Visible and Near-IR Camera Subcommittee

Next Generation Space Telescope Ad Hoc Science Working Group

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Executive Summary

- Extreme sensitivity is the primary requirement for the camera.
- We view extension into the optical and field of view - in this order - as the most important additional capabilities.
- A coronagraph built as part of the main camera would also allow the option of doing imaging with an improved PSF.
- A separate optical camera would solve the problem of optimal PSF sampling at the shortest wavelengths.
- In order to reconstruct undersampled data the autoguider must allow subpixel dithering (at least to half a pixel).

1 Introduction

In order to bound the problem the subcommittee decided to adopt a two pronged strategy by focusing on those science programs already present in the Design Reference Mission (hereafter DRM) and also by review capabilities independendly of the specifics of the DRM. Each program was inspected to identify its requirements, particularly with regards to: field of view (hereafter FOV), wavelength coverage, point spread function (hereafter PSF) quality, filter widths.

We have also considered generic science capabilities for a Camera to avoid missing some crucial capability by being too focused on the DRM. Capabilities not required by the DRM were evaluated in terms of their discovery potential.

On the basis of the DRM the subcommittee has confirmed that a camera close in FOV and sampling to that of the Yardstick is optimal to carry out the NGST DRM science. The subcommittee has also identified a bare bones camera representing the descope floor, i.e. minimum set of instrumental capabilities allowing for at least a partial completion of the DRM science.

We have considered two downscope options for reducing the optimal camera to a bare bones camera and a number of extensions to the optimal camera. Each capability is ranked considering its impact on the feasibility and completion of the DRM.

2 DRM Science Drivers

2.1 Individual DRM programs

- **Formation and Evolution of Galaxies - Imaging (P014)**

  This program surveys a large area of the sky in several filters including two in the optical (0.65 and 0.82 μm with $\lambda/\Delta\lambda = 3$). The optical is needed to better define spectral energy distributions rather than PSF quality. These observations are also used as part of the SN search program.

- **Mapping Dark Matter (P003)**

  This programs requires imaging with well characterized, stable, PSF of a large area of the sky. Several colors are obtained in order to determine a photometric redshift. The two visible colors (0.65 and 0.82 μm with $\lambda/\Delta\lambda = 5$) are needed for the photometric redshift rather than for the improved PSF in the optical.

- **Formation and Evolution of Galaxies - AGN (P017)**

  This programs surveys 16 AGN fields in order to establish a link between galaxies and AGNs. In the current implementation the program only carries out observations at 0.81 and 3.5 μm with $\lambda/\Delta\lambda = 3$. It is likely that actually the same set of filters as in P014 would be used. The program requires a 4 by 4 arcmin area around each AGN to sample Mpc scales.

- **The age of the oldest stars (P002)**

  The program carries out single field observations in three galactic globular clusters. Observations are done at 0.82 m (with l/D l = 10) and 2.2 μm (with $\lambda/\Delta\lambda = 5$). PSF wings need to be minimized. The optical is required mainly to obtain a wide color baseline rather than for PSF quality.

- **Detection of Jovian planets (P023)**

  A number of fields are observed at 5 μm with $\lambda/\Delta\lambda$ =5. There is no FOV requirement but the observations need a coronographic capability.

- **Origins of substellar mass objects (P013)**

  This is a purely Near-IR program implemented with observations of nine 4 by 4 arcmin fields.

- **Formation and Evolution of Galaxies - Clusters (P016)**

  This programs surveys 10 (or 7 as in the present DRM file) clusters to study the properties of galaxies in clusters. A relatively large area needs to be surveyed around each cluster. In the current implementation the program only carries out observations at 0.81 and 3.5 μm with $\lambda/\Delta\lambda$ = 3. It is likely that actually the same set of filter as in P014 would be used.

- **Properties of KBO (P007)**

  This program has two components: a wide survey at 0.9 μm with $\lambda/\Delta\lambda$ =3 and four deep fields at 0.9, 1.2, 1.6, 2.2 μm with $\lambda/\Delta\lambda$ =3. The program benefits from a large FOV and could be done at 1-1.2 4μm instead of 0.9 μm. The program requires the ability to track moving targets and - depending on the guider design - may require ability to center the guide star at any position on the guide array.

- **Microlensing in the Virgo Cluster (P006)**

  This program carries out a pixel-lensing based study in the VirgoCluster by monitoring on a daily basis of 6 fields of at least 2 by 2 arcmin. The PSF needs to be stable over about a month and well known. The program is implemented with observations at 0.81 μm but could most likely be carried out at, e.g., 1.25 μm provided that the PSF requirements are satisfied.

- **Ages and chemistry of halo populations (P022)**

  This program requires deep observations at 0.65 and 0.82 μm with $\lambda/\Delta\lambda = 10$. The program is limited by diffraction wings from bright stars and crowding. The main driver for the optical wavelengths is SED sampling, however the program benefits also from the improved sharpness of the optical PSF. For this program extension below 0.7 μm is crucial.

- **IR transients in GRBs and hosts (P018)**

  The program is aimed at studying the host galaxies of GRBs and is purely IR, with no special requirement on PSF or FOV.

- **IMF for old stellar populations (P021)**

  A number of fields in nearby and Virgo galaxies are observed at 1.25 and 2.25 μm with $\lambda/\Delta\lambda = 5$. The program is limited by diffraction wings from bright stars and crowding.

2.2 Optical wavelength extension and special requirements

A large fraction of DRM programs (8 out of 12) require observations at optical wavelengths (see Table 1). However, for two programs the observations are currently specified in the optical but could be carried out in the near-IR with only a modest impact on the science. Thus only 50 per cent of the DRM programs require optical observations to be completed. While higher spatial resolution is always desirable, for most of this programs the main driver towards optical wavelength is the extension into the optical of the spectral energy distribution (SED in Table 1). Such an extension is required to improve the quality of photometric redshifts or the determination of stellar properties. One specific program (Ages and Chemistry of Halo Populations) requires the improved angular resolution of optical wavelength observations in order to alleviate crowding.

The importance of optical data for the determination of photometric redshifts has been explored by Harry Ferguson (1999, in preparation). The major results are summarized below:

- photometric redshift determinations for redshift below 15 or so are extremely inaccurate when optical data are not available (compare Figures 1 and 2). The loss of accuracy is a relatively smooth function of the extension into the optical.

- simulations carried out so far seem to indicate that the limiting factor in photometric redshift accuracy is the intrinsic scatter in galaxies properties; there is no significant gain by using narrower filters (Ferguson 1999).

- the presence of even a significant red leak (1 per cent level) does not affect significantly the accuracy of photometric redshifts. The impact on other measurements needs to be more carefully assessed.

2.3 Summary of Requirements

- Most of the DRM programs require optical data to be carried out successfully.

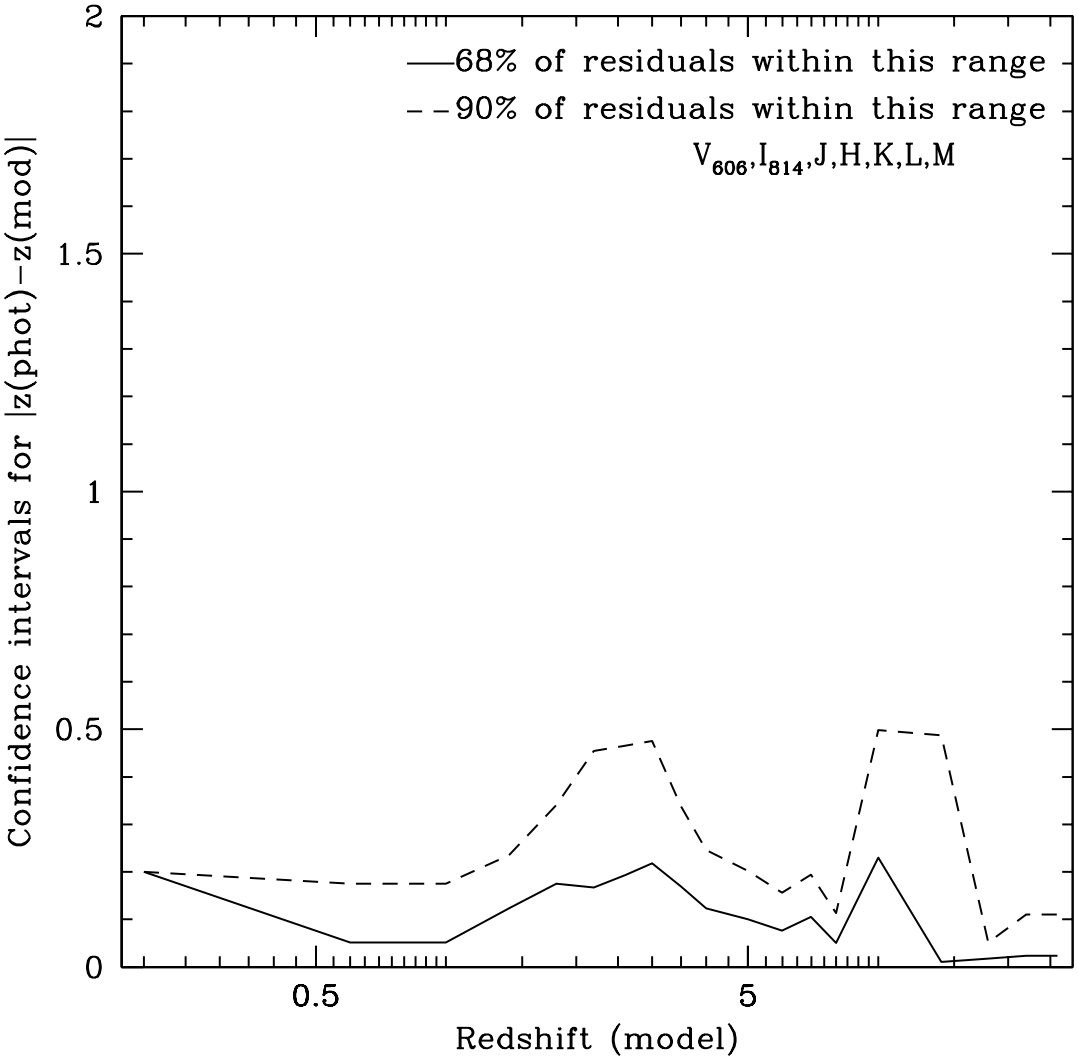

Figure 1: Error envelopes in photometric redshift determinations using V, I, J, H, K, L, M filters. The models used span a range of age, metallicities, and dust content.

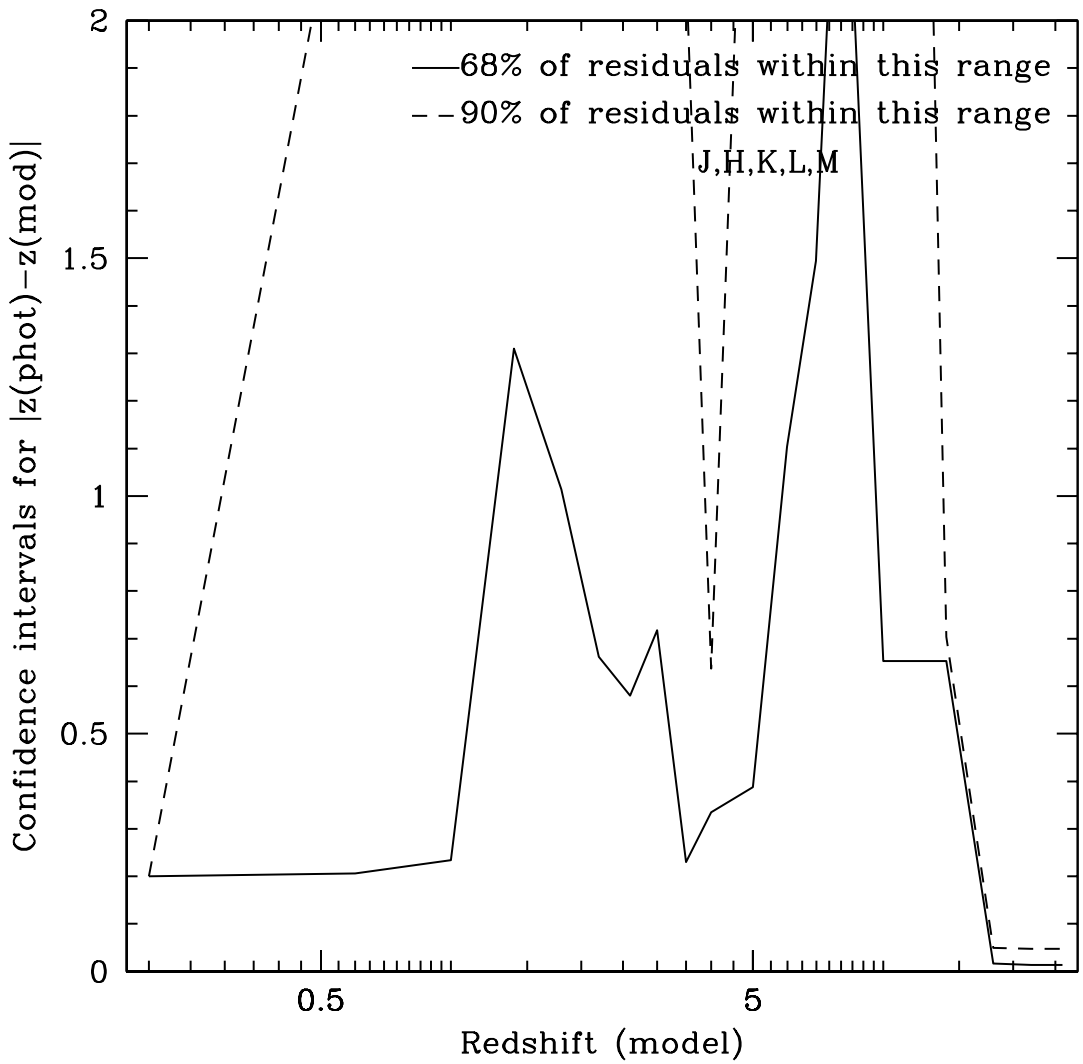

Figure 2: Error envelopes in photometric redshift determinations without availablility of optical data, i.e.,using only J, H, K, L, M filters. The models are the same as those used in Figure 1

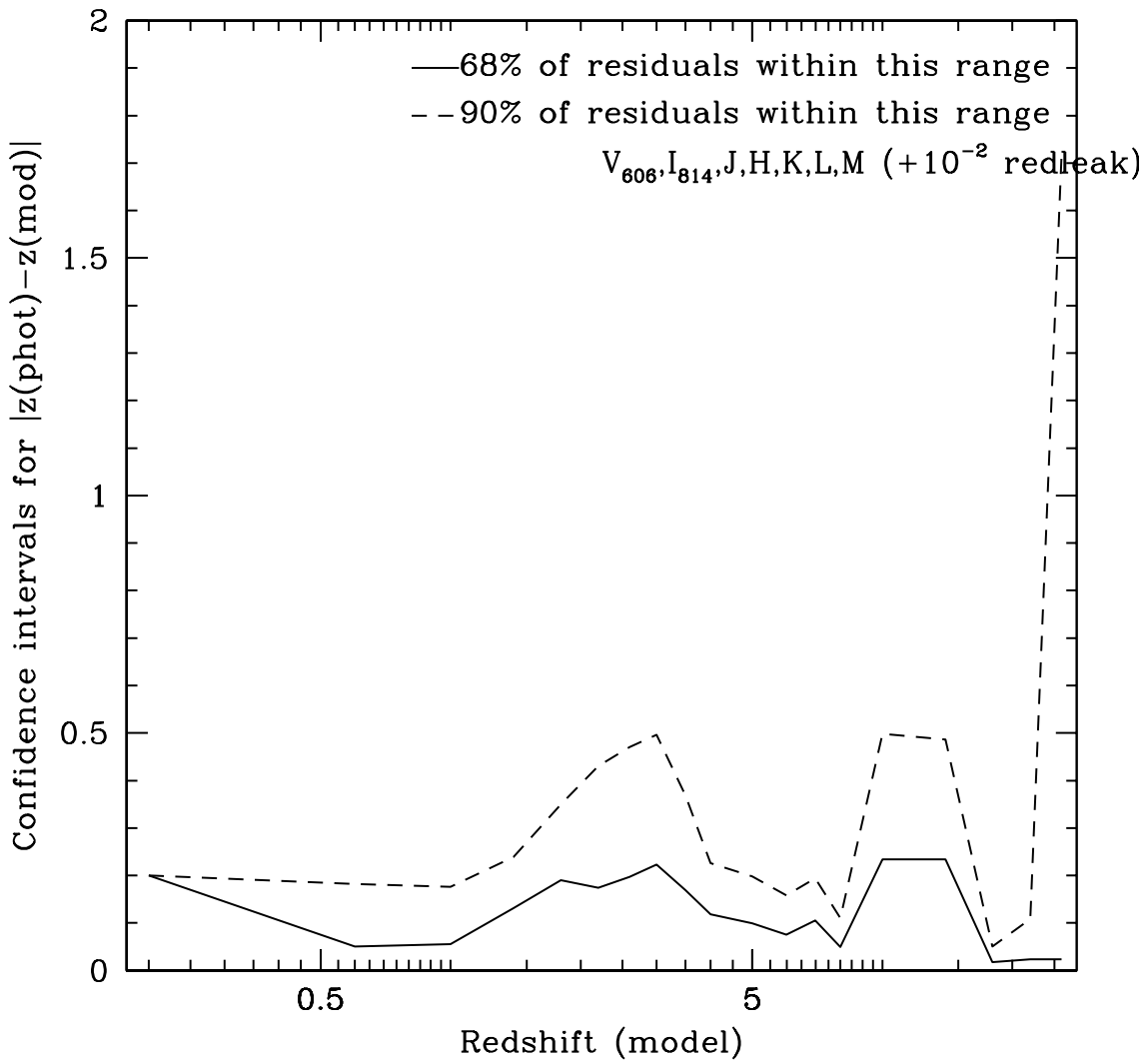

Figure 3: Error envelopes in photometric redshift determinations using V, I, J, H, K, L, M filters with a 1 per cent redleak. The models are the same as those used in Figure 1

Table 1: Summary of DRM requirements for the individual programs

DRM Program	Optical Wavelengths $\lambda(\mu m)$	Main driver SED	Main driver PSF	Notes
Form. & Evol. Gal. - Imaging	0.65, 0.82	Y	-	
Mapping Dark Matter	0.65, 0.82	Y	-	PSF stability
Form. & Evol. Gal. - AGN	0.81	Y	-	
The age of the oldest stars	0.82	Y	-	
Detection of Jovian planets	-	-	-	coronagraphy
Origin of substellar objects	-	-	-	
Form. & Evol. Gal. - Clusters	0.81	Y	-	
Properties of KBO	0.9	Y	-	feasible at 1 μm
Microlensing in Virgo	0.81	Y	-	feasible at 1 μm
Ages and Chemistry of Halos	0.65, 0.82	Y	Y	
IR Transients from GRBs	-	-	-	
IMF for old stellar pops	-	-	-	

- With the exception of one program there is no critical wavelength that needs to be reached: the shorter the wavelength cutoff in the optical the better the science.
- There is only one DRM program relying on the improved spatial resolution in the optical.
- There are no DRM programs requiring resolving powers in excess of R=10.

Table 2: The Yardstick Camera

Parameter	NIR Camera
λ (μ m)	0.6-5
FOV arcmin^2	4×4
Pixels	8k $\times$ 8k
Sampling " pix^{-1}	0.029

Table 3: ESA study NIRCAM

Parameter	NIR Camera
λ (μ m)	0.6-5
FOV arcmin^2	3×6
Pixels	6k $\times$ 12k
Sampling " pix^{-1}	0.03

3 A Camera for NGST

3.1 Review of ISIM studies Key Features

Among the NASA, ESA and CSA ISIM studies several concepts were presented ranging from simple, traditional cameras to more complex cameras to IFTS.

The Yardstick and the ESA (Posselt et al.) NIR Cameras have very similar designs and comparable field of view, wavelength coverage and PSF sampling.

IFIRS (Graham et al.) and the ESA (Posselt et al.) IFTS differ mostly with respect to the capability of the former design of obtaining data from both interferometer arms of thus simplifying calibration and increasing redundancy. For a given detector size and pixel size the Posselt et al. design has twice the field of view.

Both IFTS design allow for efficient imaging at R> 10. For low R observations in a few bands filters would probably still be the option of choice.

By obtaining data from both the interferometer arms the Graham et al. design allows one to carry out scans while using a broad band limiting filter. This produces broad band photometric data at essentially no impact in performance while obtaining also spectroscopic information within the selected broad bands.

Table 4: IFIRS (Graham et al.) IFTS

Parameter	NIR IFTS
λ (μ m)	0.6-5.6
FOV arcmin^2	5.3 $\times$ 5.3
Pixels	8k $\times$ 8k $\times$ 2
Sampling " pix^{-1}	0.039
Modes	Imaging and Spectroscopy

Table 5: ESA study (Posselt et al.) IFTS

Parameter	NIR IFTS
λ (μ m)	0.6-5
FOV arcmin^2	3 $\times$ 6
Pixels	6k $\times$ 12k
Sampling " pix^{-1}	0.03

The Arizona-Lockheed (Ennico et al.) study focuses on a number of cameras optimized in different wavelength intervals. In addition to the cameras in the table above the team has also studied a 0.4-1 m visible imager with a FOV of 1.1 x 1.1 arcmin. For 1-5 m imaging the advantage of better optimized pixel size and detector performance is obtained at the price of a reduction of the FOV in the 1-2.3 m region. The FOV at the minimum zodiacal background wavelength (around 3 m) is only 2.5 by 2.5 arcmin.

The Bally et al. ISIM concept is that of shared detector and multiple platescales. We have focussed on the latter aspect since the former is more

Table 6: Arizona-Lockheed (Ennico, Bechtold, Greene et al.) study

Parameter	NIR Mod. 1	NIR Mod. 2	NIR Mod. 3	NIR Wide Opt.	Visible Wide Opt.	Visible High Res.
λ (μ m)	1-2.3	2.3-5	2.3-5	1-2.5	0.4-0.8	0.4-1
FOV arcmin^2	0.7 $\times$ 0.7	1.5 $\times$ 1.5	2.5 $\times$ 2.5	6.2 $\times$ 7.7	6.2 $\times$ 7.7	1.1 $\times$ 1.1
Pixels	2k $\times$ 2k	2k $\times$ 2k	2k $\times$ 2k	16k $\times$ 20k	16k $\times$ 20k	10k $\times$ 10k
Sampling " pix^{-1}	0.02	0.044	0.073	0.022	0.022	0.007
Mode	Imaging & Spectr.	Imaging & Spectr.	Imaging & Spectr.	Imaging	Imaging	Imaging

Table 7: Integrated Camera (Bally et al.)

	One 8k × 8k pixels array		
Parameter	Mode 1	Mode 2	Mode 3
λ (μ m)	0.6-5	0.6-5	0.6-5
FOV arcmin^2	0.75 × 0.75	4 × 4	8 × 8
Pixels	4k × 4k	8k × 8k	8k × 8k
Sampling " pix^{-1}	0.01	0.026	0.054

Table 8: Hickson et al. Visible Imager

Parameter	VIS CAM
λ (μ m)	0.5-1.0
FOV arcmin^2	2 × 2
Pixels	12k × 12k
Sampling " pix^{-1}	0.010

of a technical nature. Mode 2 is very similar to the Yardstick camera.

The Hickson et al. ISIM study focuses on a visible imager critically sampled at 0.7 m.

ESA (Ward et al.) has also studied two optical cameras: a WFC with a field of view of 5 by 5 arcmin and a HRC with 0.7 by 0.7 arcmin FOV.

3.2 Key Features of a Camera for NGST

3.2.1 The "Optimal" NGST Camera

Most of the DRM science for NGST is related to the observation of faint targets either isolated or in crowded fields. Both the nature of DRM proposals

Table 9: ESA Study (Ward et al.) Visible Imager

Parameter	Wide Field	High Res.
λ (μ m)	0.5-1.0	0.5-1.0
FOV arcmin^2	0.7 × 0.7	5.0 × 5.0
Pixels	4k × 4k	8k × 8k
Sampling " pix^{-1}	0.010	0.037

Table 10: Bare Bones Camera

Parameter	BB Camera
λ (μ m)	1.0-5.0 (goal 0.6-5.0)
FOV arcmin^2	2×2
Pixels	4k $\times$ 4k
Sampling " pix^{-1}	0.029

and the desire of observing targets as faint as possible pushes toward using relatively broad band filters. Our conclusion is that:
the sensitivity of the camera should be maximized
and that:
it is very important to push its sensitivity into the optical.

Since most of the imaging DRM programs are of the survey type, we expect that the execution time will be inversely proportional to the FOV (see also following section). Thus, the requirement of completing the DRM science pushes toward a FOV comparable to that of the Yardstick, i.e., of the order of 4 by 4 arcmin, with sensitivity extending down to 0.6 arcmin.

3.2.2 The "Bare Bones" NGST Camera

We have also considered the above sensitivity requirements to identify a bare bones camera were sensitivity has been kept at the expense of FOV. This camera represents the most extreme downscope option **only partly able to meet the NGST imaging goals**.

3.3 Performance in executing the DRM

We have estimated the performance in executing the DRM by using the web tools available on the STScI web site. Only the imaging part of the DRM was used (as is). Only for the Ennico et al. ISIM concept the input DRM had to be rewritten to make use of the many camera options available. The performance of IFTS instruments used as imagers was assumed to be identical to that of an imager with the same FOV and pixel size.

We first focussed on a comparison between Yardstick and BB camera. The DRM execution times are summarized in Table 11 and confirm that most of the NGST DRM is in large surveys where FOV is important. Somewhat

Table 11: Total DRM execution times

Camera	Near-IR (hours)	Optical (hours)	Total (hours)
Yardstick	4591	3575	8166
Bare Bones	15480	9043	24523

Table 12: DRM execution times

Camera	Total (hours)
Yardstick	8166
Bare Bones	24523
Graham et al.	5958
Posselt et al.	7701
Ennico et al.	6417
Bally et al. - Mode 3	5523
Yardstick+Hickson et al.	32361
Yardstick+Ward et al.	7491

more surprising is the very large fraction of optical science present in the DRM.

We have also considered the total DRM execution times in hours for the various ISIM concepts. Given the importance of large FOV, we have focussed mostly on cameras or modes with the largest FOV (see Table 12). Clearly the major driving factor in the resulting execution times is once again the FOV[1]. The long integration time required by the Yardstick+Hickson et al. visible camera option is mostly due to the small FOV of the Hickson et al. visible camera. If the Near-IR camera had been used for optical observations for those programs requiring large FOV the total time would have been identical to that of the Yardstick.

[1]because of our assumptions both the ESA NIR CAM and the ESA IFTS by Posselt et al. have the same performance

4 Instrument Parameters

4.1 Field of View and Plate Scale

The linear reconstruction of images obtained with subpixel imaging can only yield a final PSF FWHM equal to the initial pixel size, i.e. can provide a well sampled PSF for initial data undersampled by no more than a factor 2.

On this basis a camera for NGST Nyquist sampled at 2 m allows good quality imaging down to 1 μm while allowing for imaging at 0.6 μm no worse than that of the WF chips of WFPC2 on HST at 0.5 μm. Nyquist sampling the camera at 3 μm would lead to improved sensitivity at the price of unacceptable undersampling in the optical.

Given the survey nature of most of the DRM the FOV of a camera should be not less than 2 by 2 arcmin. Such a FOV allows, e.g., to sample Mpc scales at high redshift. A smaller FOV would require extensive mosaicing for most observations.

The autoguider must allow sub pixel dithering (at least half pixel). The KBO search program requires pointing at at a generic location within a pixel.

4.2 Image quality and coronagraphy

Each NGST field will contain stars several (10 or more) magnitudes brighter than the targets of interest regardless of whether the camera itself is used for guiding. For this reason, crowded field photometry programs in the DRM - and perhaps the faint galaxies ones - will benefit enormously from any reduction in PSF wings.

The weak lensing program requires a PSF stable and well characterized over timescales of several months.

Add-on coronographic capabilities including a smooth pupil apodizer (on a mechanism) usable also for crowded field photometry appear particularly promising. With this mechanism a permanent dark spot at the edge of FOV could complete a coronagraph. A permanent apodization would cause a large permanent light loss and must be avoided.

A PSF study has been carried out by John Trauger and D. Moody. Its results are summarized in Table 13. The main result is that the requirement of diffraction limited imaging at 2 μm can produce - depending on the mid frequencies- PSFs of rather poor quality in the optical (e.g. at 0.667 μm)

while preserving good encircled energy properties.

4.3 Spectral coverage

Particularly if a separate optical camera is not selected it will be extremely important to extend the sensitivity of the Near-IR camera as much as possible into the optical. As shown in Table 13, the ultimate PSF quality achievable by such a camera will depend on the mid frequency errors on the OTA.

4.4 Detector Performance

Detector noise should be low enough to allow background limited observations at 3 μm in R=5 filters.

In order to allow accurate photometry and fully exploit dithering the detector MTF should be fully characterized. For data undersampled by a factor two QE uniformity inside a pixel should be better than 20 per cent in order to allow at least 5 per cent photometry.

Crosstalk between pixels exceeding 10 per cent will begin affecting the PSF FWHM at 1 μm by more than 10 per cent.

Table 13: Comparison of Image Quality Metrics. NGST 7-Hex with Arizona Active Primary

Inputs		Outputs						
Low-Freq	Mid-Freq	Strehl	Sharp	RMS	EE (vs. radius in arcssec)			
(μm)	($\times$HST)	Ratio	Ratio	(μm)	0.04	0.10	0.30	0.60
Computed for a 20% filter centered at 2.0μm on a 0.0130 arcsec/pixel grid								
0.052	0.0	0.892	0.905	0.056	0.564	0.817	0.931	0.961
0.073	0.0	0.797	0.822	0.079	0.509	0.800	0.931	0.961
0.092	0.0	0.694	0.735	0.100	0.451	0.780	0.930	0.961
0.110	0.0	0.591	0.648	0.119	0.391	0.754	0.930	0.960
0.125	0.0	0.502	0.578	0.136	0.339	0.730	0.929	0.960
0.052	1.0	0.891	0.904	0.057	0.562	0.816	0.930	0.959
0.073	1.0	0.796	0.821	0.079	0.509	0.799	0.929	0.959
0.092	1.0	0.694	0.734	0.100	0.451	0.778	0.929	0.959
0.110	1.0	0.590	0.648	0.119	0.390	0.753	0.929	0.959
0.125	1.0	0.502	0.578	0.136	0.339	0.729	0.928	0.959
0.052	5.0	0.860	0.872	0.064	0.543	0.787	0.897	0.929
0.073	5.0	0.769	0.793	0.085	0.492	0.771	0.897	0.929
0.092	5.0	0.671	0.709	0.104	0.435	0.751	0.897	0.929
0.110	5.0	0.570	0.626	0.123	0.377	0.728	0.896	0.929
0.125	5.0	0.485	0.558	0.139	0.327	0.704	0.896	0.929
Computed for a 20% filter centered at 0.667μm on a 0.00433 arcsec/pixel grid								
0.052	0.0	0.363	0.471	0.053	0.709	0.930	0.973	0.987
0.073	0.0	0.113	0.312	0.075	0.552	0.924	0.973	0.987
0.092	0.0	0.050	0.252	0.094	0.506	0.915	0.973	0.987
0.110	0.0	0.031	0.216	0.113	0.247	0.900	0.972	0.987
0.125	0.0	0.030	0.196	0.128	0.160	0.884	0.972	0.987
0.052	1.0	0.359	0.466	0.054	0.700	0.918	0.963	0.980
0.073	1.0	0.112	0.308	0.075	0.545	0.912	0.963	0.980
0.092	1.0	0.049	0.249	0.095	0.383	0.903	0.962	0.980
0.110	1.0	0.031	0.213	0.113	0.244	0.888	0.962	0.980
0.125	1.0	0.030	0.193	0.129	0.156	0.872	0.962	0.980
0.052	5.0	0.263	0.340	0.061	0.509	0.670	0.749	0.839
0.073	5.0	0.084	0.225	0.081	0.397	0.667	0.749	0.839
0.092	5.0	0.037	0.181	0.099	0.279	0.660	0.749	0.839
0.110	5.0	0.024	0.156	0.117	0.179	0.649	0.748	0.839
0.125	5.0	0.023	0.142	0.132	0.116	0.638	0.748	0.839

5 Ranking of Instrument Parameters

Downscopes and Extensions of the Optical Camera :
-2. Limit sensitivity to 1-5 μm region
-1. Reduce the FOV to 2 by 2 arcmin
0. **Baseline:** Optical Camera "Yardstick style" with 4 by 4 arcmin FOV and 0.6-5 μm sensitivity
1. Add a coronagraphic capability (plus optional pupil apodization to reduce PSF wings).
2. Separate Optical Camera with 2 by 2 arcmin FOV and Nyquist sampled in the optical.
3. Add continuous coverage at resolving power R $>$ 10.
4. Add multiple plate scales.

6 Summary

- Our conclusions were driven by our choice of relying on the actual performance in executing the DRM.
- Field of view and optical sensitivity stand as the two major characteristics of a Camera for NGST.
- Generic concern about the PSF quality have contributed in ranking highly a coronagraphic capability with smooth pupil apodization available also in non-coronagraphic mode.
- We identified optical observations as the major driver for a different plate scale. If an optical camera is included the issue of the optimal pixel size for the Near-IR camera should be revisited.
- The DRM does not rely on narrow band imaging science.