Science Drivers for NGST Small-Angle Maneuvers

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Next Generation Space Telescope Mission

Science Drivers for NGST Small-Angle Maneuvers

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TITLE
Science Drivers for NGST Small-Angle Maneuvers

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Abstract

Small changes in the pointing direction of NGST will be required as part of target acquisition and dithering. Some portion of these changes may be accomplished by moving the entire observatory, other portions might be accomplished by moving a mirror. The purpose of this document is to outline the expected scientific drivers for different kinds of motions, estimate their scale and frequency, and assess their importance to the overall science goals of the observatory. Such information is an important input to deciding how efficient and accurate to make the small-angle maneuvers, and in deciding how they should be accomplished.

1 Introduction

The Next Generation Space Telescope is envisioned as an international facility, with competitively selected observing programs spanning a wide range of topics. Over the last several years the Ad-Hoc Science Working Group (ASWG) has articulated the major scientific goals for NGST, and has constructed a Design Reference Mission (DRM) to sketch out the observations that could be used to meet these goals (http://www.ngst.stsci.edu/drm). The observations have been specified to the level of deciding the kinds of targets, sensitivity, spatial resolution, area coverage, and spectral resolution needed to accomplish the science goals. However the details of how the observations might be carried out are not included in the DRM specification. The goal of this study is to begin to explore some of the issues of observation strategy. In particular this report focuses on the need for small angle maneuvers and attempts to assess how accurately and frequently they need to be done.

1.1 Scope of this Study

This study is intended to provide a practical summary of the drivers for small NGST pointing changes. For target acquisition, we have tried to identify some of the difficulties that might be encountered and outline a strategy that would be reasonably robust in finding the desired target and putting it at the desired location. We have assumed the GSFC Yardstick concept for NGST, with the instrument complement recommended by the ASWG and the NGST project scientist as of January, 2000. For dithering (small pointing changes from exposure to exposure), we have not undertaken a detailed study to test which strategies are optimal, but have based our findings on previous studies of optimal procedures (Lauer 1999a,b; Fixsen et al. 2000), and on practical experience with HST (Williams et al. 1996; Fruchter & Hook 1998).

This study began as an attempt to construct detailed observing proposals (at the level of an HST phase-2 proposal) for several of the core DRM programs. The primary aim of the
exercise was to solidify some of the requirements for target acquisition and dithering. However, the study considered other issues as well, and these will be reserved for a future report.

1.2 Overview of Findings and Recommendations

A brief summary of the key recommendation of this report is as follows.

- Absolute pointing (after long slews) to better than ~5” will greatly simplify the target acquisition procedure and lessen the requirements for a deep NIR guide-star catalog.
- Pointing repeatability to better than ~0.2” is desirable to minimize interference from detector gaps; but minimizing such interference is not a strong requirement. More accurate repeatability (to a fraction of a pixel) is desirable for a few programs, but there are workarounds.
- Absolute knowledge of the field orientation to better than 2’ is needed to ensure that NIR multi-object spectrograph apertures fall on the desired sources.
- Field orientation repeatability to better than 17” is needed to avoid introducing detectable shear at the edges of the NIR camera field of view.
- Efficient dithering over scales of ~ 20” is required to allow faint extended sources to be detected against a bright sky background.
- Precise sub-pixel dithering over small scales is desirable to simplify the process of reconstructing a super-resolution image.

2 Primary Drivers for Small-Angle Maneuvers

Small angle maneuvers on NGST will be necessary as part of the target acquisition sequence and between exposures as part of the observing sequence. Issues such as the size and frequency of small-angle maneuvers have an important bearing on NGST design. Also relevant is the positioning accuracy and repeatability. The scientific desire is for the highest possible accuracy and repeatability, and there are quantifiable science gains to be had from each increment in these parameters. However, the scientific desires must be balanced against cost and complexity. The discussion below tries to identify the key drivers and outline the basic capabilities that would allow the scientific goals to be achieved.

2.1 Target Acquisition

For NGST, as for HST, a sequence of steps will be required to position a target at the desired spot on the detector. Target acquisition begins with a long slew (~ 90˚) from the previous target. The gyros combined with the fixed head star trackers must be precise enough to place a star within a fraction of the field of view of the guider.

HST observations typically use two pre-selected guide stars, which are located 10-20 arcminutes from each other. The limiting magnitude for guiding is V = 15. These guide stars are typically positioned to within 10 arcsec of their desired positions at the end of the slew. The fine guidance sensors then search for the stars through an outward spiral. Once the stars magnitudes and position angles are checked, the telescope is commanded to move such that the guide stars are driven to the correct location in the fine guidance sensor. The telescope is then moved to put the guide stars at the desired location. Uncertainties in target locations relative to the guide star locations are typically under 1”. Except for coronagraphic applications, this accuracy is sufficient for direct imaging. For spectroscopic observations, additional acquisition procedures using error
signals from the spectrograph itself allow the target to be centered precisely within apertures as small as 0.025” on a side. For guiding, the FGS typically uses two guide stars that are preselected from the Guide-Star catalog based on a complex set of selection criteria. Observations with one guide star tend to drift in roll at a rate of order 0.001”/sec. About 2% of observations fail due to failure of the guide-star acquisition.

The basic acquisition for NGST will be similar. If the slews can place the star on the detector to an rms accuracy of 5 arcseconds, the acquisition procedure for imaging exposures will generally amount to centroiding on the star and adjusting the telescope pointing position to move it to the desired pixel. Thus a single telescope or steering motion of a few arcseconds will be required. Pre-selection of the guide star from a catalog is essential to ensure that it can be identified unambiguously, placed sufficiently far from the edge of the detector to ensure that it is in the field, and to ensure a proper exposure time for the centroiding step. For most imaging exposures, knowledge of the target location(s) relative to the guide star to an rms accuracy of 1” would be acceptable. For spectroscopy, similar accuracy is likely to be acceptable, provided there is a separate spectroscopic acquisition sequence to place the desired targets in the apertures.

If the large-angle slews cannot get within 5 arcseconds of the desired pointing position, the situation will be more complicated. In that case, it will be necessary to have some software on board to search for a desired pattern among the brightest objects in the field. Objects fainter than those suitable for guiding may be used, since 1-2 second exposures could be used for this step without significantly affecting the overall observatory efficiency. There should be several stars per field available anywhere in the sky. However, the brightness of these stars (K_AB ~ 20) will be fainter than the limiting magnitude of ground-based catalogs either existing or in the process of being constructed. Pre-selection of these field-identification stars could pose a significant challenge. The search procedure also gets progressively more complicated as the pointing accuracy after a slew degrades. If the pointing accuracy is better than ~10”, the search can be confined to a single 2’x2’ field. If the pointing accuracy is much worse, the search algorithm has to be intelligent enough to identify the field from the subset of stars in the uplinked catalog that happen to fall in the field (and not in the detector gaps).

Once the field is located, the guide star must be moved to a desired pixel on the detector. Several factors determine the precision to which this must be accomplished. In order of increasing requirements for precision:

1. The star must be placed close enough to the desired position that uncertainties about the location of the detector gaps are not a major issue for observers. For the Yardstick NGST camera, this requires a precision of better than ~0.2”.
2. For spectroscopic observations, the target must be well centered in the slit. This minimizes wavelength uncertainties and maximizes the flux through the slit. For yardstick NIR spectrograph, the minimum slit width is 0.1”; centering to better than half of this width is not required for multiobject spectroscopy. For observations of individual point sources, higher precision is desirable.
3. The star must be placed to within 0.003” of the desired position to allow accurate image reconstruction via combination of dithered exposures (see below).

For item 2 it is almost certainly the case that a separate spectroscopic acquisition procedure will be used to align the spectrograph slits with the desired targets. This procedure will produce an error signal (which may range from a fraction of a pixel to several arcseconds depending on how easily the spectrograph slits can be reconfigured). The guide star position must then be changed to respond to this error signal to a precision of better than 0.05”.

Item 3 is not strongly driven by the core DRM science programs. For most programs envisioned, absolute position accuracy to a small fraction of a pixel is not necessary. Relative
position accuracy for dithering is more important, as is the ability to determine those relative positions after the fact.

2.2 Dithering

The standard practice for observing faint galaxies, both from the ground and with HST, is to take a series of exposures, shifting the telescope between exposures. This procedure, commonly referred to as dithering, can greatly improve the quality of the final image. There are two basic reasons for dithering. The first is to separate detector artifacts or sensitivity and background variations from true features on the sky. The second is to improve the resolution of undersampled images. Both aspects are likely to be important for NGST, and both impose different requirements on the dithering scale and accuracy.

The requirements for dithering depend strongly on the properties of the detector and the overall optical system. The most important parameters are as follows.

1. Pixel size relative to the PSF and the sources of interest. If the point-spread function of the telescope is undersampled by the detector, there is strong motivation for dithering to recover at least part of the intrinsic resolution of the telescope. Many of the galaxies targeted by NGST will be barely resolved by the intrinsic PSF of the telescope, so the motivation for improving resolution will exist as it does for HST.

2. Detector Gaps. While contiguous sky coverage is not a requirement for most DRM programs, it will often be desirable to dither to fill in the gaps. For long exposures, the anticipated restrictions on orientation will mean that the gaps rotate through the survey area. Dithering can help even out the total exposure times. The dithering scale will depend on the size of the gaps.

3. Detector Blemishes. Static hot pixels or other artifacts can be flagged, but the true sky signal underneath them cannot be recovered without dithering. The dithering scale will depend on the size of the largest blemishes.

4. Large-scale sensitivity variations (flatfielding). Variations across the field (e.g. due to vignetting) primarily affect mosaicing and galaxy clustering measurements. Variations on the scale of galaxies affect the overall sensitivity of faint galaxy surveys. Deep NGST surveys are searching for galaxies with mean surface brightness less than 1% of the sky background. The primary source of noise could be uncalibrated variations in detector sensitivity rather than photon statistics and detector noise. Uncertainties in the flatfield corrections can arise because of mismatch in color between the sky and the calibration source used to construct the flat. Also degradation of the detector over time (e.g. due to radiation damage) can lead to a mismatch between the calibration data and the science data.

5. Pixel-to-pixel sensitivity variations. Even if larger scale sensitivity variations are well calibrated, the pixel-to-pixel sensitivity variations (most likely to arise over time due to radiation damage) can become the dominant source of noise for very deep sky-limited exposures and high-background MIR imaging.

6. Intrapixel sensitivity variations. Variations of sensitivity within a detector pixel can lead to significant photometric and astrometric errors in undersampled images.

7. Background illumination pattern variations. The overall background in NGST images may be affected by scattered light, and, in the MIR, by thermal emission from the telescope. The pattern of this illumination can be non-uniform from field to field. If the variations in the background pattern are slow relative to a typical exposure time, and if they are unaffected by small changes in the telescope pointing direction, then dithering is advantageous.
8. **Dark current variations.** “Warm” pixels, with dark currents within ~5σ of the mean (such that they are typically not flagged as bad), can be a significant source of noise for dark-current limited exposures (narrowband imaging or spectroscopy). Large-scale uncalibrated dark-current variations can be a significant source of uncertainty in background subtraction, particularly in spectroscopic observations.

9. **Cosmic-Ray Persistence.** In the HST NICMOS detector, cosmic rays leave elevated dark-current levels in subsequent images. If the time-constant for the decay of this elevated dark current is longer than a typical exposure time, there is a strong motivation for dithering.

10. **Bias-level variations.** Changes in the detector bias level as a function of position are typically a problem for dithered as well as undithered images. Large-scale uncalibrated bias level variations can be a significant source of uncertainty in background subtraction, particularly in spectroscopic observations.

    The calibration and/or stability requirements on items 4-10 are rather stringent for some NGST DRM programs. This will be discussed in more detail in section 4.

    If the calibration and stability requirements can be met, then the primary motivation for dithering is to restore resolution, and the dithering steps can be small. On the other hand even the best efforts to meet the calibration and stability requirements are likely to be imperfect and dithering on larger scales will be a practical necessity for most observations.

    While the dithering strategy will vary from observation to observation, the general considerations involved in deciding how far and how often to dither are fairly simple:

    1. Dither as often as possible without significantly increasing the noise or significantly increasing the observation overhead. This means the detailed dithering strategy will be determined by the ratio of readout noise to other noise sources, and by the overhead incurred for each readout and change of the pointing direction.

    2. Dither over an area large compared to the objects of interest. While the typical galaxies being sought by NGST are small (half-light radii $\ll 1$ arcsec), the simplest way to construct a sky image is to median filter a set of unregistered dithered images. In this case the halos and scattering wings from brighter objects in the field can significantly distort the sky image derived from dithering unless the scale of the dither pattern is large enough. Self-calibration techniques (Fixsen et al. 2000) only slightly lessen the need for large dither patterns, since detector non-uniformities can exist on a variety of scales.

    3. For individual images, dither over an area small compared to the total image size, so that the high sensitivity region is as large as possible. For mosaicing, larger dither motions, with substantial overlap between steps of the mosaic pattern, are also attractive. It becomes more important to have a stable well calibrated model of the geometric distortion of the camera with such a strategy.

    4. If improving resolution is critical, at least a portion of the dither pattern should consist of small steps of a non-integral multiple of a pixel. Small steps (a few pixels) are required to keep the positioning within pixels accurate and to avoid any significant worries about geometric distortion.

    These considerations suggest that for the NGST fields of view (2′x2′ to 4′x4′) the overall scale desired for the dithering pattern is likely to be on the scale of ~20″, that individual step sizes are likely to be a few arcsec, and that dithering motions may be carried out after each exposure (roughly every 1000s). Small dither steps of a small non-integral multiple of a pixel may be superimposed on this larger pattern for programs that need the extra resolution it buys.
3 Target Acquisition

3.1 Camera acquisition

3.1.1 Position accuracy

Position accuracy for target acquisition is the accuracy to which a celestial target can be placed on the detector, given the celestial coordinates of the target and the guide star. The programs described in the NGST DRM generally do not have strong requirements for the exact placement of a given target within a given pixel. The imaging programs in particular typically have multiple targets in the field, and the loss of a few of them to detector gaps or blemishes would not have a serious impact on the scientific results.

That said, there are a few programs that desire excellent repeatability of the target acquisition. That is, once the source has been acquired once, it should be possible to come back to that source again and again and locate the source on the same physical pixel to with a fraction of the pixel dimension. The program that pushes this requirement the hardest is Microlensing in the Virgo Cluster, which is aiming for precise relative photometry of individual pixels of a galaxy image in a series of 30 exposures taken at daily intervals. The microlensing signal is expected to be a 10% variation in the flux within a pixel. Detection of that variation at the 10σ level requires relative photometry to better than 1% (0.01 magnitudes). While the pixel-to-pixel flatfield accuracy may allow that, the intrinsic pixel-to-pixel surface-brightness fluctuations due to stars in the galaxy are about 18% per PSF resolution element in the I band (according to the DRM proposal). If the PSF is undersampled and the pointing is not accurate to better than 0.1 pixels, the intrinsic fluctuations in the number of stars per pixel will dominate the errors. In actuality the observing technique would probably be to dither a small amount to allow construction of a Nyquist sampled image. So if dithering precision to the sub-pixel level over steps of order 0.1″ is possible (and if the intrapixel sensitivity is reasonably flat and stable), the requirement for precisely repeatable target acquisition is relaxed. Repeated target acquisition to within a few pixels would still be desired to reduce the need for geometric distortion corrections.

Apart from this program, any plausible coronagraphic mode in the camera would require precise target positioning. However, use of this mode would most likely involve a peak-down sequence on the target of interest, so need not impose stringent requirements on the target-to-guide-star position accuracy and knowledge of the field distortion.

For the bulk of the DRM, the primary motivation for precise target acquisition is to avoid losing sources to the detector gaps and blemishes. Once a field has been observed with one filter, there will be a strong desire to keep the same sources in all the other filters. If successive observations of a field through two different filters are offset by 1″ in each axis, then 5.8% of the field area will be lost due to the detector gaps in the yardstick design. Acquisition repeatability to better than 0.2″ is desirable to keep such losses of survey area to a negligible level. In general, observations will be dithered to fill in the detector gaps, so the actual requirement is not so much one of minimizing the loss of area as it is of enabling careful planning the of the observations.

3.1.2 Orientation accuracy

The requirement in question here is the accuracy to which a celestial field can be oriented on the NGST detector, given a desired celestial roll angle. Sources of uncertainty are the precision to which the spacecraft can achieve a desired roll using the fixed-head star trackers, the geometric stability of the focal plane relative to the fixed-head star trackers, and the precision
to which astronomers estimate their desired roll angles in the reference frame of the bright stars used by the star trackers.

For imaging there are no DRM programs that place explicit constraints on the absolute accuracy of the roll. The strongest implicit constraint is a desire for roll repeatability. Observers requesting a series of repeated images of the same field should not have to measure and rectify the images to the same roll angle. This rectification step can result in a loss in S/N and resolution, and also is time-consuming. To keep the tangential image motion to less than 0.01″ (1/3 of a pixel) at the edge of 4′x4′ field when rotating about its center, requires requires roll repeatability of better than 17″. While most DRM programs will not suffer significantly if this roll repeatability is not attained, the final co-added images will show some shear at the edges unless the individual images are accurately registered and rotated to the same orientation.

3.1.3 Acquisition Sequence

For NIR imaging, a suggested acquisition sequence is:

1. Choose the camera to be used as the guider
2. Insert the appropriate filter
3. Slew to place guide star within 5″ of the desired pixel
4. Search for brightest object within a small radius of the desired pixel
5. Move the telescope to place that star on the desired pixel

3.2 NIR Spectrograph

3.2.1 Position accuracy

Most NIR spectroscopy in the DRM is multi-object spectroscopy. Tens or hundreds of individual apertures will be configured to cover the targets of interest. The intrinsic aperture size of the spectrograph thus determines the RMS accuracy of target centering within the apertures. A typical configuration for a MEMS spectrometer would be to have a large number of apertures roughly 0.1″ wide and perhaps 0.5″ - 1″ long. It is important to ensure that the objects are as well centered in the slits. However, because the objects are distributed randomly in the field this cannot be done to better than half the aperture size. Positioning to better than ~0.05″ is not required by the multi-object spectroscopy in the DRM. However, there are a few single-object programs in the DRM, and such observations might be more common among GO programs. For individual targets, more accurate pointing can lead to higher S/N and better wavelength accuracy.

3.2.2 Orientation accuracy

Accurate knowledge of the field orientation is important for multi-object spectroscopy, since it affects whether or not all targets in the field are well centered in their apertures. Because the slit positions will be predetermined to about 0.05″, to avoid significantly degrading the S/N or wavelength accuracy with field rotations, it will be important to keep the shifts across the field to less than ~ 0.05″. For a 3′ spectrograph field, that implies an error in rotation relative to the planned orientation of less than 2 arcminutes. This requires not only accurate positioning of the spacecraft, but also accurate knowledge of the orientation of the imaging fields used to select targets, and the position and orientation of the spectrograph field relative to the fixed-head star trackers.
3.2.3 Acquisition Sequence

In general, spectroscopic acquisition will require an additional step beyond simply acquiring the guide star with the camera. This is because the position of the targets relative to the guide star will not be known to an accuracy of 0.05". A typical target acquisition would begin with acquiring the guide star in the NIR camera. Then, assuming the spectrograph has an undispersed imaging mode, an image of the spectrograph field would be taken and at least one bright pre-determined object identified. The telescope can then be moved to center this target within the desired aperture. After this the MEMS aperture mask can be configured to create the pre-planned apertures.

If there is no imaging mode on the spectrograph, the acquisition will require a peakup. This would involve placing an aperture near the expected position of a bright source in the field, and executing a pattern of small motions with the telescope to maximize the flux through the aperture.

3.3 MID-IR Camera acquisition sequence

3.3.1 Position accuracy

Because of its lower spatial resolution, the MIR camera does not require as high position accuracy as the NIR camera.

3.3.2 Orientation accuracy

Because of its lower spatial resolution and smaller field, the orientation accuracy required for the MIR camera is much less than for the NIR camera.

3.3.3 Acquisition Sequence

For MIR imaging, it will be sufficient to acquire with the NIR camera, using the sequence described in 3.1.3. An exception would be if the MIR camera has a coronographic mode, in which case a separate peak-down procedure would be needed to ensure that the target is well centered behind the occulting spot.

3.4 MID-IR Spectrograph Acquisition sequence

3.4.1 Position accuracy

Because of its lower spatial resolution and smaller field, the acquisition accuracy requirements for the MIR spectrograph are less stringent than for the NIR spectrograph. The targets must be placed within an rms accuracy of 0.5 pixels if there is a MOS mode, or within an accuracy of about 0.2 of the slit width if there is a long-slit mode.

3.4.2 Orientation accuracy

Because of its lower spatial resolution and smaller field, the orientation accuracy requirements for the MIR spectrograph are less stringent than for the NIR spectrograph.
3.4.3 Acquisition Sequence

The acquisition sequence for the MIR spectrograph will be similar to that for the NIR spectrograph.

4 Dithering

This section discusses the anticipated dithering needs for NGST. We adopt the yardstick complement of instruments, and assume the detectors are good but not perfect. The science programs addressed are those described in the DRM.

4.1 Dithering drivers

4.1.1 Dithering to improve PSF

The NGST yardstick NIR camera is Nyquist sampled at 2 μm. This pixel scale provides sufficient resolution at 2 μm and longwards, but undersamples the telescope resolution at shorter wavelengths. Dithering allows at least some of this resolution to be recovered. The DRM programs requiring the highest spatial resolution are those attempting point-source detection and photometry in crowded fields (e.g. measurement of faint white dwarfs in globular clusters), and those attempting to detect faint objects close to a much brighter point source (e.g. the AGN/Galaxy connection, and detection of extrasolar planets). If the PSF is undersampled, uncertainties of the exact positioning of the stars within the pixels introduce uncertainties in PSF fitting and PSF subtraction.

There are a variety of techniques for restoring spatial resolution from dithered images (e.g. Gull 1989; Lucy & Hook 1992; Fruchter & Hook 1998). A full Fourier reconstruction (e.g. Lauer 1999a) offers a mathematically rigorous way of doing this, but is currently only practical if geometric distortions and rotations between the images are negligible.

For all of these reconstruction techniques it is essential that the precise relative positions of the images being combined be known to a small fraction of a pixel (0.1 pixels RMS is a standard rule of thumb). If there are a sufficient number of sources in the field, these relative shifts can be determined with high precision from the images themselves. However, for fields that require short exposure times (e.g. to keep from saturating the brightest objects of interest) there may not be enough information in a single exposure to recover accurate pointing information (position and roll) to the desired accuracy. Similarly, for narrow-band imaging, there may not be enough bright sources in a single image for accurate registration. For such applications the ability to dither over small scales (a few pixels) with precise sub-pixel accuracy is advantageous. That allows a Nyquist-sampled image to be constructed without prior knowledge of the PSF.

The DRM science programs that attempt to identify faint objects near much brighter objects also would greatly benefit from being able to roll the telescope between images. This changes the position of the diffraction spikes, and allows better PSF subtraction. These DRM programs also would make use of a coronographic mode if it is available. However, if there is an accurate peak-down acquisition sequence for coronographic observations, there is much less motivation to dither.

4.1.2 Dithering to improve Photometry

Dithering can significantly improve the photometry for undersampled images. Reconstruction of a nearly Nyquist-sampled image from multiple dither positions can allow the
use of conventional PSF-fitting techniques for point-source photometry. This is particularly important for crowded fields, such as those envisioned for the DRM white-dwarf cooling function measurement and the DRM galaxy halo stellar population studies. Even without reconstructing a Nyquist-sampled image, dithered data can be used to constrain the brightnesses and positions of point sources by fitting the joint constraints from the individual images in a maximum-likelihood solution. Such techniques improve point-source detection and photometry even in uncrowded fields (e.g. Flynn & Bahcall 1996; Gilliland et al. 1999).

Variations in sensitivity over the scale of an individual pixel can significantly reduce the photometric accuracy of undersampled images. Such sensitivity variations are not corrected by flat-field calibration, and can be the dominant source of photometric error and the limiting factor for detecting compact faint sources. For HST the total flux in stellar images can vary by up to 0.03 mag in F555W WFC images and by up to 0.39 mag in NICMOS camera 3 images (Lauer 1999b). Intrapixel sensitivity variations also introduce centroiding errors. These can become the dominant source of error for programs requiring precise astrometry, and can also limit the photometric precision attainable if image registration must be done from the images themselves and either a paucity of sources or lack of knowledge of the full-field geometric distortion limits the area that can be used for image registration. Figure 1 shows centroiding errors introduced by the intrapixel sensitivity variations on the HST NICMOS camera 3.

Figure 1: NICMOS 3 centroiding errors. The plot shows the difference between the measured centroids of three stars in the HDF-S NIC3 images, relative to their true positions computed from the pointing offsets for each frame. From Stiavelli 1999.

As an example, consider a hypothetical camera with intrapixel sensitivity variations that lead to \( \sigma_s = 5\% \) rms variations in the total detected counts form a star, depending on where it is centered on a pixel. The variance in the final photometry is given by

\[
\sigma_{\text{tot}}^2 = \sigma_{\text{sky}}^2 + \sigma_{\text{dark}}^2 + \sigma_{\text{pnr}}^2 + \sigma_{\text{ic}}^2 + \sigma_{\text{targ}}^2 + \sigma_{\text{sky}}^2 + \sigma_{\text{dark}}^2 + \sigma_{\text{pnr}}^2 + \sigma_{\text{ic}}^2 + \sigma_{\text{targ}}^2,
\]
where \( t \) is the exposure time, \( c_{\text{targ,sky,dark}} \) are the count rates from the target, the sky and detector dark current, respectively, \( p \) is the number of pixels used in the photometric aperture, \( r \) is the readout noise, \( n \) is the number or readouts. In the limit of high S/N and low background, the last term dominates, and the photometric error is 5% regardless of the counting statistics for \( c_{\text{targ}} \). This is the relevant case for standard star observations, and indicates that at least for calibration, careful dithering will be required to ensure photometric accuracy.

Now consider an observation to detect faint point sources against a bright sky background. Assume a 10 hour exposure (with 38 detector readout) to detect point sources with \( K_{AB}=30 \) at 1µm with a bandpass equivalent to spectral resolution \( R=5 \). For the Yardstick NGST, the optimal aperture for photometry is 9.5 pixels, and

\[
\begin{align*}
c_{\text{targ}} &= 5500 \text{ e}^- \\
p_{\text{sky}} &= 35720 \text{ e}^- \\
p_{\text{dark}} &= 6840 \text{ e}^- \\
pnr^2 &= 608 \text{ e}^- \\
S^2 \sigma^2_{\text{targ}} &= 75625 \text{ e}^-.
\end{align*}
\]

With no intrapixel sensitivity variations, the S/N = 23.8 for this point-source detection. However, with 5% rms variations due to nonuniform intrapixel sensitivity, the last term dominates, and the S/N = 15.6. For a star one magnitude fainter, the S/N changes from 10.3 to 9.1 (i.e. intrapixel sensitivity variations become less important for detection of point sources right near the detection limit).

The effect of intrapixel sensitivity variations is suppressed for extended sources because they sample more pixels. It is also suppressed if the observation is carried out with a large number of dither positions. Precise sub-pixel dithering is more effective than random dithering at reducing the effects of intra-pixel sensitivity variations. An optimal dithering pattern would sample the pixel in a rectangular grid of \( N \times N \) sub-pixels. With precise subpixel dithering, the sensitivity variations can be accounted for as part of the photometry procedure (Lauer 1999b; Storrs et al. 1999).

4.1.3 Dithering to improve faint extended source detection

While point source detection and photometry favors small dither steps, detection of extended sources favors large dither steps. The sources being sought typically have surface brightnesses of order 1% of the sky background. The sky background in a deep NGST NIR broadband image will be sufficiently high that flatfielding errors dominate over counting statistics, and the ultimate sensitivity limit will be determined by how well these errors can be controlled.

Ignoring intrapixel sensitivity variations, the S/N for detection of an extended source encompassing \( p \) pixels is

\[
\sigma^2_{\text{tot}} = c_{\text{targ}} + p_{\text{sky}} + p_{\text{dark}} + pnr^2 + (\sigma_{\text{flat}} p_{\text{sky}})^2.
\]

Consider a source with a diameter of 0.5", with AB=30 at 3.6µm, observed for 10 hours through an R=3 bandpass. The Yardstick design gives the following:

\[
\begin{align*}
p &= 230 \text{ pix} \\
c_{\text{targ}} &= 14329 \text{ e}^- \\
p_{\text{sky}} &= 1.08 \times 10^5 \text{ e}^- \\
p_{\text{dark}} &= 1.66 \times 10^5 \text{ e}^- \\
pnr^2 &= 608 \text{ e}^-.
\end{align*}
\]

Ignoring the flatfielding errors, the source is detected at S/N = 12.

Now consider the effects of flatfielding uncertainties.
**Case 1:** As an optimistic case, assume the pixel-to-pixel sensitivity variations can be determined to an rms accuracy of 1%, and that this uncertainty scales with the square-root of the number of pixels in an aperture. (This is an extremely optimistic assumption, not met in practice for real detectors.) That gives:

\[
(\sigma_{flat pc_{sky t}})^2 = [(0.01/230) \times 1.08 \times 10^6]^2 = 2205 e^-, 
\]

which is completely negligible.

**Case 2:** As a more realistic case, assume the sensitivity variations on a scale of 0.5 arcsec can be calibrated to an accuracy of 0.2% (this is comparable to the RMS accuracy of WFPC2 flatfielding on this scale). That gives:

\[
(\sigma_{flat pc_{sky t}})^2 = (0.002 \times 1.08 \times 10^6)^2 = 4.7 \times 10^6 e^-.
\]

In this case the flatfielding errors dominate, and the signal-to-noise ratio is reduced to S/N=5.9.

**Case 3:** As a pessimistic case, consider the situation for the HST NICMOS camera 3. The sensitivity in each pixel varies with wavelength by a factor of 20-50% (Storrs et al. 1999b). The ratio of ground to on-orbit flats in the F160W filter shows an rms variation on a scale of 230 pixels of 3.0% (excluding outliers). For a given observation the errors will either be dominated by the mismatch of the sky color with the spectral energy distribution used for creating the flat, or by the evolution of the detector response between the time the flat is created and the time the observations are carried out. In any case rms variations of even 3% on a scale of 230 pixels would give

\[
(\sigma_{flat pc_{sky t}})^2 = (0.03 \times 1.08 \times 10^6)^2 = 1.0 \times 10^9 e^-.
\]

and would be disastrous for the observation described above, reducing the detection to S/N=0.44.

Clearly for detection of faint extended sources in the sky-limited regime, the crucial step is the estimation and subtraction of the sky background. The sky background is typically determined over scales several times the dimensions of the galaxies of interest. For a galaxy of diameter 0.5”, the local background may be estimated from a roughly annular region with radius of 1-4”. To average over flatfield variations, one would like this background region to sample a set of independent regions on the detector. If truly independent regions could be sampled, the noise contribution from flatfielding uncertainties would scale as \((N-1)^{1/2}\), where \(N\) is the number of independent samples. Thus if 20 independent samples could be obtained, the flatfielding uncertainties for case 2 above become insignificant relative to the sky noise, and the S/N=11.7, close to that in case 1. For case 3, to obtain S/N > 10 would require 1000 independent samples.

In practice, the flatfielding uncertainties are significant on a wide variety of scales, and the uncertainty decreases more slowly than \((N-1)^{1/2}\) (on the other hand this correlation also means that the rms estimated above for NICMOS is overly pessimistic, since the rms is smaller if one takes out the large-scale sensitivity ripples). Thus dithering over as large a scale as possible is desirable, all else being equal. However typically there is a price to be paid in loss of area×sensitivity, and the total dithering scale is kept to a small fraction of the field size to keep this acceptable. For NGST, dithering over a scale of 20” would provide more than 20 independent samples of the detector sensitivity pattern for galaxies of typical sizes of 0.1 – 0.5”. Because readout noise is expected to be a minor contributor to the overall noise budget, there will be a strong motivation to dither frequently. Low overheads for dithers on a scale of 20” can translate into significant benefits in S/N.

The situation for the MIR is similar, except that the dominant background is emission from the telescope. In this case it is the variations in the illumination pattern of this background that dominate the uncertainties, rather than variations in detector sensitivity. As long as the illumination pattern is stable over small dither motions, the argument for dithering is the same as above. However if the background pattern changes significantly (e.g. if dithering induces significant thermal transients), then the benefits of dithering may be reduced.

For both the NIR and MIR, cosmic-ray persistence in the detector is another potential source of noise. If the noise level is a significant fraction of the sky background, then it could
seriously affect the ability to detect faint galaxies (as it does for NICMOS on HST). Dithering on a timescale shorter than the decay rate of cosmic-ray persistence could mitigate the problem. However, with the larger contribution from sky background on NGST, cosmic-ray persistence is likely to be less of a problem than it was for NICMOS, at least for imaging experiments. For dark-limited spectroscopy, it could be a dominant source of error, since residual dark current from a cosmic ray could masquerade as an emission feature in a galaxy spectrum.

4.1.4 Dithering to fill gaps/avoid blemishes

The main driver for avoiding gaps and blemishes is to simplify the data analysis. Most NGST DRM programs do not explicitly require contiguous areal coverage, and so could in principle accomplish their goals in a field broken up by detector gaps. However, analysis is typically much simpler if one can simply mask out the bad or missing regions in a portion of the data, but still recover the sky signal in another portion of the data. NGST pointing restrictions may make the detector gaps rotate through the field over the many-day duration of a survey. Uneven exposure times across the field are thus probably inevitable, and dithering can help even out the exposure times so the gaps are not quite so evident.

For typical statistical measurements on a large sample of faint galaxies, mild variations in sensitivity across the field are not a serious problem. Consider an experiment to measure some quantity $\xi$, whose S/N depends on the number of galaxies detected above a fixed S/N. Ignoring the effects of clustering (which may actually dominate the errors for many types of measurements on distant galaxies), the S/N of the observation scales as the number of galaxies $N^{1/2}$, which in turn scales as the area of the field $A^{1/2}$. The number of galaxies per unit flux interval generally has a power-law behavior

$$dN(f)/df \propto f^{-\alpha}$$

with $\alpha=1.2$ to 1.6 (with a corresponding number-magnitude relation slope $\alpha-1$). The integrated number of galaxies above some detection limit $N(>f_{\text{lim}})$ varies roughly as $(f_0 - f_{\text{lim}})^{-\alpha}$, where $f_0$ is the flux of the brightest sources of interest. In the sky-limited regime, the limiting flux $f_{\text{lim}}$ varies as exposure time $t^{-1/2}$. Therefore if $f_0$ is significantly brighter than $f_{\text{lim}}$, the number of galaxies in a sample will vary with exposure time as

$$N \propto t^{(\alpha-1)/2}.$$ 

For the values of $\alpha$ mentioned above, this is a very slow function of $t$. For example, if $\alpha = 1.4$, decreasing the exposure time of a survey by a factor of two changes the number of galaxies by 13%, and decreases the S/N of the measurement by only 7%.

Not all types of measurements envisioned for NGST behave this way. Measurements that are restricted to a narrow range of magnitudes near the limit (i.e. $f_0 \approx f_{\text{lim}}$) will obviously be much more sensitive to variations in exposure time, since $N(>f_{\text{lim}})$ will have a much steeper dependence on $f_{\text{lim}}$. Studies of the most luminous objects of a particular class of galaxies in a narrow redshift range (e.g. the most massive galaxies at $z \sim 10$) could be much more sensitive to exposure time, since the slope at the bright end of a Schechter (1976) luminosity function is much steeper than the power-law behavior adopted above. Nevertheless for most NGST observations, dithering to fill in the detector gaps will be preferable to leaving gaps in the final images.

Similar considerations apply to observations with a NIR multi-object spectrograph. Even if the design of the spectrograph leaves no detector gaps in the dispersion direction, the likely gaps in the cross-dispersion direction will mean that some objects are missed in any short observation, and that different objects will be missed as the gaps rotate across the sky during long surveys. Dithering will be used to even out the exposure times. If, in addition, there are gaps in
the dispersion direction, then dithering across the gaps will be necessary to obtain full wavelength coverage for all of the objects in the field.

4.1.5 Dithering to allow self calibration

As alluded to in section 4.1.3 mismatch between the spectral energy distribution of the flatfielding calibration source and the spectral energy distribution of the sky background can be a significant source of uncertainty in faint-source detection. One traditional solution is to create sky flats by taking a large number of dithered images, masking out the sources, and averaging the unmasked regions together. In the case of very crowded fields, this procedure is difficult, and residual unmasked sources can introduce spurious variations in the apparent detector sensitivity. With enough dithering, this and other problems can be circumvented in an elegant way by solving simultaneously for the intrinsic sky image and the detector dark current or flat-field variations as a function of position (Fixsen et al. 2000; Arendt et al. 2000).

In this scheme, dithering over a large scale, with a large number of dither positions is desirable, since that provides the most information on the pixel sensitivities and dark currents. Arendt et al. (2000) have considered a variety of dither patterns and evaluated their effectiveness for reducing the uncertainties due to sensitivity or background variations (but not both) in the case of several existing detectors. They find that the ability to the ability to determine detector parameters increases monotonically with the number of steps in the dither pattern (although they have not included a read-noise penalty for taking more exposures). Good self calibration can be achieved with patterns of 20 steps or more, for a 256×256 pixel detector. Below about 20 dither steps, the detector self-calibration rapidly degrades. Dither schemes that sample a wide range of scales with the least amount of redundancy are the most effective. The scaling of the pattern size and step number with the size of the detector array has not yet been investigated, however the required number of dither steps is probably a slow function of the detector size. If it scales as the logarithm of the number of pixels, then an 8k×8k detector array would require of order 60 dither steps for a good self calibration. A good self calibration on large scales would require that the dither pattern sample scales at least ¼ the full field of view (i.e. 60” for the NGST NIR camera). This requirement can be relaxed if the smoothly varying response and background of the detector on large scales can be calibrated by other means. The requirement to sample large scales is most important for observations requiring precise, uniform photometry (e.g. stellar photometry of globular clusters). It is also important for fluctuation studies of the extragalactic background light.

The self-calibration procedure envisioned by Fixsen et al. (2000) becomes more complex when dithering (over large scales) introduces geometric distortions. In this case a detailed geometric distortion model must be applied as part of the iterative procedure to determine the true sky image. If the sensitivity varies significantly within individual pixels, or the PSF varies significantly across the field, these aspects of the detector behavior must be included in the modeling as well. Uncertainties in these aspects of the model translate into poorer models of the detector flatfield response. A stable PSF and stable geometric distortion are thus highly desirable.

Because the detector self-calibration improves as the number of dither positions increases, there is strong motivation in this scheme to keep individual exposures short and to dither frequently. A disadvantage of this approach is that it requires accurate registration of many images, and this may be difficult if the S/N of the individual images is low. Precise sub-pixel positioning over large angular motions (e.g. relative position accuracy of better than 1/3 of a pixel after a motion of 60") is thus highly desirable.

The implication of detector self-calibration schemes for dithering is a desire to dither efficiently over scales at least ¼ of the detector width. However, if this is unachievable, much of
the benefit of self calibration can be obtained if the dithering is efficient on the 20" scale advocated in section 4.1.3.

4.1.6 Dithering to construct mosaics

A final motivation for dithering is to facilitate mapping of areas significantly larger than the field of view of the (NIR or MIR) camera. For example in the Mapping Dark Matter DRM program, large area coverage is desired: the wide-field imaging survey proposes ten large mosaics of 50 to 100 fields, each observed individually for a total of about 50 minutes. For such a program, the S/N for a given amount of telescope time will depend most crucially on the overhead for telescope motions on the order of 4 arcminutes. Overheads of less than 5 minutes per step in the mosaic are clearly acceptable; overheads of more than 25 minutes clearly would start to have a serious impact. Exact positioning to a fraction of a pixel is not necessary, but positioning the fields to a relative accuracy of better than a few arcseconds is desirable to avoid having to overlap the fields by large amounts to avoid introducing gaps.

4.2 DRM Drivers for dithering

In the table below we briefly summarize the motivations for dithering for each of the DRM programs.

Table 1

<table>
<thead>
<tr>
<th>ID</th>
<th>DRM Program</th>
<th>PSF sampling</th>
<th>Intrapixel sensitivity sampling</th>
<th>Flatfielding</th>
<th>Sky subtraction</th>
<th>Filling detect or gaps</th>
<th>Mosaicing</th>
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4.3 Dithering sequences

The exact sequence for dithering depends of course on the details of the observations and the tradeoffs in exposure time vs. overhead for dithering. However, a typical example can help illustrate the frequency and types of motions that would be desirable. A schematic observing sequence that might be sensible for a deep imaging survey is as follows. This strategy assumes the telescope can maintain the same field orientation for 7 days.

**Observing strategy**

- SLEW to target
- ACQUIRE guide stars
- DO 8 times (this loop takes seven days to complete – one day per filter):
  - For filters 1 through 7 (e.g. 0.6, 0.8, 1.2, 2.1, 3.6, 4.8, and 10 \( \mu \)m):
    - HOUSEKEEPING (e.g. momentum dump)
    - CALIBRATION (e.g. darks, internal flats)
    - PATTERN_20HOUR
    - CALIBRATION (e.g. darks, internal flats)

The dithering is accomplished during the PATTERN_20HOUR sequence. For deep broadband imaging, the read-noise penalty is small, and the expected cosmic ray rate limits useful exposure times to about \( \sim 1000 \) seconds. Thus, apart from the additional overhead and complexity of data reduction, there is little motivation not to dither frequently. The dithering pattern should sample large scales to reduce the flatfield uncertainties, and should sample sub-pixel scales to increase resolution (especially valuable shortward of 2 \( \mu \)m). To achieve this, PATTERN_20HOUR might be defined as follows.

- Assume 3 1000s per hour, allowing 600s for overhead. That gives 72 exposures per day, which will be divided into:
  - 8 large-scale dither positions
  - \( \times 3 \) small-scale dither positions per large-scale dither position
  - \( \times 3 \) exposures per small-scale dither position to facilitate cosmic-ray rejection

The large-scale dither pattern should not sample preferentially along rows or columns of the detector. If the data are to be used to construct a sky flat, a square array of positions, 20” on a side, rotated relative to the rows and columns would be a sensible pattern. In this case the step size between each dither position of would be 2.5”.

For detector self-calibration, it is desirable to have a pattern with less redundancy than a uniformly sampled rectangular grid. Arendt et al. (2000) consider a variety of different dither patterns and find that those that meet the criteria of sampling a variety of scales without much redundancy are all approximately equivalent. Since the details of the dither pattern do not matter strongly, we consider here one not mentioned by Arendt et al. (2000).

The optimal pattern to minimize redundancy in one dimension is a Golomb (1972) ruler. For the hypothetical PATTERN_20HOUR sequence considered here, the telescope is stepped
along a line in intervals of an 8 step Golomb ruler. Such a ruler has markings: 0, 1, 4, 9, 15, 22, 32, and 34. For the PATTERN_20HOUR, we scale this up to 20", putting dither steps at 0, 0.588", 2.353", …, 20." The pattern is along a line, but is oriented at an angle relative to rows & columns. The first time the dither pattern is run, the angle is set at 5°. Subsequent executions of PATTERN_20HOUR are done at different angles, so that the overall pattern looks like that shown in Figure 2. One possible advantage of this strategy is that once per week the central reference position is repeated; this allows the data to be used to check for evolution in the detector sensitivity. To reduce redundancy further, the linear pattern can be scaled by a small random factor on each execution.

**Figure 2:** Rotated Golomb-ruler dither pattern for a deep imaging survey. There are 8 executions of a linear dither pattern, each rotated with respect to the others. At each of the labeled steps in the pattern, a small 3-step dither is executed to improve resolution.

The three small-scale dither positions at each step in the large-scale pattern are designed to allow reconstruction of a higher-resolution image, while still minimizing the effects of small-scale flatfielding errors and hot pixels. The steps are along a diagonal at x, y = −1.33, 0, and 1.33 pixels.

While the pattern described above is ad-hoc, the number of dither positions and the scale over which they are placed is likely to be in the ballpark required to accomplish the primary science goals of the deep imaging survey. A survey concentrating on point-source detection and photometry would reduce the number of large dither steps and increase the number of sub-pixel dither steps (a square array of sub-pixel dither steps would allow interlacing to be used as part of the image reconstruction). A survey concentrating on the longer wavelengths that are well sampled by the detector might skip the small dither steps entirely and execute a denser set of large dither steps.
4.4 References


