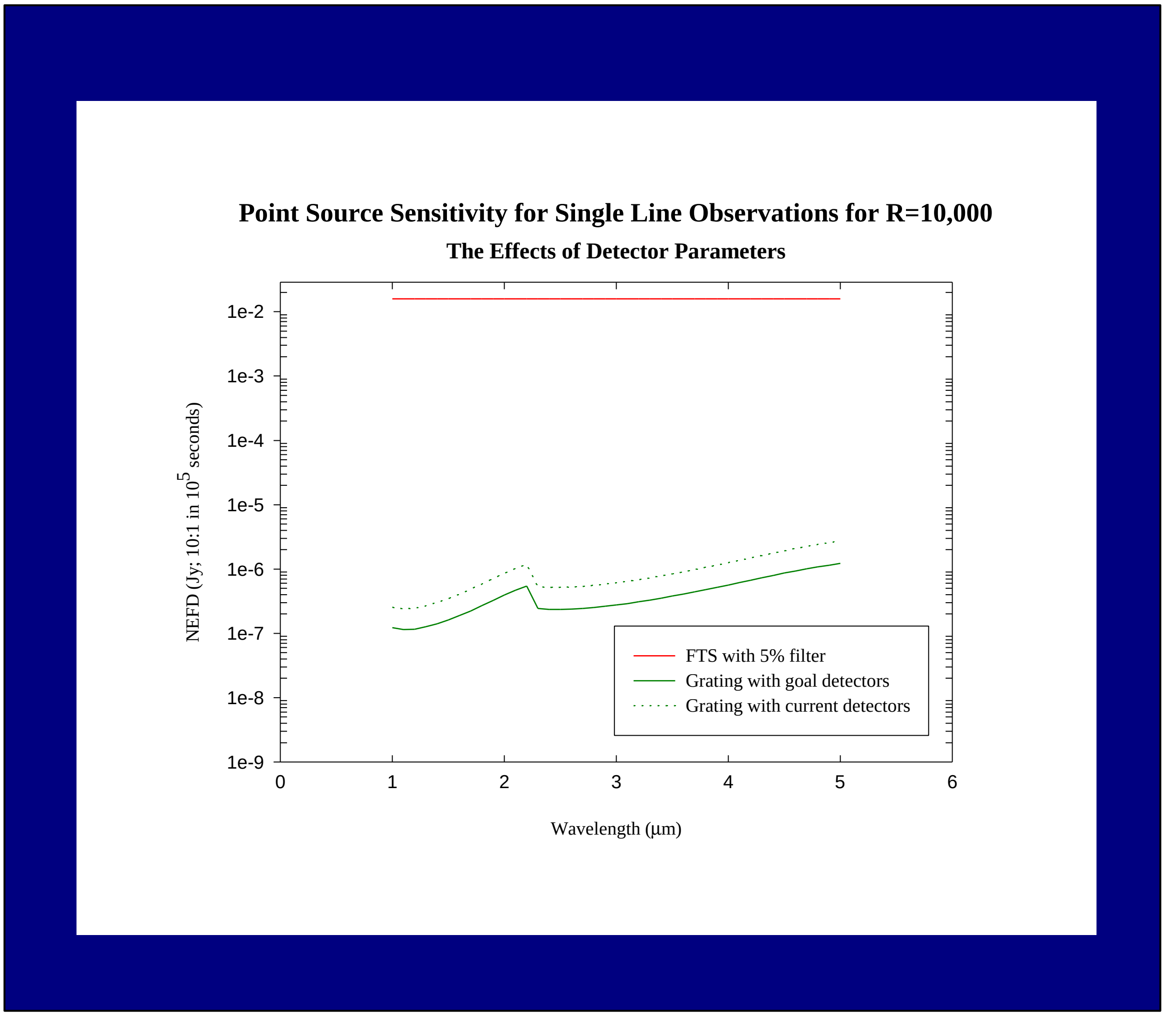

Figure 18: Point source sensitivity for single line observations for R=10,000 with current and goal detector parameters. As can be seen, the sensitivity is still much better with the grating than the FTS even with current detectors.