NICI Technical Memorandum

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Subject: Coronagraphic masks and Stops
Distribution: Dtoomey, Cftaclas

I. Introduction.

NICI will see a variety of observing scenarios so it is impossible to tailor its coronagraphic parameters to each one. Since it is a facility instrument, the goal is to provide a basic set of coronagraphic options. This note gives a spectrum of occulting mask and Lyot stop sizes for the NICI coronagraph. Working assumptions are:

a. NICI must operate over the 1 – 5.5 micron wavelength region.
b. When system, calibration and all other masks are accounted for, we will have positions for four coronagraphic masks and four Lyot stops.
c. Over as much of the operating wavelength range as possible there should be a “small” occulting mask of order 4-6 Airy rings in radius and a “large” occulting mask of order 8-10 Airy rings in radius.
d. All masks are Gaussian-apodized profiles with the “radius” interpreted as the radius at which the mask intensity transmission is 50%.

II. Occulting Masks.

There are two fundamental difficulties to coming up with a basic set of occulting mask parameters for NICI. The first is the required wavelength range and the second is the non-ideal nature of the problem. For a given one-parameter mask profile like a top-hat or Gaussian, the re-imaged pupil plane is determined in the diffraction limited case by that parameter measured in units of Airy radii ($q_o = l / D$). Ignoring for the moment that we are not in the diffraction limited domain we have a problem in that over the fivefold dynamic range of wavelength a given mask will appear to the light as having varied in size by the same factor of five. Thus a useful 5 ring mask at J is only 1.25 Airy rings in radius at $l = 5m\text{m}$.

The lack of ideal conditions in the instrument is a result of atmospheric turbulence and our connection to it through the adaptive optics system. Now there are several independent parameters that can affect coronagraph performance for a given mask size:

a. The Fried radius measures the fundamental strength of the atmospheric turbulence and sets a lower limit on the residual background in the instrument.

b. The outer scale determines the low frequency content of the wave front that contribute to the residual low order aberrations and to the background in the important region of mask transparency near the central star.
c. Guide star brightness determines the number of photons available for wave front sensing which both affects post AO wave front errors and residual tip-tilt which directly impacts mask performance.
d. Wind speed, determines the ability of the AO system to track changes in the atmosphere.

Given that each of these factors can vary independently, the parameter space for possible instrument conditions is large and a reasonable approach is too make sure that good turbulence dominated performance can be achieved under the best conditions and that a options are available to meet a range of operating conditions. Here we rely on experience with other instruments in setting the minimal need for a large and small mask over the operating band pass of the instrument. It would be ideal if we could have a range of masks at each wavelength to match all possible operating conditions but this is just not feasible.

Appendix A is a Mathcad script that gives a mask size distribution loosely optimized to give good mask coverage over the required instrument band pass. The physical mask half-power radii are: 0.3, 0.5, 0.7 and 1.0 arcsec. This set is by no means unique. As the plot in the appendix shows, the most difficult problem is getting masks in the 8-10 ring region at all wavelengths. There is no small mask (4-6 Airy rings) at the short wavelength end. We would expect, however, that AO performance and residual tip-tilt would be more of a factor at short wavelengths and 0.3 arcsec is already a groundbreaking angular scale for these types of observations. Nevertheless, we expect that there will be a range of additional masks available for insertion in the user position that both meet this need and fill in any other gaps in the baseline mask set.

III. Lyot Stops.

The Lyot stop set for NICI is somewhat easier to design. In an ideal diffraction-limited system, there is a simple relationship between the focal plane mask (measured in Airy rings) and the resulting pupil plane intensity distribution. In general, for an N ring mask, a typical Lyot stop would be undersized by a factor of $\sim \frac{1}{2N}$. This assures that the residual diffracted light is of order 0.01 of its original value, leaving the focal plane scatter dominated. Thus for a "small mask" of order 5 rings a Lyot stop undersized by 10% of the pupil should be sufficient. The pupil central obscuration should be masked by the same factor from 0.16 to 0.26 – 10% of the pupil diameter not 10% of the obscuration. No matter the wavelength, an appropriate Lyot mask for a 5 Airy ring mask should be undersized by 10% independent of wavelength. Given the guideline above for a "large" and "small" mask at all wavelengths, a minimal stop set would be undersized by 5% and 10%. Adding the presence of the atmosphere and the need for some tolerance in pupil alignment, we add masks undersized by 15% and 20% as well.

IV. Conclusions.

A range of physical occulting mask half power radii that would provide a reasonable range of mask coverage over the NICI operating wavelength range is: 0.3, 0.5, 0.7 and 1.0 arcsec. The mask sizes in Airy radii available in the standard filters is:

$$\text{MASKS} = \begin{array}{cccccc} \text{Band} & \lambda o & 0.3'' & 0.5'' & 0.7'' & 1.0'' \\ \left[\text{"J"}\right. & 1.25 & 9.308 & 15.514 & 21.72 & \left.31.028\right] \\ \text{"H"} & 1.65 & 7.052 & 11.753 & 16.454 & 23.506 \\ \text{"K"} & 2.2 & 5.289 & 8.815 & 12.341 & 17.63 \\ \text{"L"} & 3.45 & 3.373 & 5.621 & 7.869 & 11.242 \\ \left[\text{"M"}\right. & 4.8 & 2.424 & 4.04 & 5.656 & \left.8.08\right] \end{array}$$

A corresponding set of Lyot stops that will work with these masks over the NICI band pass is:

Mask Number	Inner Radius (Pupil = 1)	Outer Radius (Pupil = 1)
1	0.21	.95
2	0.26	0.9
3	0.31	0.95
4	0.36	1.0

Appendix: Coronagraphic Masks

Coronagraph Mask Sizes

Introduction.
We assume that after all overhead for clear, blank-off and user masks that we will have four positions available for NICI occulting masks. Assuming a fixed parametric form for the mask intensity profile the reimaged pupil intensity is determined by the size of the mask in Airy rings. Since this will vary with wavelength we want to assign the mask sizes so that they provide a reasonable range of options over the operating bandpass. Typically, at a given wavelength, we would want a relatively large mask, say 8-10 Airy rings and a smaller one for very close companion work, say 4-6 rings. We take the K band as the as the instrument baseline.

I. System Parameters

$\lambda 1 := 1. \quad \lambda 2 := 5.5$ System operating wavelength range (microns)

$D := 8.$ Telescope aperture (meters)

$r2s := .206265$ Converts to arcsec

$N := 200 \qquad d\lambda := \frac{\lambda 2 - \lambda 1}{N} \qquad j := 0..N \qquad w_j := (j-1)\cdot d\lambda + \lambda 1 \qquad d\lambda = 0.023$

II. Derived Parameters:

$\theta(\lambda) := \frac{\lambda}{D}\cdot r2s$ Airy ring in arcsec

$n(\lambda, s) := \frac{s}{\theta(\lambda)}$ Size in Airy rings of a mask whose angular size is s arcsec.

$\theta_K := \theta(2.2) \qquad \theta_K = 0.057$ Airy ring at K (arcsec)

III. Choosing Masks.

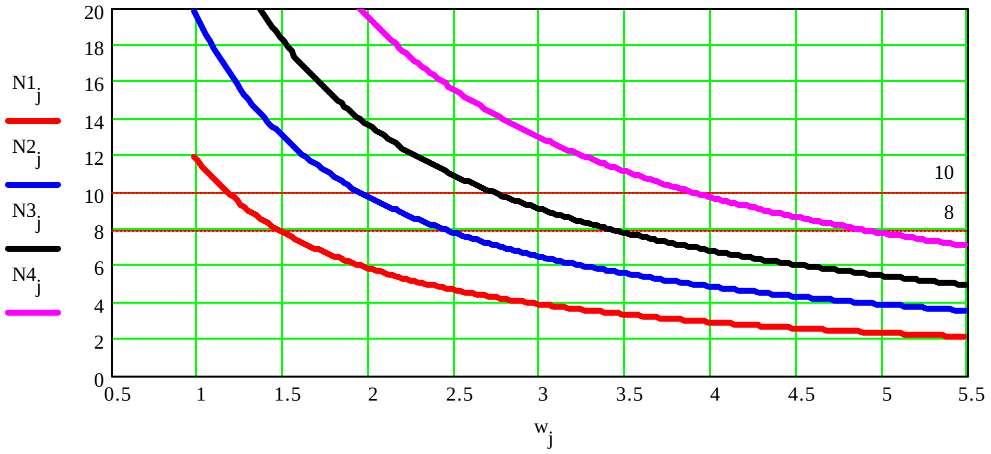
At K a half arcsec mask would be about 8.8 Airy rings so we can start with a mask that is ~0.5 arcsec and then fill in the rest based on the criteria that we get a range of mask sizes measured in Airy rings, as well as a reasonable range measured and arcsecs. There is no uniques way to do this and with four masks it is hard to cover all mask sizes at all wavelengths.

$s1 := .3 \qquad N1_j := n\left(w_j, s1\right)$

$s2 := .5 \qquad N2_j := n\left(w_j, s2\right)$

$s3 := .7 \qquad N3_j := n\left(w_j, s3\right)$

$s4 := 1. \qquad N4_j := n\left(w_j, s4\right)$



This choice gives us a reasonable coverage over the instrument operating range. Emphasis was placed more on small mask coverage at the long wavelength end rather than at J and H since we would expect the AO performance to degrade at these shorter wavelengths and because even a 10 ring mask is only 0.3 arcsec in radius.

Below we show the resulting mask size distribution at standard bandpasses:

$$\mathrm{MASKS} := \begin{bmatrix} \text{"J"} & 1.25 & n(1.25, s1) & n(1.25, s2) & n(1.25, s3) & n(1.25, s4) \\ \text{"H"} & 1.65 & n(1.65, s1) & n(1.65, s2) & n(1.65, s3) & n(1.65, s4) \\ \text{"K"} & 2.2 & n(2.2, s1) & n(2.2, s2) & n(2.2, s3) & n(2.2, s4) \\ \text{"L"} & 3.45 & n(3.45, s1) & n(3.45, s2) & n(3.45, s3) & n(3.45, s4) \\ \text{"M"} & 4.8 & n(4.8, s1) & n(4.8, s2) & n(4.8, s3) & n(4.8, s4) \end{bmatrix}$$

$$\begin{array}{c} \\ \mathrm{MASKS} = \end{array} \begin{array}{cccccc} \text{Band} & \lambda\text{o} & 0.3'' & 0.5'' & 0.7'' & 1.0'' \\ \left[\begin{matrix} \text{"J"} \\ \text{"H"} \\ \text{"K"} \\ \text{"L"} \\ \text{"M"} \end{matrix}\right. & \begin{matrix} 1.25 \\ 1.65 \\ 2.2 \\ 3.45 \\ 4.8 \end{matrix} & \begin{matrix} 9.308 \\ 7.052 \\ 5.289 \\ 3.373 \\ 2.424 \end{matrix} & \begin{matrix} 15.514 \\ 11.753 \\ 8.815 \\ 5.621 \\ 4.04 \end{matrix} & \begin{matrix} 21.72 \\ 16.454 \\ 12.341 \\ 7.869 \\ 5.656 \end{matrix} & \left.\begin{matrix} 31.028 \\ 23.506 \\ 17.63 \\ 11.242 \\ 8.08 \end{matrix}\right] \end{array}$$