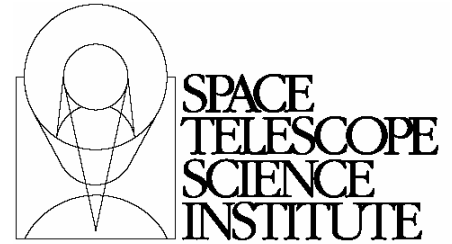




TECHNICAL REPORT



Operated for NASA by AURA

Title: An Alternative Observing Strategy for NIRSpec and its Effect on NIRSpec Target Acquisition		Doc #:	JWST-STScI-000674, SM-12
		Date:	August 31, 2005
		Rev:	-
Authors: M. Regan	Phone: 410-338-4769	Release Date: October 5, 2005	

1.0 Abstract

The quantized locations of the aperture selection shutters on the Near Infrared Spectrograph (NIRSpec) and the current baseline observation strategy of only observing targets in the central region of each slit (the sweet spot) requires that the pointing of the telescope be accurately determined (target acquisition). The baseline target acquisition method is to observe a set of reference stars, determine their centroids, and using the difference between the observed and expected centroids calculate a slew that will place the reference stars at their desired locations.

In this memo we investigate the feasibility of an alternative observation strategy that relaxes the requirements for target acquisition. This strategy allows all targets in the NIRSpec field of view (3'x3') to be observed at once. We then dither the targets in two-dimension symmetrically over a whole shutter pitch. This dithering allows errors in the slit loss correction that are due to the uncertainty in the target location to cancel out to first order.

We investigate the types of programs that the two different observing strategies are optimal for. For some cases the higher average throughput of the baseline, sweet spot, strategy is optimal. But, for most cases, the ability of the one-shutter-dither strategy to observe targets anywhere in the field of view makes up for the lower average throughput by allowing the targets to be observed in much smaller number of MSA settings. This mode also has the advantage of a much lower sensitivity to the pointing accuracy allowing the possible use of a single star for target acquisition. Even so, the baseline target acquisition mode that uses multiple reference stars will be still be needed for some observing modes.

2.0 Introduction and Assumptions

The MEMS microshutters on NIRSpec subtend an open area of 200x450mas on the sky. Because only one shutter is open for a target, this sets an upper limit of around 100mas (or about 50mas 1σ) for the pointing accuracy required to open the correct shutter. The pointing error of observations that are planned using the Guide Star Catalog (GSC 2.3) will be 300mas (1σ) and therefore cannot be used without some form of target acquisition. Once some form of target acquisition is introduced a certain degree of complexity is inevitable. This complexity is driven by features of the NIRSpec

instrument design: the MSA shutters are always in the optical path and they introduce a variable bias in the centroids of stars, the mirror that is on the grating wheel has a finite limit to its ability to repeat its position, the detector plate scale under-samples the PSF, and there is significant geometric distortion across the field-of-view.

The degree to which these various factors affect the complexity of the target acquisition process is driven by the observing strategy. The observing strategy determines the pointing accuracy needed. The driving requirement for the pointing accuracy turns out to be the spectrophotometer accuracy requirement of 10%.

2.1 Baseline Observing Mode, The Sweet Spot

In Figure 1 we plot the one-dimensional slit throughput across the slit. In the baseline observing mode we only observe targets that are in a region where the error in the location yields less than a 10% error in the flux. This area is shown in Figure 2. Note that allocating the entire spectrophotometric error budget to the uncertainty in the slit loss correction is probably too lenient. If we reserve some of the error budget for other terms we may end up with a maximum photometric error of around 5% due to the error in the slit loss correction.

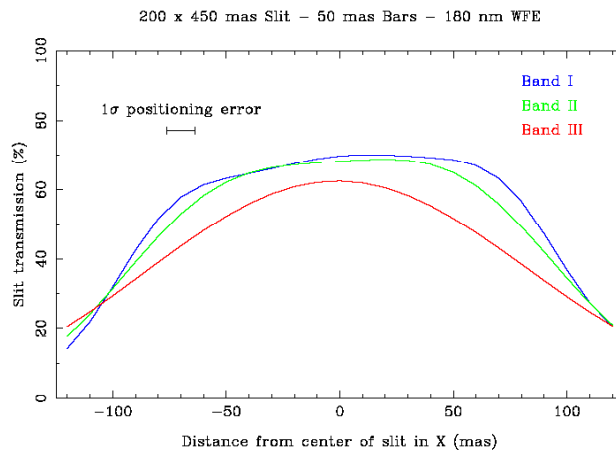


Figure 1 Slit transmission as function of offset from the center of the slit. [From Jakobsen]

In Figure 2 we plot the sweet spot for the case of a pointing error of 12.5mas and the assumption that the target is a point source.

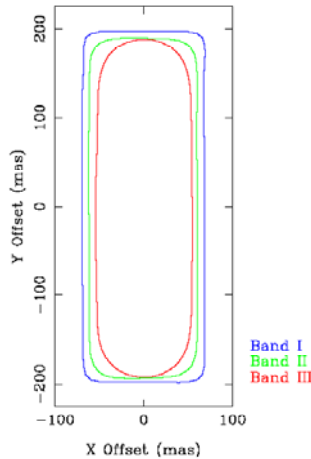


Figure 2 Sample sweet spot size for a pointing error of 12.5 mas [From Jakobsen]

In this case the smaller PSF in the shorter wavelengths yields a flatter response in the center of the shutter and thus a larger region where the uncertainty in the location does not cause the error in the slit loss correction to be larger than 10%. The memo by Jakobsen detailing the baseline observing mode uses widths for the sweet spot of 140, 130, and 110 mas for Bands I, II, and III respectively. Below, we will derive the size of the sweet spot for each band as a function of pointing error and target type.

Because all the targets will not always fall into the sweet spot, the baseline strategy is to split the observations into multiple target sets each of which observe a subset of the targets. Each subset will have a group of targets that simultaneously fall in the sweet spot. The actual number of target sets needed for a given sweet spot size and total number of targets has not been calculated. This is important because it is the total number of target sets times the integration time for each that controls how much observing time is needed. We will call the chance that a randomly placed target will fall in the sweet spot the multiplexing efficiency, m . When $m=1$ we can always observe any target in the MSA field of view. For $m<1$ there is a $(1-m)$ chance that the target falls outside of the sweet spot.

2.2 One shutter dither, an alternative

Because the size of the sweet spot inversely depends on the pointing uncertainty, we need to have an accurate target acquisition. Is there an alternative observing strategy that is not as sensitive to pointing errors? Because the general shape of the slit loss curve is that it peaks in the center of the slit and reaches a minimum on the center of the bar, all the targets on the same side of the slit will have a slit loss correction error of the same sign. This slit loss correction error is due to the difference between the actual location of the target and the expected location. The expected location is used for the slit loss correction and thus there will be an error in the correction. An observing mode that observes targets at locations symmetrically distributed across the slit has a nice feature that, to first order, the slit loss correction errors due to positional uncertainty cancel out. An under-correction on the left side of the slit is balanced by an over-correction on the right side of the slit. Similarly, a under correction when the target is in the bottom half of the slit is balanced by an over-correction when the target is in the top half of the slit. An example of this type of dither patten is shown in Figure 3.

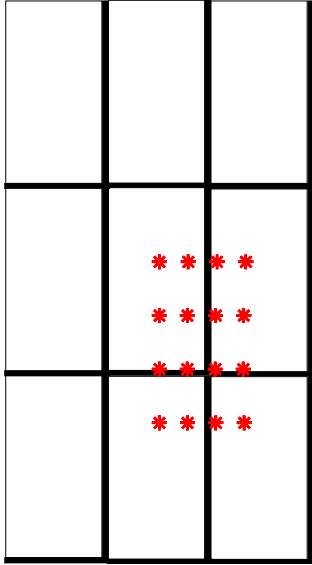


Figure 3 Sample Dither locations of a target. This shows the case of a 4x4 sub-shutter dither pattern.

There are three disadvantages to this method. One is that the average throughput is lower than in the sweet spot method because targets are being observed at locations that have, on-average, lower throughput. The second is that the MSA will need to be reconfigured after each dither to make sure that the correct shutter is being opened. Note that this is not completely new overhead because the sweet spot observing strategy also would require MSA reconfigurations every 2-4 dithers. Finally, if the pointing error is large enough, for targets on the boundary between two shutters the wrong shutter will be opened. This will lead to an additional loss of throughput.

The two observing strategies each have strengths and weaknesses. The sweet spot observing mode has higher average throughput and lower overhead. The one shutter dither has a larger multiplexing efficiency ($m=1$ for this mode), less sensitivity to pointing errors and smaller average photometric errors. To quantify these effects we have performed some modeling.

3.0 Modeling

The goals of the modeling were to understand how the assumed pointing error and target type affect the multiplexing efficiency, average throughput, and photometric error for the two observing strategies. We started with the slit throughput as a function of location calculations provided by Jakobsen and detailed in (Jakobsen 2004). These assume 60mas bars rather than the new baseline of 64mas bars but the change should not affect the overall conclusions.

The dither pattern is an input to the model and for the baseline pattern we assumed a 4x4 sub-shutter dither pattern similar to what is shown in Figure 3. This moves the source a total of 260 mas in the spectral direction, the assumed pitch in the spectral dimension and 520mas in the spatial direction, the assumed pitch in the spatial direction. In practice a smaller number of dithers can be used. The larger the step size of the dither the larger the possible asymmetry in target location can be. To simulate the effect of observing a high redshift galaxy rather than a point source, we convolved the slit throughput curves with a Gaussian with a FWHM of 250mas. This seemed to be conservative since most galaxies

are slightly larger than this (Ferguson 2004). We performed all of the calculations in two-dimensions.

3.1 Sweet Spot Observing Strategy

3.1.1 Multiplexing Efficiency

For the sweet spot observing mode we calculated the size of the sweet spot for both a point source and a galaxy by determining the range over which the error in the flux due to the uncertainty in the position is less than a threshold. We used two different thresholds: 5% for the case of observations that are sensitive to flux errors and 10% which is the value used by Jakobsen (2004). In Figure 4 and Figure 5 we plot the fraction of the multiplexing efficiency for each of these cases for point sources and galaxies.

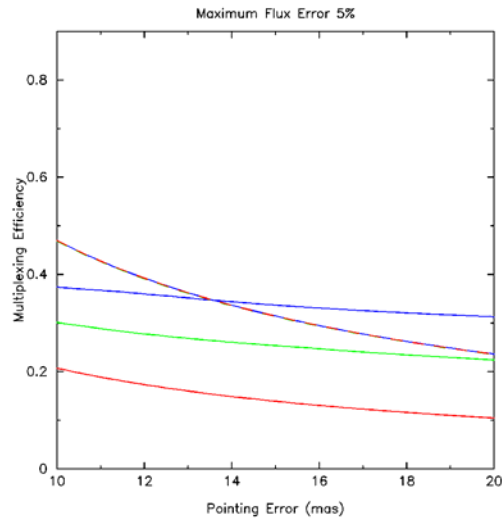


Figure 4 Multiplexing efficiency for 5% error, the multiplexing efficiency for the sweet spot observing mode when the maximum photometric error is set to be 5%. The colored lines are the multiplexing efficiency for Bands I (blue), II (green), & III (red) with the solid lines being for point sources and the dashed lines being for a 250 mas FWHM galaxy. Note that the full shutter dither mode the multiplexing efficiency is always 1.

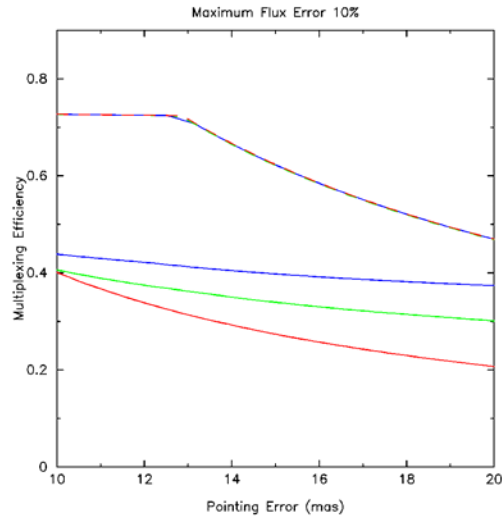


Figure 5 Multiplexing efficiency for 10 % error, the multiplexing efficiency for the sweet spot observing mode when the maximum photometric error is set to be 10%. The colored lines are the multiplexing efficiency for Bands I (blue), II (green), & III (red) with the solid lines being for point sources and the dashed lines being for a 250 mas FWHM galaxy. Note that the full shutter dither mode the multiplexing efficiency is always 1.

The figures reveal that the sweet spot observing strategy, as expected, has a low multiplexing efficiency. This can be as low as 0.1 in Band III when the maximum photometric error is 5%. In all the cases the three Bands are almost identical when the target is a galaxy. This is because the size of the galaxy is more important than the PSF and thus the wavelength is not significant.

In contrast, with the two-dimensional full shutter dither the multiplexing efficiency is always 1.0. Thus, the increase in efficiency of the instrument can be a factor of 10 higher. This increase is mitigated by the fact that the average throughput is lower for this observing strategy.

3.1.2 Average Throughput

The average throughput for various cases is shown in Figure 6 and Figure 7.

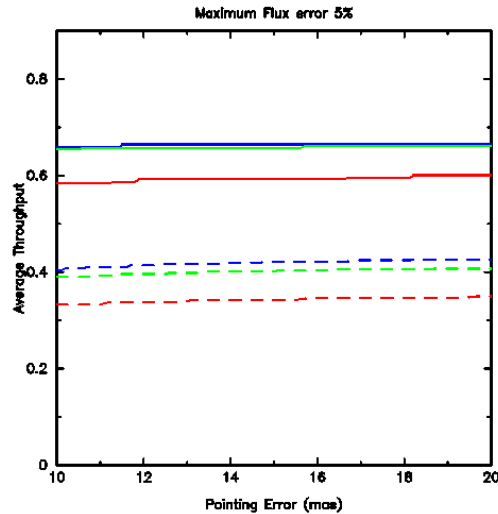


Figure 6 Average throughput for a with a maximum flux error of 5% with the sweet spot strategy. The solid lines are for a point source and the dashed lines are for a galaxy. Band I is blue, Band II is green and Band III is red. Note that the average throughput increases with increasing pointing error because as the sweet spot gets smaller the targets are constrained to be closer to the peak transmission in the slit.

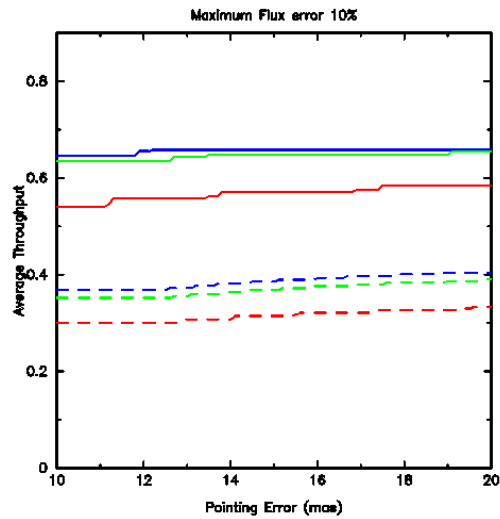


Figure 7 Average throughput for a with a maximum flux error of 10% with the sweet spot strategy. The solid lines are for a point source and the dashed lines are for a galaxy. Band I is blue, Band II is green and Band III is red. Note that the average throughput increases with increasing pointing error because as the sweet spot gets smaller the targets are constrained to be closer to the peak transmission in the slit.

3.1.3 Photometric Error

Setting a maximum photometric error to define the size of the sweet spot means that within the sweet spot there will still be photometric errors. Because in this observing strategy, targets are always observed in their same relative location within the shutter, the error in the slit loss correction caused by the uncertainty in the actual location is always the same and leads to a bias in the final flux determination. In Figure 8 and Figure 9 we plot the average photometric errors for sweet spot strategy for both point sources and galaxies. Note that, to first order, the average error is $\frac{1}{2}$ of the maximum flux error for sweet spot observing.

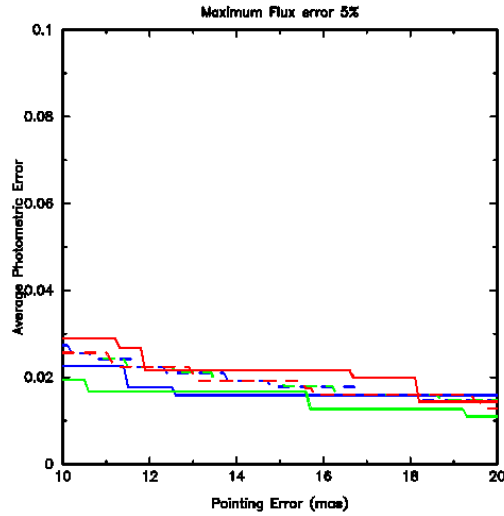


Figure 8 Average photometric error with a 5% maximum photometric error with the sweet spot strategy. The solid lines are for a point source and the dashed lines are for a galaxy. Band I is blue, Band II is green and Band III is red.

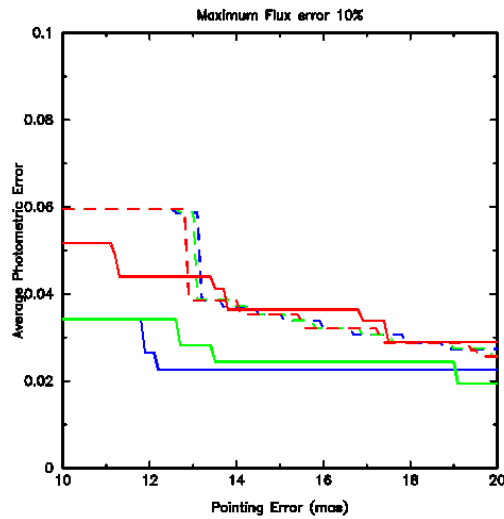


Figure 9 Average photometric error with a 10% maximum photometric error with the sweet spot strategy. The solid lines are for a point source and the dashed lines are for a galaxy. Band I is blue, Band II is green and Band III is red.

3.2 One Shutter Dither

For the one shutter dither strategy we determined both the average throughput and average photometric error by averaging over all the possible locations of targets within the shutter. For each location we dithered the target using the 4x4 dither pattern shown in Figure 3. For each possible pointing error we determined the photometric error by

comparing the actual throughput to the expected throughput. The two sources of error in this are the fact the variation in throughput between the two locations (actual and expected) and the fact that the wrong shutter may be open. The chance of the wrong shutter being open increases as the magnitude of the pointing error increases.

3.2.1 Average Throughput

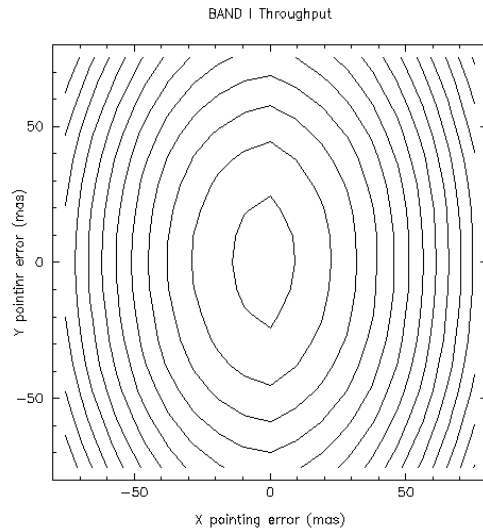


Figure 10 Average throughput as a function of actual pointing error for a point source observed in Band I. The contours are at 1% intervals and the peak throughput is 43%.

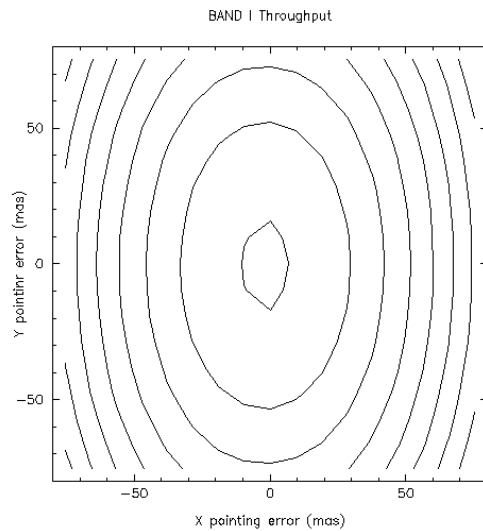


Figure 11 Average throughput as a function of actual pointing error for a galaxy observed in Band I. The contours are at 1% intervals and the peak throughput is 34%.

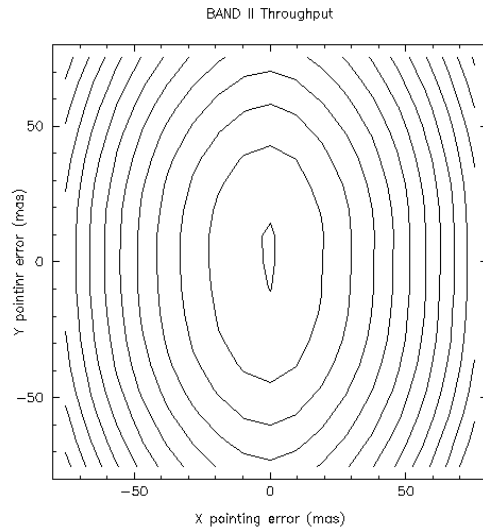


Figure 12 Average throughput as a function of actual pointing error for a point source observed in Band II. The contours are at 1% intervals and the peak throughput is 42%.

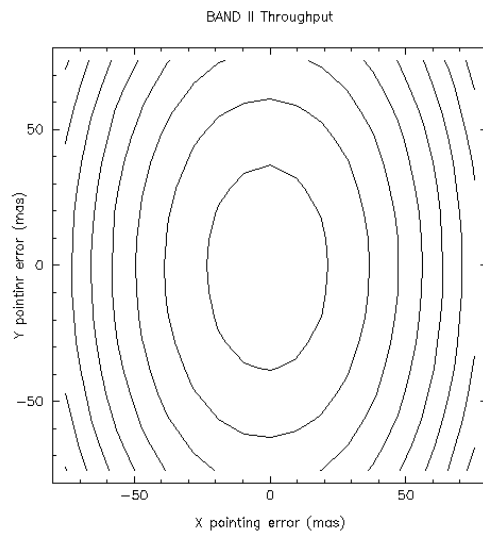


Figure 13 Average throughput as a function of actual pointing error for a galaxy observed in Band II. The contours are at 1% intervals and the peak throughput is 33%.

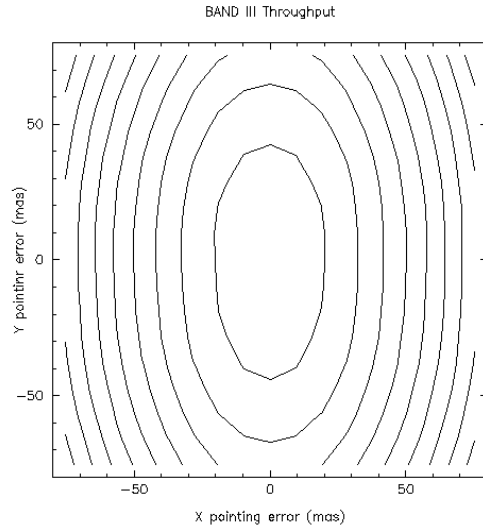


Figure 14 Average throughput as a function of actual pointing error for a point source observed in Band III. The contours are at 1% intervals and the peak throughput is 36%.

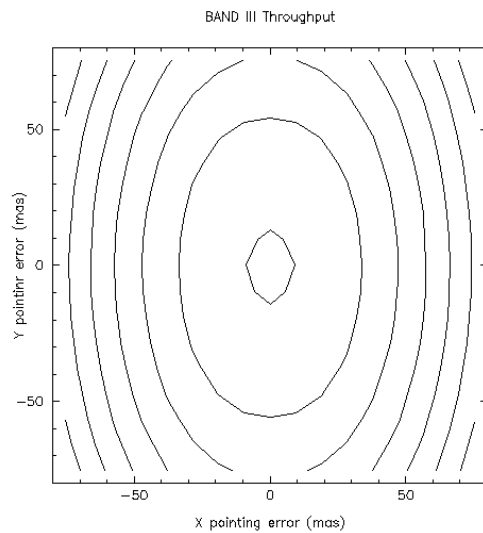


Figure 15 Average throughput as a function of actual pointing error for a galaxy observed in Band III. The contours are at 1% intervals and the peak throughput is 29%.

As expected, the average throughput is more sensitive to pointing errors in the x direction (the spectral dimension) than in the y direction (the spatial dimension). We can also see that galaxies suffer a smaller loss in throughput than point sources due to their more extended structure.

3.2.2 Photometric Error

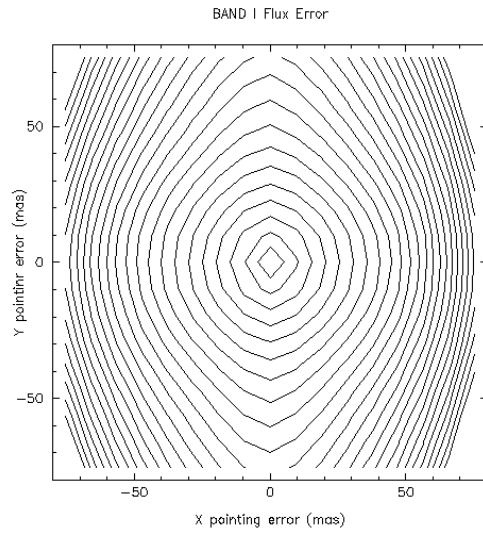


Figure 16 Average photometric error as a function of actual pointing error for a point source observed in Band I. The contours are at 1% intervals with the first one around 0,0 representing a 1% error.

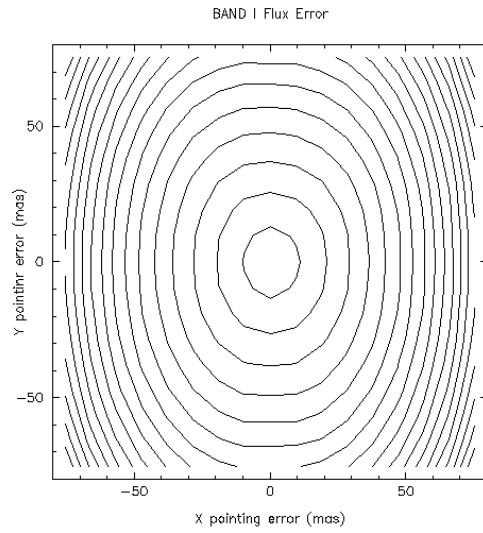


Figure 17 Average photometric error as a function of actual pointing error for a galaxy observed in Band I. The contours are at 1% intervals with the first one around 0,0 representing a 1% error.

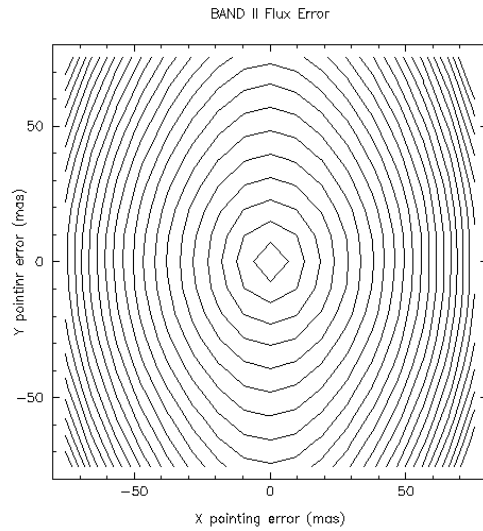


Figure 18 Average photometric error as a function of actual pointing error for a point source observed in Band II. The contours are at 1% intervals with the first one around 0,0 representing a 1% error.

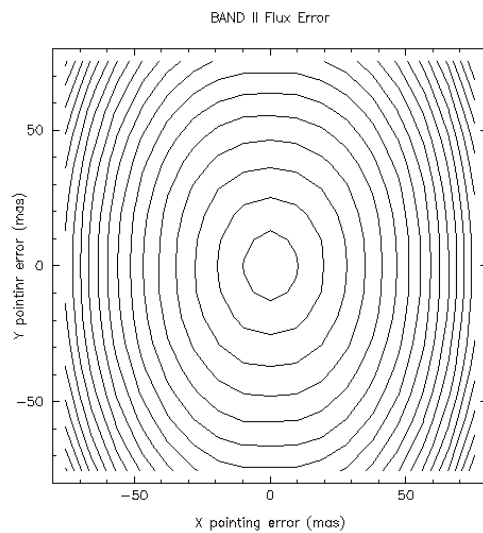


Figure 19 Average photometric error as a function of actual pointing error for a galaxy observed in Band II. The contours are at 1% intervals with the first one around 0,0 representing a 1% error.

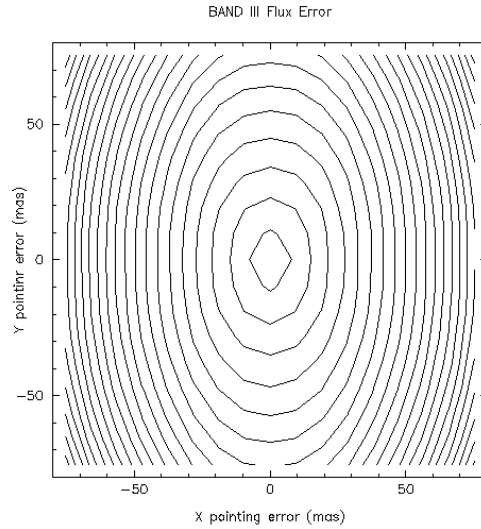


Figure 20 Average photometric error as a function of actual pointing error for a point source observed in Band III. The contours are at 1% intervals with the first one around 0,0 representing a 1% error.

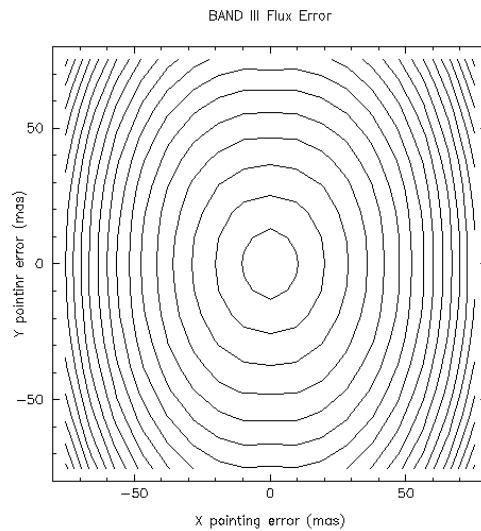


Figure 21 Average photometric error as a function of actual pointing error for a galaxy observed in Band III. The contours are at 1% intervals with the first one around 0,0 representing a 1% error.

For the photometric error we can see that, like the throughput, galaxies are less affected than point sources. We can also see that if we can determine the actual position that we observed after the fact, then we can calibrate even in the worst case to around 1% with a 10mas uncertainty in the position.

4.0 Observing Strategies, Number of Targets, and Number of Target Sets

The number of MSA target sets that a program needs to observe all of its targets is a distinguishing characteristic of the two observing strategies. The sweet spot strategy sacrifices multiplexing efficiency for throughput. So when there are a very large number of potential targets it will be optimal. On the other hand, for a smaller number of interesting targets it will take more target sets to observe them all in the sweet-spot strategy.

We used an approximation to determine how many targets can be observed from a list of possible targets. This approximation is required because the number of targets sets is not just $1/m$. This would only work if the sweet spots could be arranged in a mosaic that would cover all the possible target locations in $1/m$ pointings. Instead it is a closer approximation to assume that each new target set starts from scratch and can observe $m \times (\text{number_of_remaining_targets})$. In addition, we assume that no matter how small the multiplexing efficiency, you can always observe two targets. This is because we can move the first target within the sweet spot and we can roll about the first target. With these three degrees of freedom we should be able to always get two targets except in the case for a very small number of targets and a small multiplexing efficiency. After the first two targets are observed, we assume that the position and roll are fixed. Then the number of observable targets, N , is just $N=2+m(T-2)$ when T is the total number of possible targets and m is the multiplexing efficiency. For small values of m this may overestimate the number of target sets that are needed to reach 90% coverage.

Table 1 Number of MSA target sets needed to observe 90% of the targets

Observing Mode	5 Targets	20 Targets	100 Targets	>1000 Targets
One-shutter-dither	1	1	1	1
Sweet-spot 40% FOV	2	4	4	1
Sweet-spot 30% FOV	2	4	6	1
Sweet-spot 25% FOV	2	5	7	1
Sweet-spot 20% FOV	2	5	8	1

Table 1 shows in green which observing mode is preferred depending on the number of targets. The 100% multiplexing efficiency of the one-shutter-dither mode allows all targets to be observed in a single setting. If you have a very large number of potential targets such that there is always one available, then sweet spot observing is preferred. It is not clear if this is ever the case, especially when the sweet spot becomes very small.

In general, it looks like there will be cases for each observing mode. The higher average throughput of the sweet-spot mode may overrule the lower multiplexing efficiency for some science cases.

4.1 Observing Strategy and Pointing Requirements

The sweet-spot observing mode is highly dependent on the accuracy of the target acquisition. The size of the sweet spot decreases as the pointing uncertainty increases. This effectively decreases the efficiency of the instrument. The one-shutter-dither strategy, on the other hand, is only affected by pointing accuracy to the degree that the correct shutter is opened. As the targets are dithered over a whole shutter when they

become closer to the next shutter than to the original shutter, the next shutter must be opened.

We can determine an estimate of the needed pointing accuracy for the one-shutter-dither option by assuming that we do not want to lose more than 10% of the throughput due to a pointing error for 95% of the observations. From the throughput figures we can see that for a point source in Band I and a galaxy in Band III, a 45mas pointing error leads to a decrease in the average throughput of around 10%. Therefore, the one-sigma pointing accuracy required for the one-shutter dither is 22 mas.

Again it is important to note that the one-shutter-dither is less sensitive to decreases in the pointing accuracy than the sweet spot observing strategy

5.0 Target Acquisition Options

As was stated above because of the inaccuracy in the GSC-2, we will have to make some kind of target acquisition observation. To get to the required accuracy level we will need to also make some kind of measurement of the location of the mirror. The baseline target acquisition process is to observe a set of ~ 5 stars at two locations separated by $\frac{1}{2}$ of the shutter pitch (currently, this would be 130mas). Then, using some form of least squares solution, one would determine the location of the acquisition targets and calculate the required dither to get to the science location.

One option that is now open with the relaxed requirements of the one-shutter-dither strategy is to only observe a single target star. In Figure 22 (from Jakobsen 2004)

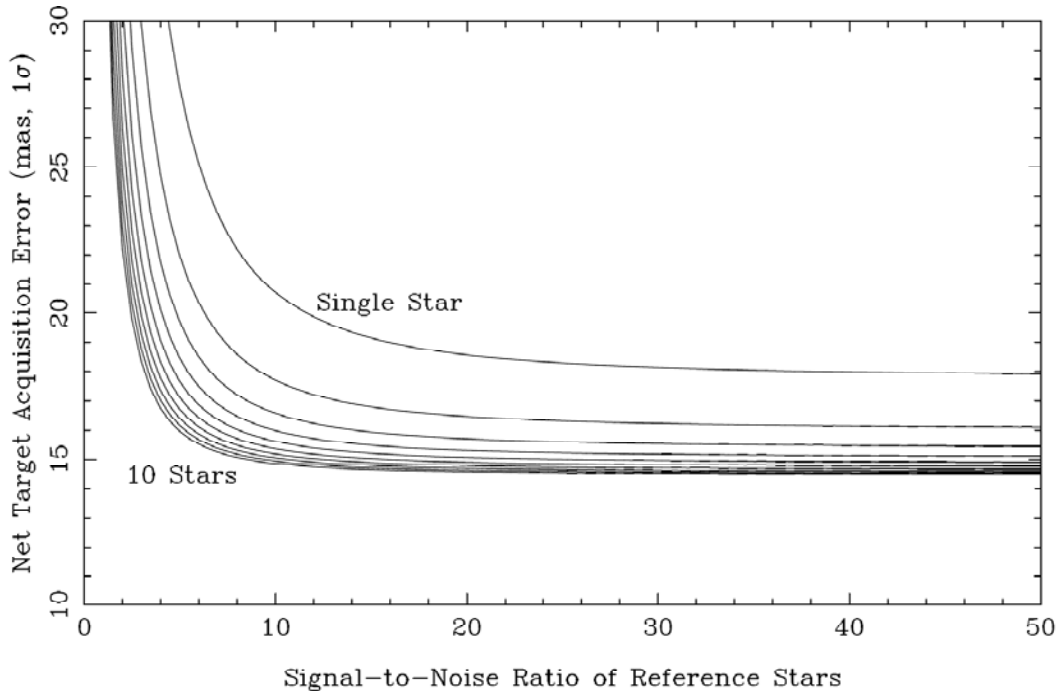


Figure 22 Accuracy of TA for different number of targets and S/N ratios

We can see that with a single star once the S/N ratio is greater than 20 the accuracy can be as good as 18mas.

A downside of using only a single target star is that if there is something wrong with the star the whole acquisition can be thrown off. The advantage is that the on-board software

is simpler in that it doesn't have to perform the least squares solution and reject any of the outliers. Whether this reduced complexity is worth the added risk needs to be addressed.

6.0 Conclusions

We have shown that an alternative NIRSpec observing strategy, one-shutter-dither, has several advantages over the current baseline strategy of only observing targets in the sweet spot of the shutters. This new strategy has around a 20% lower average throughput but compensates for that with a larger multiplexing efficiency. The decrease in the number of MSA target sets needed to observe a set of targets ranges from a factor of two to a factor of five. This more than compensates for the lower average throughput.

In addition, this observing strategy is much less sensitive to the accuracy of the target acquisition. In fact, the relaxed TA requirements for this strategy make it possible to use only a single star for target acquisition rather than the five stars required in the baseline observing strategy. This should simplify both the on-board processing requirements and the observation planning for some observations. There is still the need for the five reference star target acquisition for both the baseline sweet-spot observing strategy and for fixed slit observations.

Finally, the relaxed target acquisition requirements may even allow ground-based observations to be used for planning of MSA observations but that will require further analysis to determine the achievable accuracy of these images.

7.0 References

Ferguson, H.-C., et al. 2004, ApJ, 600, L107

Jakobsen, P. "NIRSpec Target Acquisition and the Micro Shutter Array" 2004, ESA Technical Memorandum Rev 1.0,